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The Metrics of Spacecraft Design Reusability and Cost Analysis as Applied to CubeSats

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The Metrics of Spacecraft Design Reusability and Cost Analysis as Applied to CubeSats

by

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Dedication

I wish to dedicate this thesis to my friends and family who have helped me achieve my dreams and who have never stopped believing in me.

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I would like to thank Dr. Glenn Lightsey for his constant encouragement and support of my ideas. Additionally, Lisa Guerra provided continuous insight into the world of Systems Engineering and offered suggestions and improvements to my work on a continuous basis, I thank her from the bottom of my heart. Special thanks are in order for the entire Satellite Design Laboratory, without whom, the analysis in this document would not have been possible. Specifically, I would like to thank my dear friends Henri Kjellberg and Travis Imken who always acted as the wall off which my ideas bounced. Finally, I thank the second half of "Brumble" for his endless love and support and fantastic listening skills.

Abstract

The Metrics of Spacecraft Design Reusability and Cost Analysis as Applied to CubeSats

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The University of Texas at Austin (UT-Austin) Satellite Design Lab (SDL) is currently designing two 3U CubeSat spacecraft – Bevo-2 and ARMADILLO – which serve as the foundation for the design reusability and cost analysis of this thesis. The thesis explores the reasons why a small satellite would want to incorporate a reusable design and the processes needed in order for this reusable design to be implemented for future projects. Design and process reusability reduces the total cost of the spacecraft, as future projects need only alter the components or documents necessary in order to create a new mission. The thesis also details a grassroots approach to determining the total cost of a 3U CubeSat satellite development project and highlights the costs which may be considered non-recurring and recurring in order to show the financial benefit of reusability. The thesis then compares these results to typical models used for cost analysis in industry applications.

The cost analysis determines that there is a crucial gap in the cost estimating of nanosatellites which may be seen by comparing two widely-used cost models, the Small

Satellite Cost Model (SSCM <100 kg) and the NASA/Air Force Cost Model (NAFCOM), as they apply to a 3U CubeSat project. While each of these models provides a basic understanding of the elements which go into cost estimating, the Cost Estimating Relationships (CERs) do not have enough historical data of picosatellites and nanosatellites (<50 kg) to accurately reflect mission costs. Thus, the thesis documents a discrepancy between widely used industry spacecraft cost models and the needs of the picosatellite and nanosatellite community, specifically universities, to accurately predict their mission costs. It is recommended to develop a nanosatellite/CubeSat cost model with which university and industry developers alike can determine their mission costs during the designing, building and operational stages. Because cost models require the use of many missions to form a database, it is important to start this process now at the beginning of the nanosatellite/CubeSat boom.

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Chapter 1: Introduction

Satellites have been built and launched for over sixty years. Initially, satellites were small with simple payloads. Over time these payloads became bigger, necessitating larger, more complex and expensive spacecraft. In the past decade, small satellites have reemerged as a lower cost alternative space platform. There are four classifications, summarized in Table 1.1, of small satellites which are gaining in popularity. Those spacecraft having a mass between 0.1-1 kilograms are considered “picosatellites” while those with masses between 1 and 10 kilograms are called “nanosatellites.” Larger classes of spacecraft include “microsatellites” and “minisatellites”, having masses between 10-100 kg and larger than 100 kg, respectively. The scope of this research applies to spacecraft within the nanosatellite class, as defined in Table 1.1, which are being developed at the University of Texas at Austin.

Table 1.1 – Satellite classification by typical mass ranges. [1]

Satellite classification	Typical Mass Range
Picosatellites	0.1-1 kg
Nanosatellites	1-10 kg
Microsatellites	10-100 kg
Minisatellites	>100 kg

California Polytechnic State University (Cal Poly) has established a standard launching mechanism for nanosatellites called the Poly-Picosatellite Orbital Deployer (P-POD). The P-POD is frequently flown as a secondary payload on unmanned launch vehicles, making it easier for small satellites which use the system to obtain launches. In order to use the P-POD, the spacecraft must be in the shape of 10 cm cubes – called

CubeSats. One CubeSat is called a 1-Unit (1U) cube. Multiple CubeSats may be combined to form various size configurations of Units, such as 1U, 2U, and 3U. The P-POD and CubeSat standard was first demonstrated in June 2003 with the launch of two P-POD devices and a total of six 1U CubeSats. [2]

CubeSats have the potential to change the economics of space access for numerous applications. Carolyn Johnson, a staff writer for the Boston Globe, writes in November 2011 that CubeSats:

> …have grown in importance. Some think they are poised to have a potentially profound impact on the big-budget space industry, where missions can routinely cost hundreds of millions, similar to the effect the advent of personal computers had on computing.[3]

U.S. Air Force Maj. David Shultz, head of the Colony Program Office, believes in the potential for CubeSats “to prove advanced technologies on orbit more quickly and affordably than on larger platforms.”[4] Additionally, the National Reconnaissance Office (NRO) and the National Science Foundation (NSF) are already using the CubeSats for a variety of missions, including space weather, signifying the transition from purely educational purposes to new applications in scientific research and technology validation. One of the Program Directors of the NSF CubeSat Space Weather Initiative, Dr. Therese Moretto Jorgenson, has stated that:

> An exciting possible direction for expansion of the use of CubeSats is the implementation of constellations of Earth-observing or space environment-monitoring CubeSats, which would truly transform our capability to study Earth-related problems on a global scale. Equally important, CubeSat projects can play a crucial role in ensuring that the next generation of engineers and space scientists have the skills required to carry the capability for space-based observations into the future. They offer unique opportunities for hands-on education and training

for students and young professionals in aerospace engineering and experimental space science; and they provide end-to-end experience on real space projects.[5]

The cost analysis of spacecraft missions and the associated systems engineering processes has always been an important parameter for mission planners. CubeSat projects, however, are a new development in the domain of traditional spacecraft programs and many engineering processes and practices which have been successfully implemented on larger scale satellite projects have never been applied, and may not be appropriate, on the smaller scale. Lacking a suitable body of evidence that can be applied to small satellites, many small satellite projects are operated with purely ad hoc or even without established engineering practices. A new set of practices is needed that is appropriate to the schedule, budget, and risk tolerance of this new class of satellites. These practices are used on the small satellite projects that are performed within the Satellite Design Lab (SDL) at the University of Texas at Austin.

The SDL exists as part of the Department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin (UT-Austin), and strives to further the development and potential of student built small satellites. The SDL has a tradition of designing, building, launching, and operating student built satellites, and has successfully launched two microsatellites (~25 kg each) and one nanosatellite (~1 kg) within the past 3 years. The SDL is currently designing two 3U CubeSats (~4 kg) for launch within the next two years, known as Bevo-2 and ARMADILLO. These missions are discussed in further detail in Chapter 2. The SDL employs systems engineering practices on a regular basis in order to achieve successful results. Fundamental topics in systems engineering are introduced in readily available texts [6]-[8].

Both of the current SDL projects, Bevo-2 and ARMADILLO, are led by Student Program Managers, typically graduate students, and student subsystem leads, with the Faculty Principal Investigator serving as a mentor and advisor. The management subset of the team for both satellites is approximately 15 students while the entire team is approximately 45 students. Since the SDL is completely student-run, two simultaneous satellite design projects would be an overwhelming task and the resulting designs would not represent the full design quality that is possible in the SDL. Thus, the two missions were designed with the concept of design reusability in mind. In other words, though the Bevo-2 and ARMADILLO missions have very different mission objectives and customers, the main structural design and component selections for each satellite remain very similar.

This thesis serves to document the methods for measuring reusability and to determine the level of reusability of the UT-Austin 3U CubeSat design. The thesis identifies the reusability of the spacecraft hardware and software design. The thesis also determines the reusability level of the systems engineering processes employed by the SDL in the course of developing customer deliverables. Design and documentation reusability reduces the total cost of the spacecraft, as future designs simply need to make the necessary modifications to this platform in order to create new missions. In order to accommodate this future use, the costs associated with designing, building and testing a 3U CubeSat project have been documented using a grassroots approach and the results obtained by this method are compared with typical industry models. This comparison serves to illustrate the benefits of a reusable CubeSat design as well as a student-managed satellite lab. Most importantly, the comparison also highlights the critical need for new small satellite cost models that are more accurate for this emerging class of satellites.

1.1 KEY HIGH-LEVEL DEFINITIONS

Each section within the thesis describes any relevant definitions or phrases at the beginning of the section. However, there are a few phrases which apply to the entire work and are defined here.

"Life cycle" refers to the entire lifetime of the satellite mission, from conceptual design to operations in-orbit, as shown in Figure 1.1. It is important to analyze the entire life cycle of a satellite because the design and development phases will have different requirements and associated costs than the operational phase. Because the two 3U CubeSats used for analysis throughout this thesis are currently in the middle of the D-phase, as defined by NASA, the CubeSats have not completed a full design cycle. Many costs and reusability calculations are based upon the current spacecraft pre-integration status of which is shown by the solid vertical black line in Figure 1.1.

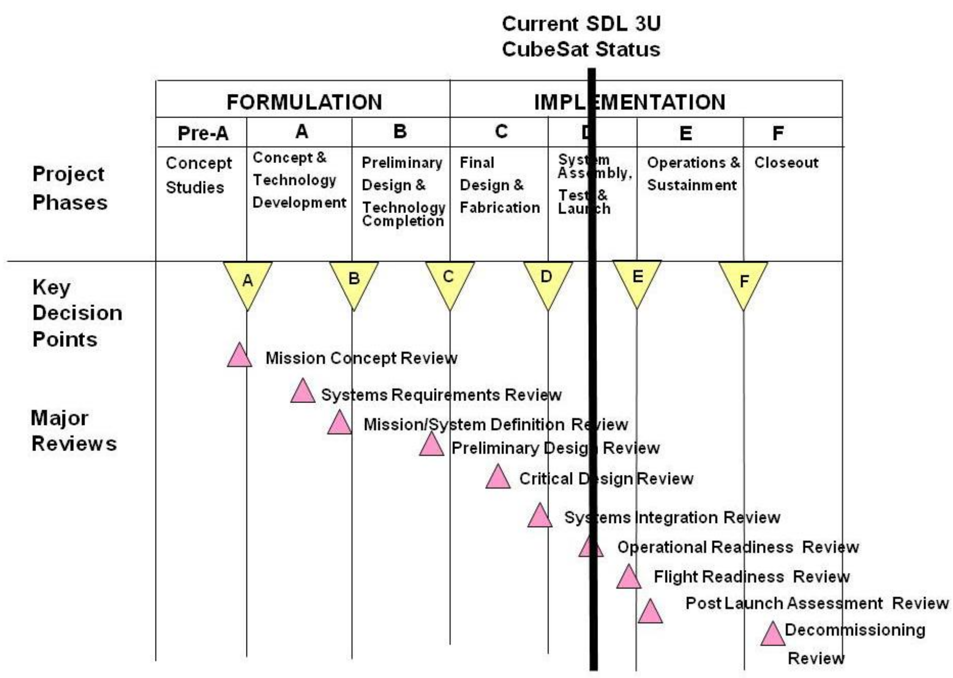


Figure 1.1 - Spacecraft life cycle. [9]

“Protoflight” components, or satellites, are often confused with the Engineering Design Unit (EDU) or flight spacecraft components. EDU components are primarily used for the interfacing between components in order to design and test the systems similar to those which will be flown on the spacecraft. Protoflight components are components which are interfaced with on a regular basis but will ultimately be part of the EDU spacecraft. These components may, however, be flight-qualified to fly on the flight unit and are treated with the same care as flight components.

“Highly capable” typically describes the UT-Austin 3U CubeSat. This description expresses the abilities of the satellite, including its six degree-of-freedom control, precise orbit determination, in-house designed cold gas thruster, and in-house designed star tracker. With these elements, the satellite is able to accomplish a wide range of mission objectives and is thus considered highly capable. While the UT-Austin cold gas thruster and star tracker are currently being developed in the SDL, to be considered a highly capable 3U CubeSat, the spacecraft need only contain similar devices and not necessarily have these devices designed in-house.

“Cost model” is often used to describe the methodology employed to determine the costs of a spacecraft mission. These costs include personnel, hardware, facilities, operations and management costs. Some specific cost models used in the satellite industry are detailed in Chapter 6.

The definition of “reusable” used within this research is not with regards to the reusability of the physical satellite, but rather with the satellite design. Throughout the thesis, the “spacecraft design” refers to the structural form or dimensions, the layout of the components, and the ability of the components to achieve specified performance requirements in order to satisfy the overall mission objectives. Thus, “reusable design” encompasses all of the trade studies and analyses from which the structural form, component layout and component selections are made. Since the satellite is so small and not designed to withstand re-entry through the Earth's atmosphere, it would be infeasible to reuse the physical satellite.

1.2 Motivation

This thesis was created from a goal to document the cost and reusability of a 3U CubeSat based upon an ARMADILLO mission objective. It also serves as an educational opportunity for SDL team members, as a resource for future small satellite mission planners, and it advances systems engineering processes for nanosatellites.

1.2.1 ARMADILLO Mission Objective Three

The ARMADILLO mission has three objectives, one of which serves as the primary motivation for this thesis. While the first two mission objectives of ARMADILLO involve the scientific experiments, the third mission objective states that the ARMADILLO mission shall "measure and track satellite life cycle costs and lead times for military, scientific, and commercial uses of a highly capable reusable 3U CubeSat bus design."[10] For the purposes of this thesis, measuring and tracking the life cycle cost is performed via a grassroots CubeSat cost analysis while in industry these metrics are typically established by parametric cost models. Lead times are affected by the initial phases of mission design – including the trade studies, preliminary mission-level analysis, etc. By measuring and tracking the design reusability of the 3U CubeSat via the hardware, software and systems engineering reusability, the SDL effectively measures and tracks the lead times necessary for spacecraft fabrication. Lead times are then decreased when the reusable design is applied to future missions in the reduced time it takes to move from the initial design phase to the EDU fabrication phase.

1.2.2 Educational Applications

Because the SDL is entirely comprised of students, the main philosophy held in the lab is to learn anything and everything necessary to make progress on the current satellite development. Many students leave their comfort zones and delve into unfamiliar concepts when joining the lab. Given this environment, small satellites are an excellent educational opportunity as university projects. The design, fabrication and test of small satellites gives students the real-world experience of being a satellite engineer while still in school. The concepts they learn in class are applied to satellite design and the lessons learned in the SDL are reapplied in the class setting. Students take these skills to industry and are already knowledgeable in many aspects of their professional duties.

The concept of design and process reusability permeates into the SDL mentality and work philosophy. Strict systems engineering practices were employed from the beginning of the Bevo-2 and ARMADILLO spacecraft designs. These practices include, but are not limited to: configuration management, mass, power and link budget analysis, interface control, orbit analysis, and requirements tracking. This method of organization allows for easier status tracking and enables the UT-Austin team to successfully meet the deadlines imposed by customers. Students are then trained on the systems engineering and configuration management practices by simply following lab protocol.

The systems engineering and configuration management practices documented throughout this thesis serve as a method of bringing new team members quickly up to speed. With a steep learning curve that a student must overcome when joining the SDL or assuming a leadership role, this thesis also facilitates the training for any new student, subsystem lead, lead systems engineer, or project manager. While beneficial to any curious student, this document is primarily geared towards those in leadership positions and will provide perspective on how systems engineering was done for the Bevo-2 and ARMADILLO missions which can be used to foster good systems engineering practices on future missions.

1.2.3 Military Applications

Because the ARMADILLO mission is an entry into the University Nanosatellite Program (UNP) competition which is managed by the Air Force Research Lab (AFRL), the SDL strives to apply this 3U CubeSat cost and reusability analysis to military applications. The government is looking for more reliable cost estimates and less expensive spacecraft missions. The cost methods described within this thesis clearly lay out each and every cost associated with the ARMADILLO mission. This improves the ability of small satellite program managers to more accurately plan and execute similar missions.

Additionally, the concept of a reusable design has direct application to the military because of their interest for rapid access to space. Spacecraft design reusability allows for a quicker design and fabrication process which enables the spacecraft to be launch-ready in a shorter period of time. As an example of the demonstrated military interest of a reusable design, the Air Force TacSat-2 and TacSat-3 satellites flew in 2006 and 2009, respectively. These two satellites had a primary mission goal of using existing technology, namely Commercial Off The Shelf (COTS) components, rather than spending resources on creating new devices in order to quickly integrate and launch military payloads.[11] These satellites, however, were on the order of 400 kg rather than the 4 kg of a nanosatellite like ARMADILLO. In addition, these satellite programs cost tens of millions of dollars rather than the projected $1.5 Million it would take to build and launch a 3U CubeSat. Through quicker design and fabrication, 3U CubeSats can help achieve rapid access to space as outlined in the Plan for Operationally Responsive Space:

> …the Commander, United States Strategic Command (CDRUSSTRATCOM) has expressed three desires: first, to **rapidly exploit** and infuse space technological or operational innovations; second, to **rapidly adapt** or **augment existing** space capabilities when needed to expand operational capability; and third, to **rapidly reconstitute** or replenish critical space capabilities to preserve operational capability.[12]

The first Operationally Responsive Space satellite (ORS-1) was launched into orbit in June 2011. ORS-1 cost less than $100 million and completed design and fabrication in approximately 30 months.[13] By developing metrics and documentation methods which demonstrate the life cycle costs and reusable design of a 3U CubeSat, the Air Force is provided with new tools to estimate the costs for nanosatellites and to show that these spacecraft are considerably less expensive than current larger scale military spacecraft.

1.2.4 Modular Spacecraft Applications

Measuring and tracking satellite life cycle costs encompasses tracking not only hardware, but personnel and miscellaneous costs as well. The measuring and tracking of lead times is accomplished via design reusability and the monitoring of the time from initial design planning to the ordering of the component. By designing with modularity in mind, the SDL is able to use the same component types or even entire subsystems on future designs. Thus, the time from initial design planning to design decision should be reduced. Currently, the trade study and detailed design phase of the design process – where components are selected based upon mission requirements – has taken approximately a year on the ARMADILLO mission. The two 3U CubeSat missions have completed the initial and final design phases and are in the midst of system assembly. Ultimately, reducing this phase will provide more time for the SDL to focus on other aspects of the project which need to be completed.

This local perspective of a modular or “standardized” 3U CubeSat design is specific to the UT-Austin Satellite Design Lab, but may be applied to a more global perspective as well. There are many commercial and academic entities which claim to have “standardized” 3U CubeSat bus designs and some that claim to have larger-scale “standardized” spacecraft designs. Table 1.2 through Table 1.4 show the elements of these “standardized” CubeSat spacecraft buses from previous and upcoming missions as well as those available through commercial markets. Some elements, such as the camera in Table 1.2, are included even though none of the missions use the element in order to show that the SDL spacecraft bus is a highly capable bus design.

Table 1.2 – Previous CubeSat missions with a "standardized" spacecraft bus.

	CP2 (Cal Poly)	QbX1, QbX2 (NRL, NRO)
Launch date	July 26, 2006 *Destroyed by launch failure	Dec. 8, 2010 *Telemetry indicates all systems nominal
Form Factor	1U	3U (Pumpkin)
ADC	Magnetorquers, 2-axis magnetometer, autonomous de-tumbling algorithm	3-axis stabilized, MAI-100
Camera	None	None
CDH		C8051F120-based Pluggable Processor Module
COM	Single dipole antenna	Unknown
EPS	2 Li-ion batteries; Dual/triple junction solar cells; Max power draw of 3.6W	ClydeSpace EPS board and LiPo batteries; deployable solar panels

Table 1.3 – Upcoming CubeSat missions with a "standardized" spacecraft bus.

	SPA-1 Trailblazer (U. New Mexico)	ALL-STAR (Colorado Space Grant)	Coral bus (ComTech AeroAstro, Utah State)	KYSAT-1 (Kentucky Space)
Launch date	Planned 2012	TBD	TBD	TBD
Form Factor	1U	3U	3U	1U
ADC	Passive	GPS; Pointing accuracy of 1 deg; gyros, reaction wheels, magnetorquers, magnetometers	3-axis, momentum biased; Slew rates up to 0.5 deg/sec; Pointing accuracy better than 0.1 deg	Passive magnetic
Camera	None	Sensor = Aptina MT9P031; Lens = Marshall Electronics	ComTech AeroAstro Miniature Star Tracker	Unknown
CDH	Arduino processor	Atmel microcontroller & GPS interface microcontroller; Kingston data memory (2 GB); Everspin Configuration Memory (4 Mb)	Unknown	FM430 Flight Module (Pumpkin), MSP430 microcontroller
COM	Unknown	In-house design and test	UHF, S-band	Microhard S-band, StenSat UHF/VHF
EPS	SPA-1 technology; Body-mounted solar panels	Unknown	2 deployable solar array wings, Li-ion battery	ClydeSpace EPS, 2 LiPo batteries, 6 Spectrolab solar arrays
THR	Unknown	Cold gas Butane; 30.1 psi @ 20 deg C; DeltaV = 10 m/s; 104 cc liquid Butane, mass 75.2 g	Unknown	Unknown

Table 1.4 - Commercially available "standardized" CubeSat spacecraft buses.

	University of Toronto Generic Nanosatelite Bus	**Pumpkin**	**Boeing Colony-2 Bus[1]**	**ISIS**
Launch date(s)	Unknown	Unknown	Unknown	Unknown
Form Factor	20 cm cube	0.5, 1, 1.5, 2 or 3U	Unknown	3U
ADC	1 arc-min pointing, 3-axis ACS w/ tiny reaction wheels, sun sensors, magnetometer,	Unknown	4 Reaction Wheels; Control system designed to last weeks before desaturation needed (size smaller than 1U); 2 IMUs	Unknown
Camera	Star tracker	Unknown	2 star trackers	Unknown
CDH	ARM7 computers: housekeeping, ADC/propulsion, payload ops	Various choices of computers, pre-written software	Unknown	Unknown
COM	UHF uplink, S-band downlink	Unknown	Unknown	Unknown
EPS	Unknown	Pumpkin-supplied	Offset solar panel design, so the panels produce disturbing torques on the satellite	Unknown
THR	Cold gas thruster may be added per customer's request.	Unknown	Unknown	Unknown

Most of these entities are not forthcoming with their technology and/or development costs. Although the concept of a standard 3U CubeSat bus has been introduced in the nanosatellite community, there has yet to be any documentation regarding the systems engineering processes which go into making these satellites

[1] Colony-2 spacecraft bus projected to be less than $250,000 each according to a SpaceNews.com article from April 2010. See http://www.spacenews.com/military/100408-nro-taps-boeing-next-cubesats.html for more information.

operational, nor have there been computations to show the actual cost of building the spacecraft. Finally, many of these buses claim to have a reusable design, but have not addressed the metrics by which they measure reusability.

This thesis establishes and documents a set of metrics by which to measure the costs and reusability associated with the design, fabrication and testing of a student-built 3U CubeSat. This process could be extrapolated for industry-built spacecraft, if the data were to become available. These analyses may then be applied in academic, government and industry settings to provide a more accurate estimate of nanosatellite costs and design reusability. UT-Austin plans to share these results with the small satellite community and hopes that by disclosing the costs and reusability of the ARMADILLO nanosatellite, this research will offer a previously unknown insight into the design reusability and life cycle costs of a student-developed nanosatellite.

1.3 Thesis Organization

This thesis explores the reasons why a small satellite would want to incorporate a reusable design and the processes needed in order for this reusable design to be implemented for future projects. Design and process reusability reduces the total cost of the spacecraft, as future projects need only alter the components or documents necessary in order to create a new mission. The second portion of this thesis details a grassroots approach to determining the total cost of a 3U CubeSat satellite development project and highlights the costs which may be considered non-recurring and recurring in order to show the financial benefit of reusability. The thesis then compares these results to typical models used for cost analysis in industry applications.

Reusability, discussed in Chapter 3, is measured by three sets of metrics. First, the hardware percent reusability is calculated based upon the component selection for both the Bevo-2 and ARMADILLO missions. The methodology and assumptions for this hardware reusability are explained along with future applications for both academic and industry purposes. Next, a method for determining the reusability of the software written for Bevo-2 and ARMADILLO is explained based upon the SDL software architecture and coding philosophy, but because of the current status of the CubeSat software, actual calculated metrics are unavailable for analysis. Finally, the systems engineering processes implemented for the Bevo-2 and ARMADILLO satellite projects are identified and the percent of these documents which are reusable for future missions is explained and calculated.

Chapters 4 and 5 specify the 3U CubeSat cost analysis method used for the Bevo-2 and ARMADILLO satellites. The cost analysis begins with the highly detailed personnel cost associated with building the two satellites. Travel and facilities costs are included with the personnel cost. The grassroots cost analysis approach continues with detailed hardware cost listed for both the flight satellite and the Engineering Design Unit (EDU) development costs.

Chapter 6 then compares this grassroots approach with cost models typically used in industry to predict the cost of a satellite mission. The various assumptions for each cost model are identified and whether the Bevo-2 or ARMADILLO mission fits or does not fit within these assumptions is discussed.

Chapter 7 concludes the thesis with a summary of the 3U CubeSat reusability and cost analysis followed by concluding remarks and recommendations. The concluding remarks note the necessity of new cost models specifically designed for CubeSat spacecraft. The key recommendations begin with suggestions for the CubeSat community and are narrowed to recommendations for the continuation of systems engineering practices in the SDL.

Chapter 2: Background

As mentioned in the introduction, the Satellite Design Lab (SDL) is currently developing two 3U CubeSats (~4 kg) known as Bevo-2 and ARMADILLO. Bevo-2 is part of a joint-university project with Texas A&M University which is sponsored by NASA Johnson Space Center, called LONESTAR (Low Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and docking). This is a series of two-satellite missions where each satellite is designed by one of the two participating universities. While the current mission is meant as a technology validation for proximity operations between the UT and A&M satellites, at the end of the third mission the two satellites will autonomously rendezvous and dock with each other in Low Earth Orbit. The second 3U CubeSat currently being designed in the SDL is an entry into the University Nanosatellite Program (UNP) sponsored by the Air Force Research Lab (AFRL). This project is titled ARMADILLO – Attitude Related Maneuvers And Debris Instrument in Low (L) Orbit. The primary scientific experiments on board ARMADILLO are a Piezo-electric Dust Detector (PDD) being developed by Baylor University and a dual-frequency software-defined GPS receiver known as FOTON being developed by the Radionavigation Laboratory at UT-Austin. The PDD is designed to collect in-situ data on sub-millimeter space debris particles. The FOTON dual-frequency GPS receiver will measure GPS radio occultations to study the ionosphere. Both satellites (Bevo-2 and ARMADILLO) have significantly advanced capabilities over the current state of the art for the CubeSat class of mission, such as active guidance, navigation, and control systems.

2.1 SATELLITE DESIGN LAB ORGANIZATION

The UT-Austin Satellite Design Lab (SDL) is comprised of approximately 45 students split into the Student Program Managers, Subsystem Leads and Subsystem Members. During the 2011-2012 school year there are three projects taking place simultaneously: FASTRAC, Bevo-2 and ARMADILLO. FASTRAC is currently in the post-launch operations phase [14] while Bevo-2 and ARMADILLO are in pre-launch design and fabrication stages. Thus, the SDL has three Student Program Managers – all of whom are aerospace engineering graduate students. The Subsystem Leads are mainly upperclassmen with a few graduate students also acting as a Lead. The majority of students (mostly undergraduate and representing a range of engineering disciplines) are assigned to work on the various spacecraft subsystems.

The spacecraft subsystems are categorized according to their various functions:

- Attitude Determination and Control (ADC) has the task of making sure the satellites will maintain the pointing accuracy needed for the mission objectives.
- Command and Data Handling (CDH) is responsible for the flight computer and the flight operations on-board the satellite.
- Communications (COM) is the primary method of interacting with ground stations while in orbit and downlinking mission data for the successful completion of the mission objectives.
- Electrical Power System (EPS) is responsible for generating and distributing the power necessary for the subsystems to operate.
- Navigation Visual System (NVS) is also known as the camera system. NVS is responsible for the operations of the on-board camera which also functions as a star tracker.

- Structure/Integration (STR) is responsible for the overall structure of the satellite. The computer modeling, drawings, structural and thermal analyses are also included. As the spacecraft transitions from design to fabrication, the Structure team becomes the Integration team. At this point, the team's responsibilities shift to managing the physical integration and fabrication of the spacecraft.
- Systems Engineering (SYS) coordinates the technical management of the mission and spacecraft design and development, including the physical and electrical integration of all subsystems to ensure a successful flight and completion of mission objectives. SYS manages the personnel, requirements, timelines, test plans and facilities. SYS is also responsible for generating mission-level simulations and analyses.
- Thruster (THR) is responsible for the in-house designed cold gas thruster. The thruster consists of three tanks, three valves and an exit nozzle. The THR team is responsible for the design, assembly and testing of the device while the 3D rapid printing fabrication task is contracted to an outside company.

Bevo-2 and ARMADILLO have very different mission objectives, but a large portion of their design processes, hardware selection and software packages are identical. The SDL has designed the spacecraft using the philosophy of design reusability, allowing future missions to simply replace the 3U CubeSat payload section and create a brand new mission. This payload section is illustrated in the ARMADILLO model shown in Figure 2.1 and contains hardware specific to the mission. For ARMADILLO, this module contains the star tracker, Piezoelectric Dust Detector and FOTON dual-frequency GPS receiver. For Bevo-2, the payload module houses the DRAGON GPS receiver in addition to the star tracker. The drawing also highlights the other two modules – the Bus and ADC modules – each roughly a 1U Cube (10 cm linear dimension). The Bus module contains the subsystems necessary for power, communications and command handling, while the ADC module is responsible for the attitude control of the spacecraft. Each spacecraft subsystem is responsible for generating its own software to operate its devices. The CDH subsystem then acts as the interface between all the subsystems and their respective components so that no two components directly communicate with each other, but rather the communication is directed through the CDH subsystem. In this way, the CDH subsystem is responsible for controlling the interaction between subsystems and ensuring functionality between components. Additionally, subsystems organize and analyze their own component testing.

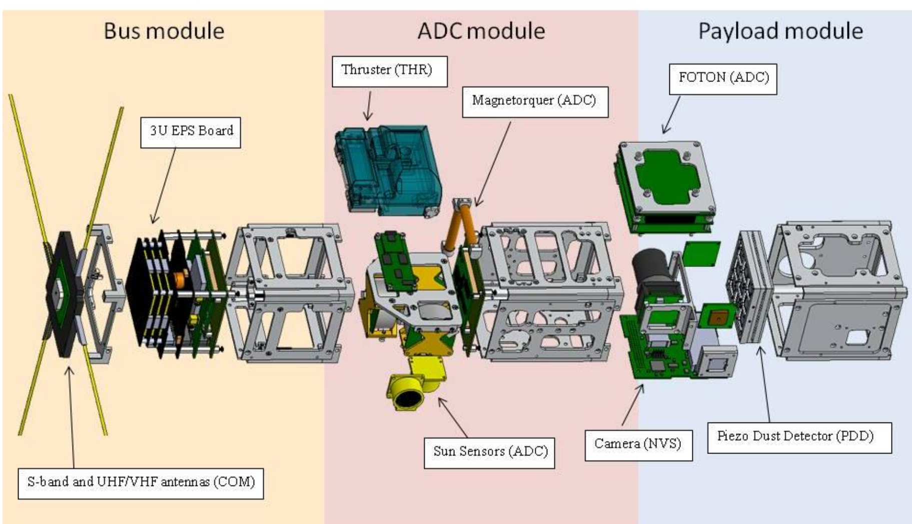


Figure 2.1 - ARMADILLO design modularity.

2.2 KEY LAB-SPECIFIC DEFINITIONS AND ASSUMPTIONS

For the purposes of the methodologies to be laid out in the following chapters, several key assumptions must be noted with respect to the design and development of the Bevo-2 and ARMADILLO satellites. These are:

1. The only contributed or donated hardware components on the ARMADILLO mission are the Piezo-electric Dust Detector (PDD) being developed, designed and delivered by Baylor University and the FOTON GPS Receiver being developed by the Radionavigation Laboratory at UT-Austin. For the Bevo-2 mission, the only donated hardware is the DRAGON GPS receiver from NASA Johnson Space Center (NASA-JSC).
2. As mentioned in the first assumption, the PDD, DRAGON and FOTON are not being built by the students in the SDL. These devices are considered donated by a subcontractor and are evaluated as a zero cost for the flight units. Because students are not developing these devices, there is no associated development cost. Both the flight and development cost methodology will be detailed in the hardware cost analysis of Chapter 5.
3. Two additional devices, the Kraken interface board and the cold-gas thruster, are being manufactured by a subcontractor. Students develop the designs and test the prototypes, but the physical fabrication, or in the case of the thruster - the printing of the device is left to a professional company. These costs are reflected in both the development and flight unit costs as detailed in the cost analysis of Chapter 5.
4. With the exception of these few subcontractors, the entire satellite is designed and built by students at UT-Austin. Additionally, the SDL itself

is student managed. Further discussion on this is explored in the previous section (2.1).

5. Because UT-Austin is designing a 3U CubeSat and desires to fly on a multitude of launch vehicles, the SDL chose to follow the 3U design specifications put forth by the CubeSat community and developed by Cal Poly.[15] Following these standards allows for easier flight qualification and potentially more launch opportunities.
6. The SDL is able to apply lessons learned from past experiences in the design, fabrication, and operation of small satellites during the past ten years. In fact, lessons are gathered on a daily basis from the two spacecraft which make up the FASTRAC mission– Emma and Sara Lily– which are currently in orbit about the Earth. Further discussion of these experiences is provided in the "Past Missions" section (2.3).
7. Most of the current SDL work is not restricted in any way. However, the Bevo-2 and ARMADILLO missions do have some components which have restricted access according to the International Traffic in Arms Regulations (ITAR). ITAR policies require that some hardware may not be accessed by non-US citizens and may not be taken out of the country without explicit consent from the US Government. Because of the use of ITAR hardware, the SDL has a separate access-restricted room in which the ITAR-related hardware is stored and tested.
8. The SDL has a Class 100 Clean Bench which is used to integrate the EDU and flight satellites for both Bevo-2 and ARMADILLO.
9. While the SDL is responsible for preliminary testing of all components and subsystems as well as initial full system testing, the pre-launch

integrators (NASA and AFRL) are responsible for flight qualifying the satellite at their respective facilities. These test costs are not included in the cost estimates.

10. Given the iterative nature of designing a satellite, the values used throughout this thesis, such as the mass and number of components within a subsystem, may change over time. Thus, a data cut-off date is necessary in order to apply all the analyses in this thesis to a common set of data from a given point in time. Because it is a student lab, a data cut-off date was chosen to correspond with the end of the semester: December 11, 2011. This is the date where all data was saved in separate files and used for analysis. Because this data cut-off date is not reflective of the end of the project life cycle, costs are extrapolated based upon accumulated data. This extrapolation process is explained in Chapters 4 and 5.

These assumptions apply to all aspects of the two satellite projects. Specific assumptions will be identified in each section of this thesis as warranted. For ease of later use, all assumptions are gathered in one location – Appendix A.

2.3 Past Missions Developed in the UT-Austin Satellite Design Lab

The University of Texas at Austin (UT-Austin) has learned the benefit of following systems engineering practices through participation in three satellite design projects to date; two of these projects were entries into the University Nanosatellite Program (UNP) competition run by the Air Force Research Lab (AFRL). In this section, a brief overview is given for each satellite mission while the systems engineering approach UT-Austin now employs is explained in a later section (3.5).

2.3.1 FASTRAC

Formation Autonomy Spacecraft with Thrust, RelNav, Attitude and Crosslink, also known as FASTRAC, was the winning entry of the University Nanosatellite Program UNP-3 competition in January 2005. FASTRAC is comprised of the two satellites shown in Figure 2.2 – named Emma and Sara Lily – with the goal of demonstrating two-way inter-satellite crosslink, performing on-orbit real-time relative navigation using the Global Positioning System (GPS) and demonstrating real-time GPS attitude determination.

As part of the UNP regulations, the design and fabrication of the two FASTRAC satellites were completed entirely by students. Faculty and industry contacts, however, served as advisors and mentors. Additionally, it should be noted that based on Table 1.1, FASTRAC is considered a microsatellite. With a total mass of approximately 25 kilograms each, the two spacecraft do not meet CubeSat specifications.

FASTRAC was launched aboard STP-S26 on November 19th, 2010 and has been operational since it powered on at 30 minutes after separation. The first beacon was reported five hours after launch. As of the time of this writing (Spring 2012) nearly all of the mission success criteria have been accomplished. The two spacecraft have provided many lessons in documentation methods, ground operations, and satellite design processes which are currently being applied to the Bevo-2 and ARMADILLO satellites. FASTRAC's success serves as a role model for future university satellite design projects.

Figure 2.2 - FASTRAC satellites.

2.3.2 Bevo-1

Bevo-1 was the first of four missions in a joint-university NASA-sponsored satellite program called LONESTAR, Low Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and docking. UT-Austin and Texas A&M each designed and built two picosatellites which were launched together aboard Space Shuttle STS-127 Endeavour on July 15th, 2009, as shown in Figure 2.3. The main mission objectives of the LONESTAR-1 mission were to demonstrate a CubeSat compatible spacecraft bus and to test a Dual Radio Frequency Astrodynamic GPS Orbital Navigator (DRAGON) designed at NASA Johnson Space Center (NASA-JSC). Unfortunately, upon ejecting from the Space Shuttle Payload Launcher, the two satellites failed to separate and thus neither satellite could successfully accomplish its mission objectives. However, both satellites were successfully integrated and demonstrated to work prior to launch.

At the end of three missions, the LONESTAR program plans to demonstrate the autonomous rendezvous and docking of two small satellites (less than 50 kg each).

Currently, UT-Austin is designing and building the Bevo-2 satellite for the second of these four LONESTAR missions which is planned for launch in 2013.

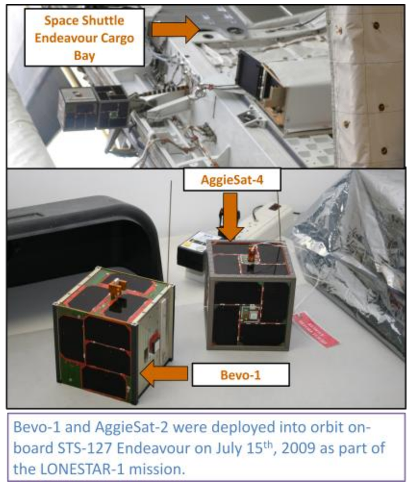


Figure 2.3 - Bevo-1 and AggieSat-2, part of the LONESTAR-1 mission. Above: Deployment of Satellites from STS-127. Below: Close-up view of picosatellites.

2.3.3 Texas 2-STEP / ARTEMIS

The Texas 2-STEP mission began as ARTEMIS (Autonomous Rendezvous and rapid Turnaround Experiment Maneuverable Inspection Satellite), which was the UT-Austin entry into the UNP-4 competition in January 2005. ARTEMIS was re-branded as Texas 2-STEP for the UNP-5 competition.

The main objectives of Texas 2-STEP were to rendezvous a chaser and target satellite from a minimum stand-off distance and to demonstrate the maneuvering satellite capabilities necessary for proximity operations as well as the on-orbit demonstration of a camera. Additionally Texas 2-STEP aimed to develop a reusable satellite bus design in order to demonstrate rapid integration of a flight-ready satellite.

Having not been selected as the UNP-4 or UNP-5 competition winner, the Texas 2-STEP project was concluded without launch into orbit. But the lessons learned from the design process have been implemented into SDL projects since then.

2.4 The Future of the SDL

FASTRAC, Bevo-1 and Texas 2-STEP all helped to shape the systems engineering processes currently employed in the SDL. Since the SDL intends to continue performing funded student-built small satellite missions, documenting and iterating upon the cost and systems engineering processes used throughout the course of these past missions helps to better prepare the SDL to successfully design, fabricate and operate future missions.

Future opportunities to continue applying the systems engineering lessons on a regular basis are available through competitions like the University Nanosatellite Program, in which ARMADILLO is a current entry or through a potential third mission of the LONESTAR series where Bevo-2 is the present spacecraft. With small satellites becoming more prevalent in university settings, launch opportunities for student-built spacecraft continue to increase through the efforts of entities like the Educational Launch initiative for Nanosatellites (ELaNa). With the multitude of opportunities for student-built spacecraft missions, the systems engineering practices learned through past and present SDL missions in addition to the resources documented throughout this thesis will serve as a foundation for future missions.

Chapter 3: Measuring Design Reusability

3.1 Introduction and Purpose

As described in Chapter 1, the two satellite missions currently being developed at UT-Austin, Bevo-2 and ARMADILLO, have very different mission objectives, but a good portion of their hardware selection, software packages and design processes are identical. The UT-Austin team has maintained the goal of not only accomplishing the third ARMADILLO mission objective of measuring and tracking reusability, but to ultimately reduce the amount of time and money required to produce a flight-worthy 3U CubeSat satellite. Thus, the SDL has designed to a standard of reusability which allows for future missions to simply replace the 3U CubeSat payload section and create a new mission.

Because of the nature of a student-run lab, there is a high turnover of students each semester. In an effort to reduce the amount of time it takes a student to understand the system in development, this reusability philosophy ensures documentation of all the design decisions and analyses. Documents maintained on a regular basis are detailed in a later section but include the mission overview, component trade studies, test plans and results, and mission budgets – including mass, power, link and telemetry budgets. A new student can simply read the mission overview and current subsystem updates in order to comprehend the overall status of the mission. This is one of the many lessons learned from previous satellite projects where much knowledge was lost as students left the SDL. The philosophy of reusability implemented into the hardware, software and systems engineering processes is essential to successfully inform new students of the current mission status.

The task of measuring reusability starts by first defining “reusability” not with regard to the reusability of the physical satellite, but rather with the satellite design. Reusability in this sense is the choice of hardware, software and other implemented processes which may be slightly altered or completely reused on a future mission with different mission objectives. For example, the Bevo-2 and ARMADILLO missions have different objectives – one mission will validate technology necessary for autonomous rendezvous and docking while the other will characterize the LEO space debris environment. However, both spacecraft have the same core needs for an on-board flight computer and power system. Thus, the Bevo-2 and ARMADILLO spacecraft design processes chose the same Phytec LPC3250 flight computer and ClydeSpace 3U Electrical Power Supply. These components are considered reusable hardware between the two missions. In terms of software reusability, the specific software design philosophy will be detailed in a later section but it is noteworthy to mention that should a component be used for the same task on two separate missions, the component software drivers are reusable and need only be added to the proper software directory. Finally, mission documents may have varying degrees of reusability, but the overall template of the document provides a starting point for future missions. For instance, writing requirements is often a tedious task and a systems engineer may not know where to start. The mission requirements written for ARMADILLO and Bevo-2 provide a starting template on which to iterate for future missions.

The purpose and applications of this research, as explained in the introduction, are then highly varied. A reusable satellite bus could be used for military applications where it is necessary to quickly respond to some event. Or, the reusable design could be a high school or university project at a place which has limited previous experience.

3.2 OVERALL METHODOLOGY

The reusability of the satellite naturally splits into three categories alluded to above: hardware, software and systems engineering processes. Because of the large differences between each of these categories, each has its own method of determining its percent reusability as well as accompanying assumptions.

3.3 HARDWARE REUSABILITY

3.3.1 Purpose

A satellite is comprised of many components. Depending upon design philosophy, these components could be highly specific to one mission, or applicable to a broad range of mission objectives. By choosing components which have a broad range of performance characteristics applicable to multiple mission objectives and documenting the trade studies made for these design decisions, the SDL reduces the amount of time necessary to make these same design decisions in the future. Additionally, with two satellite projects being designed concurrently, it alleviates a lot of stress and work from the students since they only have to research and select components which satisfy typical mission objectives of a highly capable 3U CubeSat.

3.3.2 Assumptions

While the overall assumptions are listed in the Introduction, in order to complete this hardware reusability analysis, several assumptions are made which are specific to hardware reusability:

1. Hardware reusability is measured by the amount of necessary hardware the Bevo-2 and ARMADILLO 3U CubeSats have in common.

2. The definition of necessary hardware for each mission is based upon the hardware needed to satisfy mission requirements as stated in the requirements verification matrix for each mission and listed in Appendix E.
3. Hardware reusability is calculated with respect to the spacecraft bus elements and does not include the Bevo-2 or ARMADILLO payloads. Thus, the analysis gives a hardware reusability value for the spacecraft bus as it applies to future missions.
4. Component refers to the piece-level of the subsystem. For instance, within the CDH subsystem, the flight computer is considered a single piece, or component. While the flight computer is comprised of resistors, capacitors, etc., the reusability analysis relies only upon comparison between the Bevo-2 and ARMADILLO components.

3.3.3 Methodology

Simply listing and qualitatively comparing the hardware on Bevo-2 and ARMADILLO would not be a sufficient reusability analysis. Instead, a mathematical representation of this reusability is detailed in a set of steps taken to obtain the hardware reusability values in two ways. The first method calculates the number of components which change between the Bevo-2 and ARMADILLO missions. The second algorithm calculates the mass change between missions. These steps are:

1. List hardware by subsystem and components for both missions.
2. Identify for which mission the component is being used and how many components are in that subsystem for the particular mission.

3. Determine the percent reusability of each component.
    a. If the component is being used on both missions, then it is 100% reusable in both methods (number of components and mass).
    b. If the component is being used on only one mission: Calculate the total change per component line either via mass or number of components, based upon which method is currently being employed.
        i. For calculation by component number, find the percent change by taking the number of components which change between the two missions and dividing it by the total number of components in that section.
        ii. For calculation by component mass, determine the total mass which changes between two missions.
4. Calculate subsystem non-reusable (NR) value.
    a. For calculation by component number, find the mathematical average of the components percent change within the respective subsystem. Note that to find an accurate subsystem non-reusable value, the components which do not change are not included in the mathematical average.
    b. For calculation by component mass, determine the total mass change between the two missions for the respective subsystem.
5. Determine the system non-reusable value.
    a. For calculation by component number, find the mathematical average of the subsystem percent non-reusable values.

b. For calculation by component mass, sum all the subsystem non-reusable mass values to obtain a system non-reusable mass value. Given a mass limit, a system percent non-reusable may be calculated.

As detailed in the assumptions section (3.3.2), this method assumes that the components on both missions meet a certain set of criteria detailed in the mission requirements verification matrix (RVM) located in the appendix. A subset of component parameters from the RVM, monitored by the respective subsystem, deemed necessary for a broad range of mission objectives is listed below. For a component to qualify for reusability between the two 3U missions, the component must fit these parameters:

1. Structures:
    a. Assumed mass limit of 4 kg; (3U CubeSat definition)
    b. 340.5mm total length (3U CubeSat definition)
    c. 6061-T6 Aluminum (UT-Austin choice, common in industry)
2. Command and Data Handling
    a. Power: 0.25 A on a 3.3 V bus with interface board
    b. Interfaces: 7xUART, 2x12C, 2x12S, 4xSPI, 1xUSB OTG, etc
3. Communications
    a. Be able to downlink approximately 2 MB per day
4. Electrical Power Systems
    a. Regulated 5V and 3.3V buses limited at 2.5A each
    b. Unregulated bus between 6.2V and 8.2V at 4A each
    c. 30 W-hrs of energy storage
5. Camera (Navigation Visual System)
    a. At least 1 MP grayscale image camera

   b. Space-worthy lens
6. Attitude, determination and control
   a. Pointing accuracy of one degree
   b. Maintain steady pointing for at least twenty minutes during science operations.
   c. Position accuracy of +/- one kilometer
   d. Rotational maneuvers at a minimum 0.1 deg/s and a maximum of 80 deg/s
7. Thruster
   a. Able to provide at least 10 m/s of deltaV

These components serve as the spacecraft bus. Additionally, this reusable design has a payload section which fits within linear dimensions of 11.2 cm (length) x 9.7 cm (width) x 9.7 cm (depth). After removing the camera and S-Band radio payloads, these dimensions yield a volume of approximately 795 cm^3. So, for instance, a TI-83 calculator is an example of a payload which would not fit within the 3U payload volume constraints, as the calculator has the dimensions of 19.05 cm x 8.255 cm x 1.905 cm with a volume of 300 cm^3. A more well-known example which would fit within this payload volumetric constraint is an iPhone with dimensions of 11.52 cm x 5.86 cm x 0.93 cm giving a volume of approximately 63 cm^3. While the volumetric and linear dimension constraints are set by the 3U CubeSat form factor and the associated launch mechanisms, the mass and power distributions are determined by the mission developers. Thus, it is important to note that meeting the volume constraint does not guarantee that the spacecraft constraints, such as mass and power, will be met by the chosen payload. A trade study is necessary to ensure all mission requirements will be met by selecting a particular payload.

3.3.4 Results and Analysis

The algorithm in the previous section is applied on a continuous basis to the two 3U CubeSat missions being developed at UT-Austin: Bevo-2 and ARMADILLO. The phrase "applied on a continuous basis" is used because as the design matures, the mass and component selection may or may not change. It is these two approaches, mass and number of components, which the hardware reusability applies in the outlined methodology. The data for the mass and number of components aboard each of the Bevo-2 and ARMADILLO spacecraft is up-to-date as of December 11, 2011 (per the data cut-off assumption mentioned in Chapter 2).

The algorithm is now applied for the number of components which change between the Bevo-2 and ARMADILLO missions. These results are summarized in Table 3.1, and the full table may be seen in Appendix B. The methodology identified above first identifies how many components are on each mission. The "On Both?" column compares whether both missions have the same number of components; the result is in binary – a "1" means the two missions have the same number of component whereas a "0" means they do not. The "Change" column is a second check to determine if there was a change between the two missions; again, the results are binary – a "1" means there was a change and a "0" means there was not. The percent change column is calculated by taking the number of components which change and dividing this value by the total number of components within that section. For instance, in the COM subsystem, the S-band radio and antenna components differ between the two missions in the "S-Band" section. The number of components which change, one per line, is then divided by the total number of components in that section, two. One half is 50 percent. Each component within a section in the subsystem is computed. From these values, the subsystem percent non-reusable (NR) is computed by taking the mathematical average of all the component percent changes not equal to zero, thus the percent non-reusable only accounts for those components which change between the two missions.

Completing these calculations for all the subsystems aboard the two satellites, the entire system-level percent NR is then calculated by taking the average of all the subsystem percent NR values. From this value, the percent reusable may be determined by simply subtracting the percent NR from 100%.

The same type of hardware reusability analysis is completed for the mass of the components. This serves as another method of measuring the hardware reusability. Table 3.1 summarizes the mass change per subsystem between the Bevo-2 and ARMADILLO missions. Only those sections which experience a mass change between the two missions are shown in Table 3.2, for the entire table see Appendix B. Note that unlike the reusability by number of components, the "Change" column shows the calculated change in mass between the two missions.

A few key differences are noted between the two methods of calculating hardware reusability from Table 3.1 and Table 3.2. First, the GPS receivers in the ADC section have different masses since the FOTON and DRAGON hardware models are not the same receivers. In the STR section, the mounting and payload shell of Bevo-2 is more massive than ARMADILLO. Because the Bevo-2 mission is entering the machining of the Engineering Design Unit parts as of February 2012, the structural mass values may change in future design iterations due to lessons learned during the EDU fabrication. The ARMADILLO payload shell mass, however, will remain near the documented value in order to stay under the mass limit. In comparison to the Bevo-2 shell, the ARMADILLO payload shell was made lighter in order to accommodate a 400 gram Piezo-electric Dust Detector (PDD) which is the main scientific objective of the ARMADILLO mission.

Table 3.1 - Hardware reusability calculations by number of components per subsystem.

			Bevo-2	ARMADILLO	On Both?	Change	% change (B => A)	% non-reusable
ADC								**0.00%**
	Actuators							
	Sensors							
	Flight Computer							
CDH								**0.00%**
	CDH Computer							
COM								**50.00%**
	UHF/VHF							
	S-band							
		Radio	0	1	0	1	50.00%	
		Antenna	0	1	0	1	50.00%	
	GPS Antenna							
	Cross-link							
		Radio	1	0	0	1	50.00%	
		Antenna	1	0	0	1	50.00%	
EPS								**0.00%**
	Main EPS							
	Solar Power							
NVS								**0.00%**
	Camera							
STR								**11.11%**
	Wall Shells							
	Connectors/Caps							
	Component Mounting							
		Reaction Wheel Mount	1	1	1	0	0.00%	
		Magnetorquer Mounts	1	1	1	0	0.00%	
		GPS mount	1	1	1	0	0.00%	
		Electronic Stack Brackets	4	4	1	0	0.00%	
		Payload mount	0	1	0	1	11.11%	
		Camera Mount	1	1	1	0	0.00%	
	Integration							
THR								**0**
	Pressurant							
	Valve							
							TOTAL %Non-reusable	**8.73%**
							TOTAL % Reusable	**91.27%**

Table 3.2 - Hardware reusability by mass of components per subsystem.

mass in grams (g)			Bevo-2	ARMADILLO	On Both?	Change	Total Non-reusable mass
ADC							**265**
	Actuators						
	Sensors						
		GPS	100	365	0	265	
	Flight Computer						
CDH							**0**
COM							**152.9**
	UHF/VHF						
	S-band						
		Radio	0	42.9	0	42.9	
		Antenna	0	20	0	20	
	GPS Antenna						
	Cross-link						
		Radio	50	0	0	50	
		Antenna	40	0	0	40	
EPS							**0**
	Main EPS						
	Solar Power						
NVS							**0**
STR							**201.84**
	Wall Shells						
		Payload Shell	332.24	233.82	0	98.42	
	Connectors/Caps						
	Component Mounting						
		GPS Mount	86.14	63.94	0	22.2	
		Payload Mount	0	76.83	0	76.83	
		Camera Mount	23.97	19.58	0	4.39	
	Integration						
THR							**0**
	Pressurant						
	Valve						
						Total NR mass	**619.74**
						Total mass limit	**3600**
						Total reusable mass	**2980.26**
						%NR	**17.22%**
						%R	**82.79%**

The number of components provides a good overview of how many components may be reused from mission to mission, provided the selected component meets the set of hardware parameters listed in the methodology section. Mass is always a premium aboard satellites, however, and so the mass analysis provides a more direct comparison between the two missions and just how much mass will need to be replaced from mission to mission. When working with 3U CubeSats, a 4 kg mass limit is imposed from the launch mechanism providers – most notably Poly Picosatellite Orbital Deployer (P-POD).[16] With this in mind, the mass reusability algorithm described within this section provides information which may be vital to choosing components during the spacecraft design process.

Many times, systems engineers are concerned with increasing their mass margin in order to have a level of safety should sudden mass increases occur. Mass margin is considered the percent difference between the allocated mass, which typically includes a contingency value, and the design mass limit. The percent non-reusable value is calculated based upon the non-reusable components highlighted in Table 3.2 excluding a 400g allocation for payload mass. This non-reusable mass, excluding the payload, could be considered the mass margin. If they are not absolutely necessary, the non-reusable components may be removed in order to gain the associated non-reusable mass and thus increase the mass margin. Alternatively, if the mass limit is increased, the reusability of the spacecraft will increase. Since often times the mass limit is a hard requirement which cannot be changed, this method of increasing mass margin is less likely.

Table 3.3 directly compares the two methods of hardware reusability in terms of the change in mass and the change in the number of components. These similar results are expected as the components which change will also yield a change in mass. However, the two methods differ because components have different masses and adding or removing these components will affect the total mass more than the total number of components. The two methods verify each other through similar, and yet different, methodologies yielding results within 10% of each other.

Table 3.3 - Summary comparison of hardware reusability methods.

Hardware reusability by number of components		Hardware reusability by mass of components	
TOTAL %Non-reusable	8.73%	TOTAL %Non-reusable	17.22%
TOTAL % Reusable	91.27%	TOTAL % Reusable	82.79%

Using the methods described to determine reusability, the 3U CubeSat bus design created by the Satellite Design Lab at the University of Texas at Austin is calculated to be approximately 87% reusable for two different 3U CubeSat missions. This value represents a mathematical average between the hardware reusability calculations by component number and by component mass.

3.4 Software Resuability

3.4.1 Purpose

Hardware is not the only element which goes into the design, fabrication and operation of a satellite. Software is a necessary part of any mission which enables the satellite to complete its objectives. Many satellite engineers believe that the software coding is the most difficult portion of any satellite design project. Thus, it is to the advantage of the engineer to have other proven code on which to base their current programming task. Software reusability is applicable to any satellite design project and provides a method to quickly develop the mission software.

Software reusability is a widely discussed topic, not only in the satellite design community, but in the computer science community at large.[17] The methods of implementing and tracking software reusability greatly differ by industry and even academic institution.[18] The application of these reusability techniques is of interest to the students in the SDL for time-saving purposes, but also to others for the purposes of quickly designing, fabricating and flying small satellites. UT-Austin has sought to implement the modularity of its hardware design to the design of the software architecture. It is not so much the design of software reusability, but rather the tracking which is more difficult for the SDL since most of the high-level spacecraft flight software has not been written as of February 2012. However, it should be noted that the lag of software development behind hardware development is typical in satellite design programs and it is therefore not unusual that a student-lab experiences the same issue. Usually, the tracking of software reusability is calculated via the comparison of multiple mission software packages, but the current Bevo-2 and ARMADILLO software status does not allow the SDL to calculate software reusability in this way. The following section strives to lay out the method by which the software reusability is established and tracked throughout the course of the Bevo-2 and ARMADILLO missions as well as into the future with upcoming projects.

3.4.2 Assumptions

The SDL software design philosophy also follows the modularity approach. The satellite subsystems are each responsible for their respective sections of software. The main flight computer managed by the Command and Data Handling (CDH) team is then responsible for integrating all the subsystem code into the proper modes and formats.

It is the duty of the CDH team to ensure that all subsystems follow the software Interface Control Documents (ICD) established by the CDH team. Therefore, it is an assumption made for the methodology listed below that the subsystems have indeed followed this philosophy.

3.4.3 Methodology

With software modularity in mind, the Bevo-2 and ARMADILLO CDH and SYS teams have developed a method by which the reusability of software code is tracked. These steps are very similar to the algorithm to measure hardware reusability:

1. List high-level CDH functions which incorporate the subsystem functions used on the Bevo-2 or ARMADILLO missions. For example, CDH would call a function to "Take image of moon", which at the very minimum means ADC must maintain a specified pointing accuracy, the camera system must take a picture and EPS must provide both subsystems power.
2. Determine whether or not the function will be used on the Bevo-2 and ARMADILLO missions. For example, some subsystem functions may call sub-functions which are necessary for ARMADILLO objectives but may not be necessary for Bevo-2 objectives. Removing these lines of code, however, is more work than it is worth. Including the unused sub-functions does not cause any harm to the subsystem code. But it is important to know which functions are used on one or both missions.
3. List the Lines of code (LOC) for each function.
    a. At Preliminary Design Review (PDR) status for both Bevo-2 and ARMADILLO.

   b. At Critical Design Review (CDR) status for both Bevo-2 and ARMADILLO.
4. Calculate the percent change.
   a. By number of functions which change between missions.
   b. By LOC change between missions.
   c. By LOC from design review to design review; this acts more as a status report than a true measure of software reusability.
5. List all subsystem functions in a separate spreadsheet tab to give a "Software Parameters" list which future payloads or components will have to satisfy (i.e. device must be able to give CDH its voltage, send a picture, etc.). This gives a better idea of what makes the software reusable and the constraints being imposed upon software modules.

The above methodology is a very simple first set of reusability analysis. Suggested future steps, not explored within this thesis, could be taken to give a higher fidelity model of software reusability include:

1. Determine software reusability as it applies to satellite operations, such as function calls, rather than the implementation of software code. This means that when the flight computer commands another subsystem, the number of subsystem-specific functions that are actually used during that particular code execution is measured. This gives a better idea of how much of each subsystem code is reusable for each type of function execution.
2. Measure reusability in terms of how each subsystem performs tasks. For the purposes of the current methodology, each subsystem is being

considered a “black box” with which the CDH communicates. As long as the subsystem is able to provide the minimum information needed, it is considered autonomous. To achieve a higher fidelity model of software reusability, determine exactly how the subsystem manages its function executions. This would potentially allow for better restructuring and better organization of subsystem code so that it is more reusable for future missions. In other words, if there is a subsystem function which accomplishes two tasks, this function could be broken into two separate codes so that in the case when future missions do not need one of those tasks to be completed, the code is more efficient.

3.4.4 Status of software reusability tracking

Because the Bevo-2 and ARMADILLO missions are still in the beginning of their software coding stages, only the individual subsystem code has been written to date. The mission-level code which interfaces all the subsystem functions will be the next task to be completed in the upcoming months. Because this high-level software has not yet been written, reusability results according to the methodology laid out in the previous section are not yet available. However, these metrics will be established and tracked throughout the remainder of the spacecraft design cycle.

3.5 Systems Engineering and Processes Reusability

3.5.1 Purpose

Effective satellite systems engineering ensures the successful on-time and under-budget delivery of an operational satellite. According to the Department of Defense, systems engineering is “an approach to translate operational needs and requirements into operationally suitable blocks of systems…Systems engineering principles shall influence the balance between performance, risk, cost, and schedule.”[19] As such, many of the documents and processes created for satellite systems engineering deal with monitoring requirements and budgets as well as documenting test results.

The ARMADILLO and Bevo-2 projects are fortunate to have had a previous graduate student, Dax Garner, who wrote his Master’s thesis on the systems engineering processes of a CubeSat – “Systems Engineering Processes for a Student-based Design Laboratory.”[20] These documents and processes served as a “minimum set of deliverables” necessary for the successful design, fabrication and launch of a CubeSat:

- Identifying the scope: stakeholders, needs, goals and objectives
- Creating the Concept of Operations
- Defining the subsystem architectures
- Defining the system and subsystem hierarchies
- Creating, defining and documenting the interface controls
- Writing functional and performance requirements with rationales and traceability in mind
- Defining and implementing trade studies
- Managing resources
- Defining risk management through risk analysis and mitigation
- Defining a configuration management and documentation standard

These deliverables were used as a starting point for the systems engineering of Bevo-2 and ARMADILLO and have been iterated upon since the beginning of the design cycle. This section details the current set of processes and documents used on a regular basis and how these deliverables can be reused for future missions just as the above set of "minimum deliverables" was the starting point for this thesis.

3.5.3 Assumptions

1. The Systems Engineering deliverables produced during the development of ARMADILLO and Bevo-2 are primarily based upon the list of deliverables required by the University Nanosatellite Program competition run by the Air Force Research Lab.[21] These deliverables are standard for many government institutions. Therefore, the set provided by AFRL is used as the basis for determining reusability of the deliverables.
2. In addition to the deliverables required by the UNP competition, several other systems engineering processes were established by iterating upon the processes created by Garner and described in his thesis. These processes are directly applicable to future missions. These additional processes are identified separately from the design review deliverables with their respective percent reusability also identified.
3. The definition of systems engineering percent reusability applied in this thesis is not based upon the differences between Bevo-2 and ARMADILLO as it is with hardware and software reusability, because the two missions produce the same deliverables and processes dependent upon what is required by the mission technical support (NASA and AFRL).

3.5.4 Methodology

1. As per assumption 1, list the deliverables required by AFRL.

2. As per assumption 2, also list the systems engineering processes put in place for the ARMADILLO and Bevo-2 missions.
3. Identify the reusability of each document. Document reusability is subjective to the input of the lead systems engineer and the scale was defined in-house within the SDL as:
    a. 100% : No changes need to be made to the document for use on future missions.

       For example, Lessons Learned throughout the design and fabrication of the Bevo-2 and ARMADILLO missions will serve as a reference for future missions. New Lessons Learned documents may be created for future missions, but the reference document will remain unchanged.
    b. 90% : Only links or titles need to be changed from one mission to another

       For example, document templates such as ICD templates, Trade Study templates need only be replaced with proper mission names and updated list of required document sections.
    c. 75% : Minor changes of mission-specific details need to be made to document for applications to future missions.

       For example, Internal Review and Documentation Plans since these processes are specific to how the Satellite Design Lab has been managed and details may be modified as specific to the current mission.
    d. 50% : Major changes of mission-specific details need to be made to document applications to future missions.

For example, documents (budgets, test results) specific to subsystem details for a particular mission and subsystem results/data need only be modified for future missions.

e. 25 % : The framework/template of the document is applicable to future missions, but new information and data must replace previous mission information and data.

   For example, documents (organization chart, requirements, risk analysis) which are highly specific to the given mission and organization of the team working on that mission but still provide a basic foundation for future missions.

f. 10% : Only the basic document information (i.e. title page and revision history) may be used as a template for future missions.

   For example, documents (personnel budget) which contain data and analysis that must be updated from mission to mission but provides a reference and basic document layout for future missions.

g. 0% : The document needs to be completely rewritten for application to future missions.

   For example, email communications or responses to mission technical support are only applicable to the mission at hand and no part of the document may be reused for future missions.

4. To add realism fidelity to this model, difficulty weights are added to each deliverable and process based upon the level of difficulty needed to produce that document. Weights should apply as if a general student were writing the document, not necessarily having the experience that a Project

Manager or subsystem lead has. In order to determine a weight which is unique to the deliverable/process and not unique to the person, a subset of five SDL team members were asked to weight, based on a 1-5 scale, each of the deliverables and processes based upon their experience and perceived difficulty of each document. The average of these values was then used as the associated weight for each deliverable or process.

5 : Lots of thought, effort and time required to specifically tailor document.

4 : Document requires some thought and lots of time but relatively simple to produce.

3 : Mainly thought goes into this document; easy to produce otherwise

2 : Number crunching makes this document simple to produce, but still time consuming.

1 : Simple outline is provided in template; Only basic thought goes into producing this document.

5. Determine total document percent reusable
    a. For non-weighted percent reusable:
        i. AFRL deliverables: add all AFRL deliverables percent reusable, divide by total number of items to obtain an average AFRL document percent reusable.
        ii. UT processes: add all UT-defined processes percent reusable, divide by total number of items to obtain an average UT-defined document percent reusable.
    b. For weighted percent reusable:

i. Find the sum of all the weights for both AFRL and UT-defined processes.
ii. Find the weighted percent reusability value of each document by multiplying the percent reusable by the weight value.
iii. Sum the weighted percent reusability for AFRL and UT-defined processes.
iv. Calculate the total weighted percent reusability by dividing the weighted sum by the sum of all the weights.

3.5.5 Results and Analysis

The above methodology is applied to the set of deliverables required by AFRL for the University Nanosatellite Program (UNP) Flight Competition Review (FCR). These FCR deliverables are currently in development as the ARMADILLO spacecraft approaches the penultimate design review – Proto-Qualification Review (PQR) in August 2012. Having already completed the Preliminary and Critical Design Reviews (PDR and CDR, respectively) and approaching the PQR is consistent with the spacecraft design status according to the NASA life cycle graphic of Figure 1.1. FCR is the final review associated with the competition phase of the program. These deliverables represent the documentation required throughout the competition. They are shown along with the associated percent reusable, difficulty weights and computed weighted percent in Table 3.4.

Table 3.4 - Deliverables (AFRL defined) with percent reusable, difficulty weight and weighted percent reusable.

Deliverables	% Reusable	Difficulty weight	Weighted reusable	Deliverables	% Reusable	Difficulty weight	Weighted reusable
SCR presentation slides	25.00%	3.25	0.81	**Link Budget**	50.00%	4.00	2.00
PDR presentation slides	25.00%	3.60	0.90	**Data Budget**	50.00%	3.50	1.75
Mission Overview	25.00%	3.00	0.75	**Board test results**	25.00%	4.25	1.06
Concept of Operations	50.00%	3.00	1.50	**Structural Analysis**	25.00%	3.60	0.90
Overall Project Timeline	50.00%	3.60	1.80	**Thermal Analysis**	25.00%	4.20	1.05
Project Gantt Chart	50.00%	3.80	1.90	**Materials List**	50.00%	2.00	1.00
Integration and Testing schedule	50.00%	3.33	1.67	**Radiation Mitigation Design**	50.00%	3.25	1.63
System block diagram	50.00%	2.50	1.25	**EMC/EMI Mitigation Design**	25.00%	2.80	0.70
Software block diagram	50.00%	2.50	1.25	**ICD master list**	25.00%	2.25	0.56
Subsystem block diagrams	50.00%	2.75	1.38	**ICDs**	25.00%	2.75	0.69
Personnel budget	10.00%	1.40	0.14	**Pressure Profile**	25.00%	2.00	0.50
Requirements Verification Matrix	25.00%	3.20	0.80	**ADC assembly procedure**	90.00%	2.80	2.52
Requirements Rationales	25.00%	3.40	0.85	**Bus assembly procedure**	90.00%	2.60	2.34
SRR deliverables document tree	25.00%	2.75	0.69	**Payload assembly procedure**	50.00%	2.80	1.40
SCR deliverables document tree	25.00%	2.75	0.69	**Spacecraft assembly procedure**	90.00%	3.25	2.93
PDR deliverables document tree	25.00%	3.50	0.88	**Ground Support Design**	50.00%	3.00	1.50
Press Related Info	75.00%	1.75	1.31	**Frequency Allocation Paperwork**	25.00%	3.67	0.92
Mass Budget	50.00%	2.40	1.20	**System functional test results**	50.00%	2.00	1.00
Power Budget	50.00%	3.00	1.50	**Facilities and Resources**	90.00%	2.00	1.80
Power Modes Budget	50.00%	3.00	1.50	**Ground Station Equipment**	90.00%	2.00	1.80

The same methodology is applied to the systems engineering processes developed in the SDL. These processes were developed to help standardize the documentation process as well as keep good systems engineering practices throughout the design cycle. The processes are listed with their percent reusable, weight and computed weighted reusable in Table 3.5.

Table 3.5 - Systems engineering processes (UT defined) established with the percent reusable, weight and weighted percent reusable.

SYS process	% Reusable	Weight	Weighted reusable
Word Document Template	90.00%	1	0.9
Excel Document Template	90.00%	1	0.9
Trade Study Template	90.00%	1.4	1.26
Internal Review Plan	75.00%	1.6	1.2
Documentation Plan	75.00%	1.8	1.35
Organization Chart	10.00%	2.2	0.22
Preliminary Risk Analysis	25.00%	3	0.75
Certification Logs	90.00%	1.6	1.44
Hardware Control Plan	90.00%	1.75	1.575
Mission calendars	10.00%	2.6	0.26
Action item logs	10.00%	3	0.3
Contact lists	10.00%	1.6	0.16
Lessons Learned documents	100.00%	2	2
PDR notes	100.00%	1.8	1.8
Hours tracking	90.00%	1.4	1.26
Subsystem updates	10.00%	2.8	0.28
Subsystem development plans	50.00%	2.8	1.4
Personnel questionnaire form	100.00%	1.6	1.6
Physical Electronics ICD template	90.00%	2	1.8
Physical Hardware ICD template	90.00%	2.2	1.98
Software ICD template	90.00%	2.25	2.03

As explained in Step 5 of the methodology section, the total percent reusable for each of the sets of deliverables/processes is calculated. This total is shown for both the non-weighted and weighted cases in Table 3.6.

Table 3.6 - Total systems engineering percent reusable with and without weighting.

Without weighting			With weighting		
	Deliverables	**SYS processes**		**Deliverables**	**SYS processes**
Sum reusable	1785%	1105%	**Weighted Sum reusable**	5079.58%	1849.50%
# of documents	40	18	**Total Weight**	117.20	34.95
Total % reusable	**44.63%**	**61.39%**	**Total weighted % reusable**	**43.34%**	**52.92%**

What is interesting about the analysis shown in Table 3.6 is the closeness of the total percent reusable values between the weighted and non-weighted methods. Specifically for the list of deliverables required by AFRL, the two methods differ by less than two percent. Because the weight values were determined by averaging responses provided by team members, it represents the collective opinion on the difficulty of document production. It is interesting to note that this collective opinion on the document difficulty roughly corresponds to the percent reusability of that document as is represented by the non-weighting case. The difference between the UT developed systems processes points out the benefit of using a weighted difficulty score. The percent reusability scale was determined by the author and mildly reflects the difficulty of the documents. Having the author also determine the weights would be circular logic and would simply reinforce the scale by which the documents are already scored on percent reusability. Thus, the weighted score more accurately reflects the true difficulty of the documents. With that said, the weighted method validates the accuracy of the AFRL document reusability by the similarity of the numbers between the weighted and non-weighted cases.

3.6 Reusability Conclusions and Future Applications

While having different mission objectives, the Bevo-2 and ARMADILLO hardware and systems engineering processes were shown throughout this chapter to be highly reusable. Table 3.7 summarizes these hardware and systems engineering reusability calculations. Note that the systems engineering percent reusable values are taken from the weighted method which was deemed to be more accurate. The main purpose of reusability for both hardware design and systems engineering is to serve as a template for future missions. Rather than spending time and money developing many of these processes and initial trade studies, future teams may start with the documents developed during the Bevo-2 and ARMADILLO mission design phases.

Table 3.7 - Reusability Summary.

	% Non-Reusable	% Reusable
HW By Mass	17.22	82.79
HW By Components	8.73	91.27
AVG HW	12.98	87.03
SYS Deliverables	56.66	43.34
SYS Processes	47.08	52.92
AVG SYS	51.87	48.13

Hardware reusability, summarized in Table 3.7 was determined through a system of component comparisons, by number of components and component mass, between the Bevo-2 and ARMADILLO missions. It is acknowledged that these two missions were initially planned to be very similar for the purposes of sharing resources and that this methodology simply highlights the comparison rather than detailing the differences.

However, the methodology created can be applied to other 3U CubeSat spacecraft designs as well and the comparison between Bevo-2 and ARMADILLO simply served to develop the methodology and test it with a known highly similar set of two missions.

The hardware reusability analysis gives future teams an idea of the payload size or spacecraft mass margin which may be incorporated into the spacecraft design given a set mass limit and the desire to use the reusable components detailed in this chapter. Additionally, if future teams desire to include the reusable components into the spacecraft design, then they become aware that the design focus should be on the non-reusable components in order to fully develop the capabilities of these components which may or may not have been included in a previous design. Finally, by establishing this reusable spacecraft bus, future teams may focus more on the scientific experiments which will be placed on board the spacecraft rather than the spacecraft design itself. Future design teams will then be able to communicate in a much more detailed manner with payload providers outside of the SDL with regards to interface requirements and payload development. Teams focusing on experiments or the non-reusable components not implemented on this 3U CubeSat spacecraft bus before allows for more science exploration and expansion of 3U CubeSat capabilities.

Chapter 4: Measuring Personnel Cost

4.1 Introduction and Purpose

Many universities and corporate entities claim that they have a "reusable" or "modular" 3U spacecraft bus design, however many of these designs fail to release the costs associated with the device. In contrast, UT-Austin is able to directly account for the cost of each research assistant – graduate or undergraduate – as well as every component, as no donations have been made to the 3U bus. The entire UT-Austin mission cost, including personnel, travel, facilities and hardware costs, can then be determined. From this well defined, reliable and reusable cost analysis, future design teams will be able to use the reusable design without spending time, money and energy determining the associated costs.

In order to determine personnel expense associated with the development of the satellite, the cost value of all the labor hours which go into the development and building of these two 3U CubeSats is counted. The personnel costs are derived in two ways. The first method is through a government-like pay grade and step scale developed especially for the SDL. The second method is by directly accounting for the cost of the Principal Investigator (PI), Undergraduate Research Assistants (URAs), the Graduate Research Assistants (GRAs) who are employed by the SDL through the PI.

While Chapter 5 details the hardware costs associated with the 3U CubeSat missions, this chapter focuses on the non-hardware costs. Namely, this chapter determines the personnel costs of undergraduate, graduate and faculty team members. Besides directly accounting for the labor costs of these team members, the chapter outlines the travel costs associated with conferences and design review trips. Additionally, this chapter accounts for facilities costs which are not the costs associated with the use of the SDL or other lab spaces, but rather the non-hardware costs which are necessary for the development of a 3U CubeSat spacecraft design. Student, faculty, travel and facilities costs are captured according to the Work Breakdown Structure (WBS) of Figure 4.1. For a complete acronym list, see the Appendix.

The WBS shown in Figure 4.1 is based upon the typical diagrams used at the Jet Propulsion Laboratory. Because a student-built 3U CubeSat design project is inherently structured differently than industry-built designs, Figure 4.1 has noticeably fewer categories. Standard elements of the industry design process, such as Contamination Control, need not be considered as an entire block in itself and instead may be factored into other blocks such as Quality and Assurance (Q&A). In this way, the WBS of Figure 4.1 is representative of a small satellite project and serves as an example WBS for future student-built spacecraft missions.

While Chapter 5 considers the hardware costs of the Payload (5.0), Flight System (6.0) and Project Hardware Engineering (2.3), this chapter focuses on 1.0 Project Management (1.0) and the Project Systems Engineering (2.1) costs. The PI – faculty advisor – is considered the Project Management (1.1) cost while all the students are combined to give the Project Systems Engineering (2.1) costs. Two methods were employed to calculate the student cost. The first system is a government-style pay-grade scale based upon the student's experience. The second method is by directly accounting for which students are given URA and GRA appointments. Both methods are explained in the following sections. The student costs are combined together in one cost, which are paid by URA and GRA appointments, to respect the privacy of the student pay grade system. In other words, the personnel data received for this thesis was given with aliases instead of names, and thus all students are combined together, rather than separating project managers and subsystem leads. Therefore, the entire student cost is considered one value and is placed in the Project Systems Engineering (2.1) section because all students work on systems engineering tasks of documentation and hardware integration. Finally, travel and facilities costs are documented as well and considered part of Travel (1.2) and Facilities (1.3), respectively.

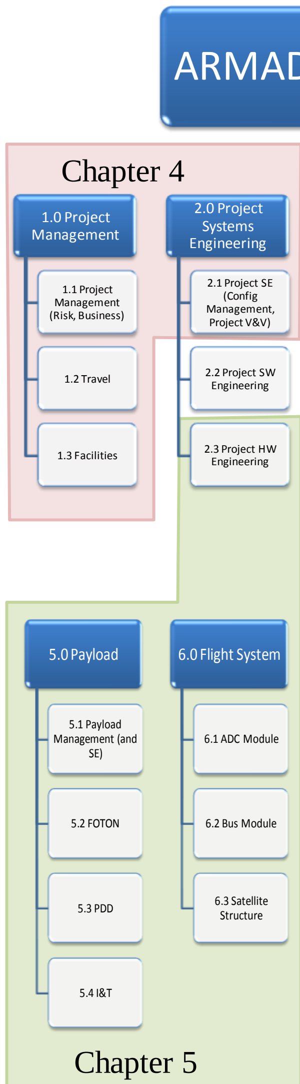


Figure 4.1 - ARMADILLO Work Breakdown Structure.

4.2 Overall Methodology

The SDL has several students appointed as Undergraduate Research Assistants (URAs) and Graduate Research Assistants (GRAs) working on the 3U CubeSat designs. However, these students represent only a small fraction, approximately 20-25%, of the satellite team. While the data is readily available for the actual cost of these URAs and GRAs, another system needed to be established in order to account for the rest of the team members who were not directly paid for their research time.

Based upon previous experience with industry and government internships, the fairest and simplest method of determining the monetary value of each team member was determined with a government-style pay scale. By analyzing the methods employed by the Office of Personnel Management (OPM) and modifying the qualifications of obtaining certain pay grades and steps, a preliminary version was created and applied to the students working in the Satellite Design Lab (SDL) over the summer months. The basic government qualifying education required for each pay grade is shown in Table 4.1 for the equivalent system of students working in the SDL. Some modifications with regards to the number of years experience or education were made to better reflect the qualifications of individual team members.

In addition to the pay grade qualifications shown in Table 4.1, step increases are given based upon experience in a person's given field. While using basically the same pay grade qualifications, the step increase schematic is tailored much more towards the experiences of a typical college student working in the satellite lab. These credentials are: the number of semesters worked in the SDL, previous satellite and work experience, relevant skills they bring to the team, any publications or presentations given as well as any honor societies in which they belong or competitive fellowships they have won.

Table 4.1 - Office of Personnel Management and SDL pay grade qualifying education requirements.

GRADE	QUALIFYING EDUCATION	SDL Equivalent
GS-1	None	Currently in High School
GS-2	High school graduation or equivalent	Graduated High School, but have not completed a semester of undergraduate work
GS-3	1 academic year above high school	Have completed 1-2 semesters of undergraduate work
GS-4	2 academic years above high school, or Associate's degree	Have completed 3-6 semesters of undergraduate work
GS-5	4 academic years above high school leading to a bachelor's degree, or Bachelor's degree	Have completed more than 7 semesters of undergraduate work but have not graduated yet.
GS-7	Bachelor's degree with Superior Academic Achievement for two-grade interval positions, or 1 academic year of graduate education (or law school, as specified in qualification standards or individual occupational requirements)	Have an undergraduate degree but less than 1 year in graduate school
GS-9	Master's (or equivalent graduate degree such as LL.B. or J.D. as specified in qualification standards or individual occupational requirements), or 2 academic years of progressively higher level graduate education	Graduate student in their first or second years of graduate school work
GS-11	Ph.D. or equivalent doctoral degree, or 3 academic years of progressively higher level graduate education, or *For research positions only*, completion of all requirements for a master's or equivalent degree (See information on research positions in the qualification standard for professional and scientific positions.)	Graduate student obtained Master’s Or With 3 years or more of graduate school work but has not obtained PhD
GS-12	*For research positions only*, completion of all requirements for a doctoral or equivalent degree (See information on research positions in the qualification standard for professional and scientific positions.)	Graduate student obtained PhD Or Post Doc in the lab

4.2.1 Defining Pay Grade

A student's pay grade is first based upon whether or not they are a graduate, undergraduate or high school student. For a high school student, they are limited to the GS-1 pay grade. Undergraduate and graduate students have more flexibility based upon how many semesters they have completed in their respective programs. It should be noted here that the students are not actually paid the amount their pay grade indicates – only those students serving as URAs or GRAs are paid. These pay grades simply allow for the tracking of experience on the team and an estimate of the industry-equivalent personnel cost of the ARMADILLO design and fabrication.

Since undergraduates, by definition, have obtained their high school diploma, these students begin at the GS-2 pay grade. Because students gain knowledge each semester of classes, this system chooses to reflect each additional semester of experience, yielding one important difference between the SDL pay grade scale and the government scale: even if a student is in between an academic year, they are considered to be at that pay grade level. For instance, if one student is starting her second semester she is considered a GS-3 in the SDL system; whereas with the government she would not be considered a GS-3 until finishing her second semester which is equivalent to a full academic year. Undergraduates move up to the GS-4 pay grade once they have completed their first full academic year but are not considered at the GS-5 level until they are almost completed with their degree, typically in the seventh semester or more. This follows the government education qualifications path at a basic level.

Graduate students are slightly different because they already have a Bachelor's Degree. Because of this, they start at a GS-7 level and do not move up to the GS-9 level until they have completed their first full academic year of classes (by university standards based upon hours per semester). The GS-11 level is reserved for students who have been in their program for at least three years. However, it is worth noting that a student cannot be considered a GS-12 until they obtain their PhD, per the government pay grade system. Currently, the SDL does not have any students at the GS-12 level.

Figure 4.2 shows a cut out of a flow chart from which a student's pay grade is based upon their education. The entire flowchart, located in Appendix F, also shows the hourly wages for each pay grade and step with cost of living already factored in for the Austin, TX area; since Austin is not listed by the Office of Personnel Management as a specific city with a General Schedule (GS) locality pay scale, the "Rest of U.S." GS pay scale is used for the Austin area.

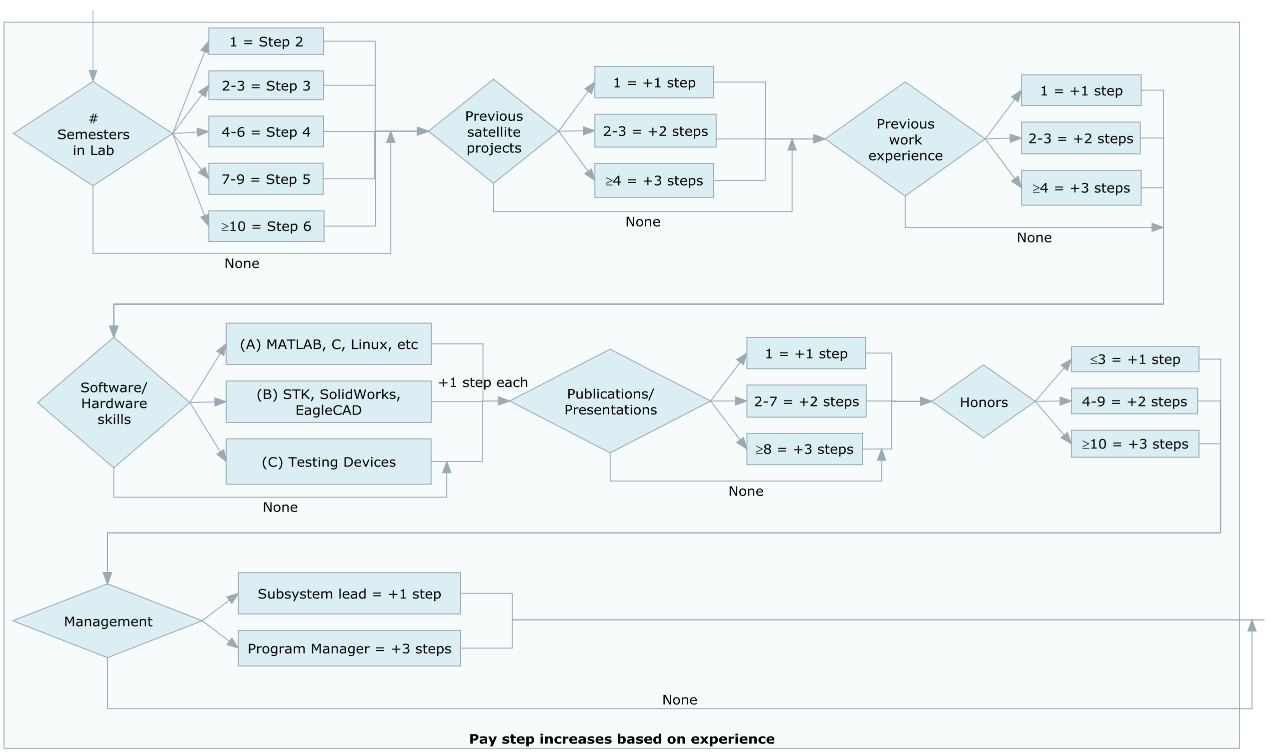


Figure 4.2 - Pay scale determination flow chart cut out.

4.2.2 Defining Pay Step

While the pay grade is based upon education, the pay steps are based upon work and satellite experience, any relevant skills, publications or presentations, honor societies or fellowships awarded as well as the student's role on the SDL team. The method for determining a student's pay step is best explained using an example in addition to the cut-out flowchart shown in Figure 4.2. For the full Pay Scale Determination Flow Chart, see Appendix F.

A typical student is starting her second semester as an undergraduate student. This automatically puts her in the GS-3 pay grade. She worked in the SDL her first semester on campus, starting her at Step 2. She does not have any previous satellite experience but did intern at a local engineering consulting firm during the summer between high school and college giving her +1 Step. Currently this amounts to the GS-3 / Step 3 level. At this internship, she learned some basic CAD modeling skills, giving her another +1 Step. She does not have any publications or presentations but she belongs to the Society of Women Engineers yielding another +1 Step. She is not in a management role and so her final pay grade is the GS-3 / Step 5 level. This amounts to an hourly wage of $14.31 on the General Schedule.

The number of semesters, previous satellite and work experience all provide the fundamental building blocks of working in the lab. Often the first semester in the lab is a steep learning curve, thus after one semester the student increases a pay step. However, each concurrent semester the student becomes more and more familiar with the satellite projects and their role on the team, thus there are larger wait periods before the next step increase. Many students in the SDL have participated in other student satellite projects at UT-Austin, but still deserve credit for this experience, so they receive an additional pay step increase. Internships or other previous work experience are very common with SDL members and are given the proper weight. Many students have had one internship, but those students with multiple internships are given additional pay step increases.

Software/Hardware skills are essential for building a satellite. The Software/Hardware skills block in Figure 4.2 is unique of all the blocks by including groupings (A), (B), (C) to show similar skills yielding the same step increase, because, for instance, most people who know C and Linux also know MATLAB. STK, SolidWorks and EagleCAD are all examples of modeling software that provide the same level of insight into the satellite design. Testing devices are more specific to certain payloads and processes and is thus given a separate scenario. These skills may be mixed and matched at the (A), (B), and (C) levels for +1 step increase each. Additionally, this approach creates a system that encourages students to work in different areas over time and increases their overall skill set by graduation.

Producing and delivering publications and/or presentations are common among the satellite lab duties, but should still be rewarded. A student with more than one publication or presentation and has shown themselves to be regularly publishing is therefore given more weight. It should be noted that these publications and presentations should be at conferences, workshops or in journals. Regular presentations in the course of satellite work such as design reviews will not be attributed to a student's pay step.

The Honors block consists of the membership to honor and professional societies or being the recipient of a competitive fellowship award. These memberships are also very common among SDL members, specifically the following three societies: American Institute of Aeronautics and Astronautics (AIAA), Sigma Gamma Tau and Tau Beta Pi. The commonality of belonging to these three societies is the reasoning behind the first block containing "less than three". The SDL currently does not have anyone with more than ten societies or fellowship awards, but it is possible and should be given extra weight.

To reflect the work load disparity between team members and team management, extra pay steps were given to subsystem leads and program managers. A subsystem lead is a step above a SDL team member in both time commitment and expertise. Being a satellite program manager is much more time-intensive on many levels including interacting with team members, subsystem leads and customers in addition to accomplishing regularly assigned duties. However, a program manager who is also a subsystem lead is only awarded the Program Manager step increase of +3 steps because most of their duties are aligned with their roles as subsystems leads.

4.2.3 Hourly Salary and Raises

At the beginning of each new semester, pay steps are reevaluated to reflect the additional number of semesters in the student's degree program and also the number of semesters spent working on the satellite projects. In addition, any new skills, knowledge or presence the student brings to the team will be evaluated and reflected in their pay grade/step. Any time a team member increases their knowledge and presence on the team either via learning a new hardware/software skill, publishing or giving a presentation, being awarded a fellowship, joining a new honor or becoming part of satellite team management they will receive the respective step increase.

Should a student exceed the Step 10 level, they will proceed to the equivalent wage in the next grade and continue up the scale. The exceptions to this rule are when there is a hard requirement for obtaining the next grade such as when a PhD is required for GS-12 and a Bachelor's degree to obtain the GS-7 level. Students reaching Step 10 on the grade below will be capped at that grade until they meet the requirement for the next grade. While the government pay grade scale may not enforce such a pay step capping technique, within the SDL it helps to regulate the student pay grades and acts as incentive for finishing their degree.

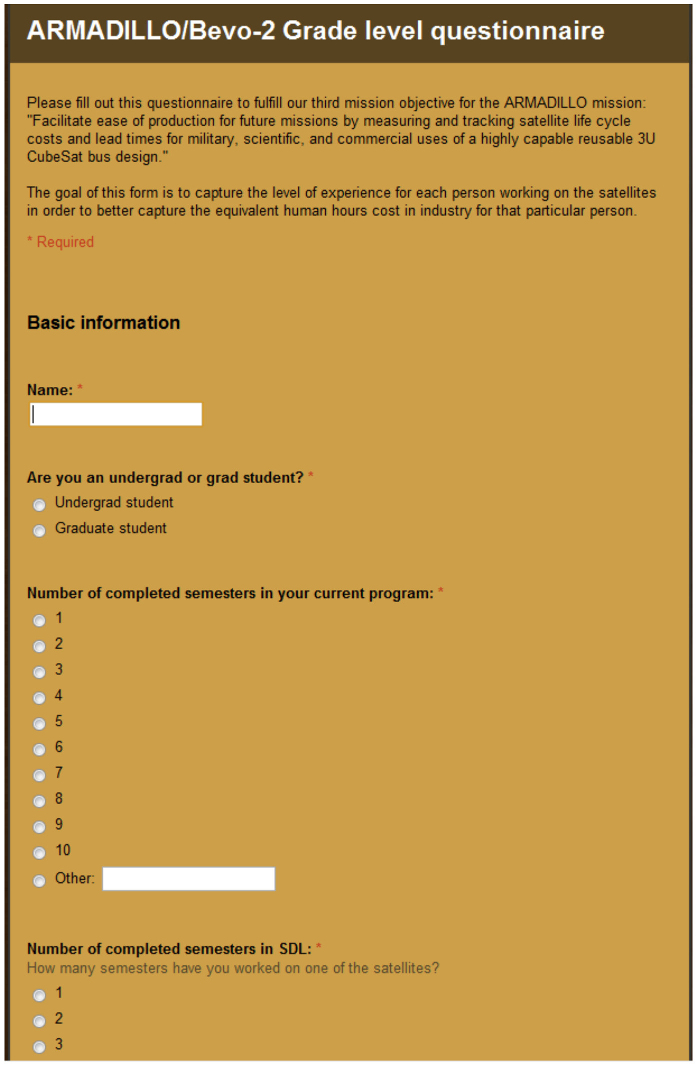
4.3 Case Study: Summer 2011

Before applying this methodology to the entire satellite team during the Fall 2011 semester, it was first tested on those students who worked on the satellites over Summer 2011. Each student was asked to fill out a Google Form consisting of the following areas:

1) Name
2) High school, Undergraduate or Graduate student
3) Number of semesters completed in current program
4) Number of semesters completed in SDL
5) Degree pursuing
6) Previous satellite experience
7) Previous work experience
8) List any hardware or software skills
9) List any technical publications or presentations related to the SDL
10) List any honor societies or fellowship awards
11) Are you a subsystem lead or program manager?

Figure 4.3 shows the first four questions which must be answered by team members while the rest of the questions are answered in later sections of the form. These responses are captured in a Google Spreadsheet where the data may be sorted by any category, person or timestamp. From these questions, following the flowchart in Figure 4.2 yields the pay grade and scale for each student working in the SDL over the summer. It is once again noted that students who reach the Step 10 level on any grade other than GS-5, GS-7 or GS-9 are capped at that level until they meet the requirements to proceed to the next pay grade. These requirements usually entail completing a degree or another semester/academic year in their program.

The students who reach Step 10 on the GS-5, GS-7 or GS-9 levels are then moved to the next grade, which does not require an additional qualification, by locating the same or lesser hourly wage and continuing to count their step increases. For example, a student who is at GS-5, Step 10 ($20.62/hr) but still merits 3 more pay increases will then move to GS-6, Step 5 ($20.04/hr) because Step 6 is more than their previous hourly wage and continue to GS-6, Step 8 ($21.80/hr).



ARMADILLO/Bevo-2 Grade level questionnaire

Please fill out this questionnaire to fulfill our third mission objective for the ARMADILLO mission: "Facilitate ease of production for future missions by measuring and tracking satellite life cycle costs and lead times for military, scientific, and commercial uses of a highly capable reusable 3U CubeSat bus design."

The goal of this form is to capture the level of experience for each person working on the satellites in order to better capture the equivalent human hours cost in industry for that particular person.

* Required

Basic information

Name: *

Are you an undergrad or grad student? *

- Undergrad student
- Graduate student

Number of completed semesters in your current program: *

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- Other:

Number of completed semesters in SDL: *

How many semesters have you worked on one of the satellites?

- 1
- 2
- 3

Figure 4.3 - First version of grade level questionnaire.

Table 4.2 - Partial results for the first version of hours tracking methodology.

Timestamp	Name:	2-week period:	Please select how you would like to enter your time	Number of hours worked the first week:	Number of hours worked the second week:
8/16/2011 16:52:23	Student A	27 June - 10 July	On a weekly basis	3	0
8/16/2011 17:17:25	Student B	16 May - 29 May	On a weekly basis	6	6
8/16/2011 17:17:58	Student B	30 May - 12 June	On a weekly basis	0	0
8/16/2011 17:18:19	Student B	13 June - 26 June	On a weekly basis	10	10
8/16/2011 17:18:39	Student B	27 June - 10 July	On a weekly basis	10	10
8/16/2011 17:18:56	Student B	11 July - 24 July	On a weekly basis	10	10
8/16/2011 17:19:14	Student B	25 July - 7 Aug	On a weekly basis	10	10
8/16/2011 17:19:48	Student B	8 Aug - 21 Aug	On a weekly basis	12	20
8/16/2011 17:20:34	Student C	16 May - 29 May	On a weekly basis	1	1
8/16/2011 17:20:54	Student C	30 May - 12 June	On a weekly basis	1	1
8/16/2011 17:21:14	Student C	13 June - 26 June	On a weekly basis	1	1
8/16/2011 17:21:24	Student D	16 May - 29 May	On a weekly basis	20	17
8/16/2011 17:21:35	Student C	27 June - 10 July	On a weekly basis	1	1
8/16/2011 17:21:47	Student D	30 May - 12 June	On a weekly basis	8	15
8/16/2011 17:21:55	Student C	11 July - 24 July	On a weekly basis	1	1
8/16/2011 17:22:13	Student C	25 July - 7 Aug	On a weekly basis	1	1
8/16/2011 17:23:31	Student D	13 June - 26 June	On a weekly basis	16	16
8/16/2011 17:24:05	Student D	27 June - 10 July	On a weekly basis	16	4
8/16/2011 17:24:33	Student D	11 July - 24 July	On a weekly basis	16	12
8/16/2011 17:25:24	Student D	25 July - 7 Aug	On a weekly basis	24	24

Table 4.3 - Calculated pay grades and total cost for summer 2011 test phase.

Name:	**Hourly Salary**	16 May - 29 May	30 May - 12 June	13 June - 26 June	27 June - 10 July	11 July - 24 July	25 July - 7 Aug	8 Aug - 21 Aug	**Summer hours total**	**Summer personnel expense total**
Student 1	$49.00	0	0	70	70	70	70	70	350	$17,150.05
Student 2	$21.44	2	30	36.5	41	41	28	50.5	229	$4,909.76
Student 3	$23.89	0	0	0	3	0	0	0	3	$71.67
Student 4	$23.98	37	37	40	40	40	40	40	274	$6,570.52
Student 5	$21.44	10	5	20	20	20	20	32	127	$2,722.88
Student 6	$23.73	80	5	2	2	2	2	0	93	$2,206.89
Student 7	$38.42	12	43.25	32	20	28	48	40	223.25	$8,577.27
Student 8	$23.89	15	0	0	0	0	0	40	55	$1,313.99
Student 9	$22.05	30	0	16.5	27	35	2	0	110.5	$2,436.53
Student 10	$20.21	7	40	36	43.25	21	50.5	40	237.75	$4,804.93
Student 11	$24.67	4	2	0	0	0	0	0	6	$148.02
Student 12	$23.98	20.25	23	6	10	3	10	10	82.25	$1,972.48
Student 13	$27.49	0	48.5	0	0	10	0	27.5	86	$2,364.53
Student 14	$28.26	4.5	10	80	80	80	80	40	374.5	$10,583.37
Student 15	$44.61	25	16	10	30	34	9	65	189	$8,431.29
								TOTAL	**2440.25**	**$74,264.18**

4.3.1 Results summary

With hourly wages taken from the Office of Personnel Management using their locality pay tables, the approximate total cost of the students working approximately 2440 hours over the summer is $74,265. If an average junior-level engineer in industry has a $64,000 salary, then this person could expect to make roughly $16,000 over a three month summer working full-time. The 15 students of the summer SDL team did not work full 40-hour work weeks but yet their total cost is equivalent to the summer cost of almost five full-time junior-level engineers.

While comparisons may be drawn with industry based upon baseline salary, it does not take into account additional benefits such as health insurance, paid days off, cost to run the facilities, etc. It should also be noted here that the work completed by the summer SDL team was in preparation for the Preliminary Design Review of both the Bevo-2 and ARMADILLO spacecraft. This review is focused primarily on basic interfacing with components and trade studies for component selection, as shown in Figure 1.1. The additional cost of benefits is considered the "burdened labor rate" and the could be anywhere between 30-300% the average salary. Many corporations or government institutions will not disclose their burdened labor rate, so for this analysis the burdened labor rate required by the University of Texas at Austin, approximately 50%, is used as a comparison point. With this in mind, the equivalent industry cost with overhead of this student labor would be approximately $111,396.27.

While having the total cost of student labor is helpful, the number of hours spent on the satellite must be compared with the tasks accomplished during these hours in order to gain an understanding of the work efficiency of the team members. For summer 2011, the following large tasks were accomplished by subsystem in an effort to establish baseline interfacing capability with the components:

Attitude Determination and Control (ADC)

- Hardware configuration selection: placement of devices in module
- Interface object software : Coding of device interfaces and getting devices to talk with the computer and with each other

Command and Data Handling (CDH)

- Kernal installed on computers and documentation to complete in the future

Communications (COM)

- Link budget research and analysis
- UHF/VHF radio at breadboard level
- Telemetry budget research and analysis
- Frequency allocation paperwork started
- Trade studies finished

Electrical Power Systems (EPS)

- Designed solar panel “couplet” : layout of solar cells which allows ease of solar cell replacement
- EPS ground support board designed and used in testing
- EPS, battery board, solar cell, couplet trade studies completed
- Initial EMI/EMC and radiation analyses completed
- Power and energy budgets analyzed and updated

Navigation Visual (NVS)

- Lens options selected and purchased
- Initial writing and optimization of star tracking software

Structure/Integration (STR)

- Printed and assembled rapid prototype of 3U model
- Initial thermal analysis
- Initial structural analysis
- Assembly procedures defined and followed; lessons learned obtained through assembly of rapid prototype

Systems (SYS)

- Military relevance case completed: compilation of mission heritage and direct quotes from industry and military personnel proving why the ARMADILLO mission is necessary
- Established contacts throughout industry as advisors to the team
- Updated requirements based upon feedback from System Requirements Review
- Preliminary risk analysis completed
- Preliminary testing and integration schedule determined
- Initial personnel cost method developed and summer 2011 results provided feedback to alter method for school year analysis

Thruster (THR)

- Completed test module design for thrust determination
- Completed valve trade study

4.3.2 Lessons Learned

Based upon the responses gathered during the summer 2011 case study of this process, the following lessons were learned:

1. Be sure to include the word "completed" in the questions:
    a. How many semesters in your program?
    b. Number of semesters in the Satellite Design Lab (SDL)
2. Competitive fellowships are considered as honors in the section "List academic honor societies or professional societies"
3. To use this form as a general team information form:
    a. Ask for an email address

b. Ask for their University EID (the university's method of identification)
c. Ask if they have experience on any particular subsystem
d. Ask if they would like to work on any particular subsystem
e. Ask for their graduation date (for planning purposes)

4. Ask for their role on the team. Options are: team member, subsystem lead, program manager.
5. Continue to document subsystem updates as a status mark for the amount of work completed during certain periods of time.
6. Count the number of responses gathered for each two week time period in order to provide a "Percent reporting" and add realism to the number of hours collected.
7. Continue to remind students to submit the hours they have worked. It is a new system and students will need time to adapt.

4.3.3 Summer 2011 Case Study Conclusion

The previous case study served as a test example of this cost analysis process and helped to find some errors and bugs in the questionnaire as well as in the management of the process. Next, the same process was applied to all the team members of the Bevo-2 and ARMADILLO missions during the fall 2011 semester. This pay scale determination process is still a work in progress and may be modified to reflect experiences of a fairly large portion of the satellite lab, i.e. more branches of the "software/hardware skills" section. However, the process will not be changed to reflect a single person's experience.

4.4 UT STUDENT RESULTS: 2011-2012 SCHOOL YEAR

The summer 2011 testing phase proved worthwhile for discovering additional questions which would help to more fairly determine each student's pay grade and step as well as more accurately reflect the total cost of the satellite development. The results for the fall 2011 semester are shown in Table 4.4. It is interesting to note that the total number of hours recorded as worked for each two week time period remains relatively constant with a few exceptions. The time period between 17 October and 13 November also corresponds to a design review for the Bevo-2 mission, resulting in more hours worked during this period. The 28 November through 11 December timeframe corresponds to the end of the semester and finals. Because the SDL encourages students to focus on their studies first and foremost, this drop in hours worked is also expected.

Table 4.4 - Fall 2011 hours tracking summary.

	22 Aug - 4 Sept	**5 Sept - 18 Sept**	**19 Sept - 2 Oct**	**3 Oct - 16 Oct**	**17 Oct - 30 Oct**	**31 Oct - 13 Nov**	**14 Nov - 27 Nov**	**28 Nov - 11 Dec**	**12 Dec - 25 Dec**	**26 Dec - 8 Jan**		
Total bi-weekly hours	354.75	395.75	367.5	382	464	486.75	346.25	244.25	64.5	124	**Total Hours**	**Total Cost**
Response count	21	26	26	27	26	23	23	25	9	15	**3129.75**	**$73,588.39**
Percent Response	48.84	60.47	60.47	62.79	60.47	53.49	53.49	58.14	20.93	34.88		
Avg hrs/ person	16.89	15.22	14.13	14.15	17.85	21.16	15.05	9.77	7.17	8.27		

A lesson learned throughout periodic analysis of these numbers showed that it is beneficial to also look at how many students submitted their hours in order to distinguish the zero hours worked from the zero hours entered. This is why the summary table of Table 4.4 has "Response count" and "Percent Response" rows. Note that there are approximately 50 students on the two satellite design teams; so, on average, about half the students are logging their hours for each two week time period. Based upon the number of responses, the average hours per person who entered their hours can then be calculated and is shown in Table 4.4 as well. The amount of time worked greatly varies from person to person, but the "average hours per person" row gives a rough idea of how much dedication the students have to these satellite projects. Full-time industry employees are required to work 80 hours per two-week time period. With this standard, Table 4.4 illustrates that students are working quarter time on the satellite amidst the rest of their class work. While not all students submit their hours every two weeks, the hours submitted are representative of those students who spend the most time on the satellite design. Since these students represent the majority of the work being accomplished on a regular basis, it is the accumulation of these submitted hours which is used as a basis for the total number of hours which go into designing a 3U CubeSat. It would be unreasonable to linearly scale the hours based upon the percent reporting because there is a large disparity in the hours students work based upon their role on the team.

Those roughly 3000 hours spent on the satellite were very productive and much was accomplished throughout the semester. The self-reported accomplishments are commensurate with the design status during the fall 2011 semester. The ARMADILLO spacecraft had just completed Preliminary Design Review (PDR) and was working towards Critical Design Review (CDR) while the Bevo-2 spacecraft successfully completed both PDR and CDR during the fall 2011 semester. The following accomplishments demonstrate this design status:

Attitude Determination and Control (ADC)

- All components have been interfaced with and are now functioning, with the exception of the magnetorquers which were received in mid-December
- Designing of flight version of ADC and CDH computers

Command and Data Handling (CDH)

- Flow diagrams established for satellite software operations modes.
- Interfacing with all subsystems going well

Communications (COM)

- Parser written for code
- Telemetry packet format discussed with CDH
- Frequency allocation paperwork almost complete

Electrical Power Systems (EPS)

- Received and tested new EPS
- Writing of safety procedures
- Testing of solar cells

Navigation Visual (NVS)

- First iteration of star tracking software created, tested and being refined
- Interfacing with ADC and CDH going well

Structure/Integration (STR)

- Finishing CAD of spacecraft
- Began spacecraft drawings to send to machine shop

Systems (SYS)

- Flat Sat integration of most satellite components
- Reusability metrics established and tracked
- Cost models established and analyzed
- Hardware control methods established including certification logs
- Action item tracking and closure
- Detailed Concept of Operations defined
- Test plan updates and check-off lists created
- First iteration of Flat Sat wiring diagrams

- Refining of STK mission-level analyses
- Requirements status tracking

Thruster (THR)

- Fourth iteration of thruster designed, ordered and received.
- Adapter designed and tested for R-236fa tank

4.5 Actual Personnel Costs

While the previous sections detailed how the personnel cost could be calculated for the entire satellite in an industry-equivalent manner, the following section details what the actual cost of the satellite personnel is according to how many Undergraduate Research Assistants (URAs) and Graduate Research Assistants (GRAs) are appointed to work on the two satellite projects. The section also accounts for the travel and facilities costs associated with both projects. Furthermore, the Principal Investigator (PI) is also a part of the team, and adds a cost to the project. The costs listed in Table 4.5 are given since September 2010 when the majority of development work was started on the Bevo-2 and ARMADILLO missions. The listed costs also show how many students were being paid to work in the lab. With approximately 50 students on the team, Table 4.5 shows only about 10 students (graduate and undergraduate combined) holding research assistant positions. These costs only account for one-fifth of the student workforce, but this one-fifth tends to be the most dedicated personnel. The personnel costs listed in Table 4.5 already include University overhead costs. The travel costs are separated from these personnel costs and listed by the total amount spent, accounting for the overhead costs. More travel has been completed for the ARMADILLO project and so it is the ARMADILLO travel costs which will be used for future analysis. The overhead costs are not included in the government-like pay grade and pay scale method unless the "burdened labor rate" analysis is included as detailed in the Case Study section.

The facilities costs associated with the Bevo-2 and ARMADILLO 3U CubeSat design are not the costs of using the lab space, but rather the necessary tools for the spacecraft designs. Furthermore, since most of the testing is completed by students, facilities costs are minimal compared to the personnel labor hours already captured through the government and actual cost methods described previously. Additional facilities costs may occur through testing by the project integrators – NASA and AFRL – at no cost to the university. These facilities costs are captured in Table 4.6 and are considered as the Facilities Costs (1.3) block in the WBS shown in Figure 4.1. Note that these facilities costs are shared between Bevo-2 and ARMADILLO, and it is infeasible to separate the facilities costs into two separate mission costs as what is needed for one mission is needed for the other. Additionally, many of the typical spacecraft facilities costs associated with the ground station have already been developed through the FASTRAC mission.

Table 4.5 - Actual personnel costs (2010-2012).

3U CubeSat Actual Personnel Costs						
Subcategory cost ($)		Cost (ea)	Quantity	Total (USD)	Total ($)	ARMADILLO Total ($)
Undergraduate Research Assistants						$40,500.00
Fall 2010		$1,500.00	0	$0.00	$0.00	
Spring 2011		$1,500.00	5	$7,500.00	$7,500.00	
Summer 2011		$6,000.00	4	$24,000.00	$24,000.00	
Fall 2011		$1,500.00	6	$9,000.00	$9,000.00	
Graduate Research Assistants						$339,000.00
Fall 2010		$20,000.00	5	$100,000.00	$100,000.00	
Spring 2011		$20,000.00	5	$100,000.00	$100,000.00	
Summer 2011		$13,000.00	3	$39,000.00	$39,000.00	
Fall 2011		$20,000.00	5	$100,000.00	$100,000.00	
Faculty PI Involvement						$104,720.00
2010-2011 School year		$52,360.00	1	$52,360.00	$52,360.00	
2011-2012 School year		$52,360.00	1	$52,360.00	$52,360.00	
Travel						$20,698.25
Bevo-2					$4,168.93	
	Bevo-2 SCR :: 9/10/2010	$900.00	1	$1,386.00		
	Bevo-2 PDR :: 8/26/2011	$580.54	1	$894.03		
	Bevo-2 CDR :: 11/14/2011	$1,226.56	1	$1,888.90		
ARMADILLO					$20,698.25	
	UNP Kick-off :: 1/16/11 - 1/18/11	$2,400.00	1	$3,696.00		
	CubeSat workshop:: 4/19/11 - 4/23/11	$2,000.00	1	$3,080.00		
	SHOT1 :: 6/8/11 - 6/11/11	$1,170.00	1	$1,801.80		
	PDR/Small Sat :: 8/6/11 - 8/14/11	$6,342.92	1	$9,768.10		
	Satellite Fabrication :: 11/9/11-11/12/11	$1,527.50	1	$2,352.35		

Table 4.6 - Facilities costs (2010-2012).

	Level 2			Level 1
Subsystem Cost ($)	CBE ($)	Quantity	Total ($)	Total ($)
Tools				$59,730.14
Light Source Illuminator	$320.00	1	$320.00	
Gooseneck Light guide	$137.00	1	$137.00	
Scale	$347.17	1	$347.17	
Boom microscope	$789.96	1	$789.96	
Electronic load	$1,050.00	1	$1,050.00	
Squeeze Wire Strippers	$31.65	1	$31.65	
Small wrench set	$28.65	1	$28.65	
Clean Bench	$8,078.35	1	$8,078.35	
Disposable respirators	$20.10	1	$20.10	
Cold Protection gloves	$4.03	2	$8.06	
McMaster component tags	$3.83	1	$3.83	
FlatSat case	$176.75	1	$176.75	
Banana plugs and Kapton tape	$55.62	1	$55.62	
Vacuum Chamber	$48,683.00	1	$48,683.00	
Books				$50.60
C++ Programming books	$25.30	2	$50.60	
Software				$6,215.84
EagleCAD	$899.00	1	$899.00	
SmartDraw	$197.00	1	$197.00	
Thermal Desktop	$4,500.00	1	$4,500.00	
Thermal Desktop Compiler	$269.84	1	$269.84	
AutoCAD	$350.00	1	$350.00	

4.6 Extrapolating Costs for the Full Design Cycle

The costs outlined in the government-scale method are specific to the fall 2011 semester while the costs detailed in the "Actual personnel costs" section account for the past 1.5 years of satellite development. To accurately compare the two personnel cost methodologies, the costs will be extrapolated for the entire development life cycle from initial design to delivery. The projected measured costs are detailed in Appendix C but were found by associating costs with similar previous costs, subject to the following assumptions:

- The same level of funding exists for the remainder of the design cycle. Namely, for the future semesters, the same number of GRAs and URAs and the same level, and therefore cost, of PI involvement.
- For the Bevo-2 mission, one additional design review at the same cost level as the last design review.
- For the Bevo-2 mission, a cost level of student launch support equal to two people sponsored at the cost of the most recent design review each.
- For the ARMADILLO mission, the remaining trips are assumed to cost approximately the same as the trips already taken. This is assumed with the exception of the final two design reviews and the desire to bring a few more students than previous design reviews. For this reason, the cost was increased an additional $1000.
- Because testing is completed by NASA or AFRL representatives and is not part of the UT-Austin cost, the testing costs are not captured in this projected cost spreadsheet.

The Bevo-2 flight satellite will be delivered to Texas A&M University in August 2012 while the ARMADILLO mission continues its development phase until the Flight Competition Review (FCR) in January 2013. For simplicity of calculations, it will be assumed that both missions will conclude at the end of the spring 2013 semester. Recalling the total number of hours worked during the summer 2011 and fall 2011 semesters as shown in Table 4.7, the extrapolated total cost associated with the Bevo-2 and ARMADILLO design cycle are given in Table 4.8. The measured personnel costs directly accounts for the PI cost as well as the university overhead whereas the government method accounts for the PI when also including the 50% overhead. The PI is included at this point because the PI cost already includes university overhead unlike the student labor costs captured in the government method.

Table 4.7 - Fall 2011 and summer 2011 hours and cost summary.

Fall 2011 hours	3129.75
Fall 2011 total cost	$73,588.39
Summer 2011 hours	2440.25
Summer 2011 total cost	$74,264.18

Table 4.8 - Comparison of government method and actual student personnel costs.

Total ($)	3U CubeSat Total
Total measured personnel cost (w/ PI)	$923,580.00
Total government method cost (w/o PI)	$590,058.68
Total government method cost w/ burdened labor rate of 50% + PI Cost	$1,042,168.02

The projected personnel costs of Table 4.8 may then be directly compared with the actual student personnel costs. The total government method costs with the associated burdened labor rate is approximately $100,000 more than the actual measured personnel cost. This actual measured cost represents an average workforce of five undergraduate and graduate students, and PI, including the university overhead. The discrepancy, then, between the two methods lies in the number of students supported. The government method accounts for the efforts of all students while the actual cost method only supports an average of ten students. Since the students actually being supported by URAs and GRAs typically produce the majority of the work hours which are captured in the government method it is reasonable to conclude that the government method, including the overhead and PI cost, is accurately capturing the cost of the entire team. The rest of the team may then be considered part of the $100,000 difference between the actual measured cost and the government method calculation. It should be noted that the costs identified are associated with the design of two 3U CubeSat spacecraft. However, because both missions require the same level of student labor as well as the same tools and facilities, the identified costs would be identical for each mission and are therefore representative of a 3U CubeSat design project in general. It is fortunate for the UT-Austin team that the SDL is able to leverage the funding of one or both spacecraft for the development of both missions. Thus, for the first time, the student labor cost of building a CubeSat in a university lab has been quantified.

4.7 Recurring and Non-Recurring Personnel Cost

Having established the metrics for spacecraft design reusability from Chapter 3, summarized in Table 4.9, it is possible to distinguish the recurring and non-recurring personnel costs associated with the 3U CubeSat mission. While the hardware percent reusability is useful in describing the multilateral application of the SDL 3U CubeSat bus, the systems engineering percent reusable is useful in determining the recurring and non-recurring personnel costs. The one-time set of labor hours spent developing interfaces and documentation may be considered the non-recurring costs, since it is not transferable from mission to mission, and may be calculated using the percent non-recurring systems engineering value in Table 4.9. Similarly, the recurring personnel costs are those interfaces and documents which may be reused from mission to mission and are captured by the percent reusable systems engineering value of Table 4.9. Using the average systems engineering percent reusable and percent non-reusable for the recurring and non-recurring costs, respectively, the total personnel costs may be multiplied by the respective factors to obtain the recurring and non-recurring costs given in Table 4.10.

Table 4.9 - Reusability summary.

	% Non-Reusable	% Reusable
HW By Mass	17.22	82.79
HW By Components	8.73	91.27
AVG HW	12.98	87.03
SYS Deliverables	56.66	43.34
SYS Processes	47.08	52.92
AVG SYS	51.87	48.13

Table 4.10 - Personnel recurring vs. non-recurring costs for Bevo-2 and ARMADILLO.

Total ($)	3U CubeSat Total	3U CubeSat Recurring	3U CubeSat Non-recurring
Total measured personnel cost	$923,580.00	$444,519.05	$479,060.95
Total government method cost	$590,058.68	$283,995.24	$306,063.44
Total government method cost w/ burdened labor rate of 50% + PI Cost	$1,042,168.02	$501,595.47	$540,572.55

4.8 Personnel Cost Conclusion

While the government method accounts for all the students in the lab, it is a hypothetical cost value and the wages are not actually paid to the students. Nor does this method account for the PI costs unless specifically factored into the cost values, as in

Table 4.8. The pay scale method is meant more for comparison to industry personnel costs than the actual measured cost method which accounts for the tangible money spent on lab personnel, PI costs, and travel. The main purpose of the pay scale method is to help determine the money required to design and fabricate two 3U CubeSats simultaneously.

The personnel costs outlined throughout this chapter will be compared to costs estimated via industry cost models based upon the WBS of Figure 4.1. Table 4.11 then summarizes all the personnel costs in their respective elements of the ARMADILLO WBS for later comparison. Recall that the Project Management (1.1) cost is solely the cost of the PI and the student labor costs are captured in Project Systems Engineering (2.1). The student labor costs are the actual costs of the URAs and GRAs working in the SDL. The Travel (2.1) and Facilities (1.3) are included within the Project Management (1.0) block as well. Note that Project Hardware Engineering (2.3) costs will be detailed in Chapter 5.

Table 4.11 - Personnel Cost Summary in WBS elements.

ARMADILLO WBS		**Cost ($)**
1.0 Project Management		$273,296.63
	1.1 Project Management	$157,080.00
	1.2 Travel	$50,220.05
	1.3 Facilities	$65,996.58
2.0 Project Systems Engineering		$939,688.68
	2.1 Project Systems Engineering	$766,500.00
	2.2 Project Software Engineering	$0.00
	2.3 Project Hardware Engineering	$173,188.68

Chapter 5: Estimating Flight and Protoflight Unit Hardware Costs

5.1 Introduction and Purpose

It is common practice among many university projects to accept donations from companies who wish to flight qualify their hardware or simply to obtain publicity for their company. With these donations, the schools are unable to directly account for all the hardware costs which go into building their satellites. Even if the universities developing these reusable CubeSat bus designs wanted to share their design and cost information, it would not be 100% accurate given the hardware donations schools may receive.

Recall the tables of CubeSat missions which claim a reusable bus design as outlined in the motivation discussion of Chapter 1. Each bus has a combination of different components leading to no standard CubeSat design. It is difficult to obtain cost information on these university or industry-built buses. Many companies refuse to share such information to the detail which is needed for comparison to the ARMADILLO bus. In general, many companies offer tiers of prices corresponding to the abilities of the spacecraft bus. In conversations at the 2011 Small Satellite Conference, the standard value of an industry-built 3U CubeSat platform was approximately $250,000. This value, however, was not clarified as to what the cost included and was merely the estimate of representatives of the respective designs. Thus, it is difficult to compare this value to the costs of the ARMADILLO hardware.

In the interest of documenting design reusability for future missions, the SDL has developed a grassroots tracking approach which accounts for all design costs, including flight and development hardware, needed tools, personnel and travel costs. By documenting these costs for the ARMADILLO mission, the template now exists for other missions to understand the costs which go into the development of a 3U CubeSat. As Chapter 4 detailed the personnel costs associated with the ARMADILLO mission, this chapter details the hardware costs necessary for developing and fabricating the ARMADILLO 3U CubeSat.

The methodology of this chapter is best understood through the ARMADILLO Work Breakdown Structure (WBS) illustrated in Figure 4.1 and further broken down by subsystems of the spacecraft in the diagram of Figure 5.1. The hardware cost analysis of this chapter is organized according to the WBS of Figure 5.1. Referring back to Figure 4.1, note that the Principal Investigator, travel and facilities costs are captured as part of the Project Management (1.0) block while the Project Systems Engineering (2.1) block accounts for all student costs. These costs are explained in more detail in Chapter 4. The cost associated with the Launch Systems and Science blocks does not apply to the ARMADILLO mission since the launch is provided through NASA CubeSat Launch Initiative and the science data will simply be given to the science team and does not incur any cost on the ARMADILLO mission. The Mission Operations and Mission Assurance costs are factored into the personnel costs of Chapter 4 and are based upon the hours tracking method. The Project Hardware Engineering (2.3), Payload (5.0) and Flight System (6.0) sections which will be captured in this chapter.

5.2 Overall Methodology and Assumptions

This method of determining hardware cost is very clear-cut and simply consists of listing the spacecraft components, the quantities and the total costs. Recall that the facilities costs are accounted for in the analysis of Chapter 4. However, a few comments must be made regarding the payloads aboard the ARMADILLO and Bevo-2 spacecraft.

1. The only contributed or donated hardware on the ARMADILLO mission is the Piezo-electric Dust Detector (PDD), being developed by Baylor

University, and the FOTON GPS Receiver, being developed in the Radionavigation Lab at UT-Austin. For the Bevo-2 mission, the only donated hardware is the DRAGON GPS receiver from NASA Johnson Space Center (JSC).

2. The SDL has purchased a deployment mechanism for the Bevo-2 mission while the ARMADILLO spacecraft deployment mechanism will be provided through the Educational Launch of Nanosatellites (ELaNa) program.
3. As mentioned in the first comment, the PDD, FOTON, and DRAGON are not being built by the students in the SDL and are assumed to arrive in the SDL already space-qualified. These are considered to be "subcontracts" and the SDL simply purchases these devices as Commercial Off The Shelf (COTS) components.
4. The SDL will build as complete a protoflight unit as possible. This device is also known as the Engineering Design Unit (EDU). Because of the expense of the components, some subsystems of the protoflight unit may not completely represent the flight unit configuration. The hardware costs associated with developing and building this EDU are considered the non-recurring engineering costs.
5. The SDL purchases as many prototype units as is practical to give students the most possible interfacing opportunities.
6. Ultimately, only one flight unit is produced with the required number of components needed for full satellite functionality. The costs associated with fabricating this flight unit are considered to be the recurring costs.

Whereas the traditional WBS breaks the Flight System block of Figure 4.1 into subsystem elements, the SDL approach highlights the ARMADILLO modularity and subsystem functionality by creating three modules, as shown in Figure 5.1, within the Flight System block: the Attitude Determination and Control (ADC) module, spacecraft bus module and satellite structure. Each spacecraft subsystem is responsible for its flight software. This flight software is then managed and integrated by the CDH team. Since the payload module is its own block (5.0) then it need not be considered within the Flight System block. The Attitude Determination and Control subsystem is usually considered part of spacecraft bus design. For the SDL, this module, including the cold-gas thruster (THR) and camera (Navigation Visual System - NVS) serves a broad range of mission objectives and stands as a separate module because of its ability to be placed on many different 3U CubeSat missions. A similar thought process is applied to the spacecraft bus module which includes the more typical components of the flight computer (Command and Data Handling - CDH), communications (COM), and power subsystems (Electrical Power System - EPS). While satellite structure (STR) is typically another subsystem, for the purposes of the cost analysis it is considered a module. This module contains the costs associated with machining and integrating the entire spacecraft.

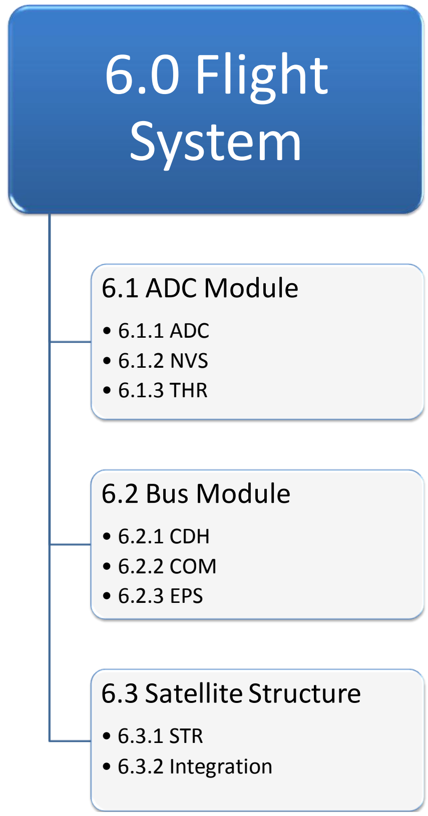


Figure 5.1 - Flight System WBS.

These Flight System modules are then further detailed with the list of each component within the subsystems of each module. For both the flight hardware and development hardware spreadsheets, the cost of each component is listed together with the number of components needed. This yields a total component cost for each subsystem and consequently each module. For the development system, the number of components needed for prototyping is distinguished from the number needed for a protoflight unit to highlight the costs associated with learning to interface with components as opposed to building an Engineering Design Unit (EDU). For the flight system, the number of components currently in-house is listed so that a total in-house cost may be established helping to determine the additional funds necessary to complete the flight unit. The difference between the prototyping, engineering design and flight units is portrayed in the Venn diagram of Figure 5.2. Note that the first overlapping region between Prototyping and Engineering Design Unit (EDU) indicates where a spacecraft model is used for interfacing with components which are similar to the components on the flight unit, as opposed to pure prototyping. The second overlapping region illustrates the connection between the EDU and the flight unit – the protoflight unit. This protoflight unit is used as an EDU for interfacing practice, but the components are flight-worthy and may be qualified for flight.

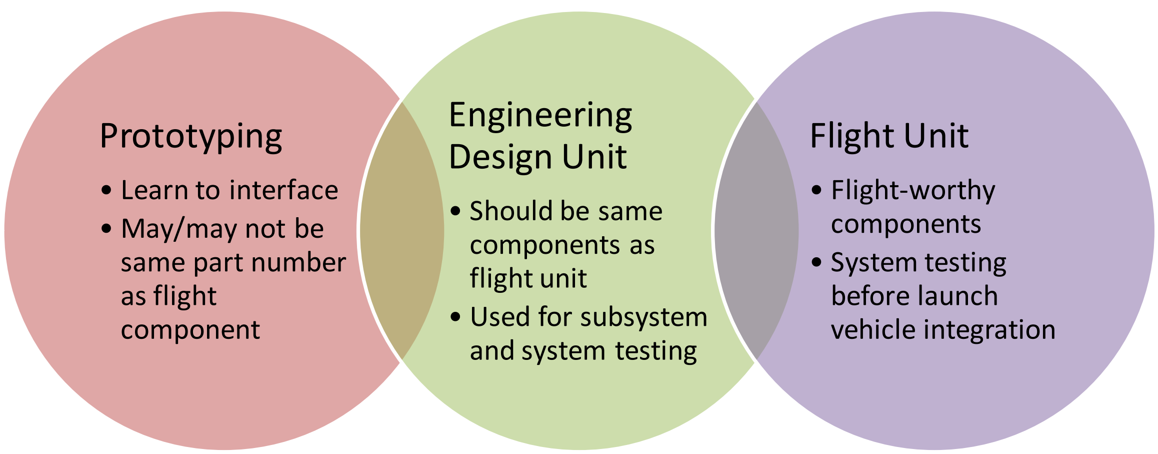


Figure 5.2 - Difference between prototype, engineering design units and flight units.

The development, payload and flight unit costs catalogued throughout this chapter are specific to the ARMADILLO and/or Bevo-2 missions. The Development Costs section relates to both missions as many of the components are the same between the two spacecraft – see Chapter 3 and the reusability discussion for specific components that are similar and dissimilar between the missions. The Payload Costs section details the payloads for both missions. The Flight Unit Costs listed in this chapter, however, are given only for the ARMADILLO mission because it has a more expensive component – the S-Band radio – and more detailed machining which is projected to cost more than the Bevo-2 machined parts. For a complete table of 3U CubeSat flight hardware costs for both the Bevo-2 and ARMADILLO missions, see Appendix G. These costs of the prototype, protoflight and flight units are then compared in Chapter 6 to typical industry models.

As explained in Larson [22], recurring hardware costs are considered costs associated with flight hardware manufacturing, integration and testing. Non-recurring hardware costs are then associated with the design, drafting and engineering of the protoflight EDU. As these definitions apply to the 3U CubeSat design, non-recurring costs are deemed to be development costs while the recurring costs are interpreted as flight unit costs, since the flight unit cost represents the cost of additional units after the development cycle has concluded.

5.3 Development/Non-Recurring Costs

ARMADILLO development, or non-recurring, costs consist of the prototyping and protoflight units necessary to gain experience with components as well as those components needed to complete a protoflight EDU. Prototyping units may or may not be the same part number as the eventual protoflight or flight unit hardware, but offer the students the experience of working and interfacing with components. Protoflight units are those components which are interfaced with on a regular basis and will ultimately end up on the EDU spacecraft so extra precautions are taken through quality assurance methods such as certification logs. Oftentimes, components are too expensive to buy multiple protoflight units to serve as both EDU and prototype units. With some components, such as the reaction wheels, the component is too expensive to purchase the same number of units needed for protoflight components for the EDU as the flight spacecraft.

As mentioned in the Methodology section, the hardware development cost spreadsheet has been set up to follow the WBS of Figure 5.1 and to highlight the modularity of the ARMADILLO spacecraft. The components are listed according to their subsystem and are further noted as part of a certain section. For instance, with the ADC module, all the sensors are grouped together into the "Sensors" section. Furthermore, the number of components used purely for prototyping versus those which will be part of the protoflight unit are distinguished from one another. This gives a total cost for the module in terms of prototyping and protoflight development costs.

The summary of the ADC module costs are shown in Table 5.1. For the complete table, see Appendix G. Many development kits went into the ADC module in order to better understand how to communicate between all the various sensors and actuators and the ADC computer. The protoflight units, however, are the more expensive components of the ADC module. The sun sensors and reaction wheels are too expensive – $12,000 and $10,000, respectively – to buy extras with which to prototype. Thus, these devices are only part of the protoflight cost and are the main factor in why the protoflight unit is much more expensive than the prototyping module. Because the SDL projects that the camera subsystem (NVS) will eventually be integral to the ADC subsystem, it is included in Table 5.1.

The thruster is now on its fourth iteration and it is this fourth version which is the configuration to be included on the protoflight and flight spacecraft. The costs associated with all four models are listed in Appendix G as well as the other components needed to test each thruster iteration. It should be noted that the Thruster is being developed in-house, but the necessary 3D rapid printing is being contracted to an outside company. The flight unit, though, will be made of the 3D printing plastic and so the costs in Table 5.1 accurately reflect the flight unit cost.

Table 5.1 - Development costs for ADC module.

		Component		Subsystem		ARMADILLO Prototyping	ARMADILLO Protoflight
Subsystem Cost ($)		Prototype Section Total (USD)	Protoflight Section Total (USD)	Prototype Total	Protoflight Total		
ADC module						$ 7,390.05	$ 42,294.07
ADC				$3,652.50	$37,924.28		
	Actuators	$0.00	$13,000.00				
	Sensors	$3,652.50	$24,924.28				
NVS	Camera	$2,080.20	$1,804.50	$2,080.20	$1,804.50		
THR				$1,657.35	$2,565.29		
	Device	$1,537.53	$973.94				
	Valve	$119.82	$1,591.35				

Next, a summary of the spacecraft bus module development costs is listed in Table 5.2. For the full spacecraft bus module development costs, see Appendix G. As with the ADC module, most of the prototyping costs are associated with the development kits and components used for initial testing. The spacecraft bus module includes three subsystems, the CDH, COM, and EPS. In terms of WBS elements, these subsystems are shown as part of the Flight System (6.0) diagram in Figure 5.1.

Table 5.2 - Development costs associated with the spacecraft bus module.

	Component		Subsystem		ARMADILLO Prototyping	ARMADILLO Protoflight
Subsystem Cost ($)	Prototype Section Total (USD)	Protoflight Section Total (USD)	Prototype Total	Protoflight Total		
Spacecraft Bus module					$ 68,634.16	$ 51,161.02
CDH			$22,369.53	$9,199.00		
Flight Computer	$22,109.65	$9,199.00				
Cables/fasteners	$259.88	$0.00				
COM			$19,348.55	$20,199.02		
UHF/VHF Radio	$0.00	$10,150.00				
GPS	$21.06	$44.42				
Development/Prototyping	$19,309.09	$0.00				
S-Band	$18.40	$10,004.60				
EPS			$26,916.08	$21,763.00		
Electronics Board	$ 15,084.00	$ 7,542.00				
Battery	$ 6,442.00	$ 3,221.00				
Solar Power	$5,355.02	$11,000.00				
Banana plugs	$35.06	$0.00				

The third and final module is the structure module which includes the fasteners, cables and wiring needed to interface with all the satellite components as well as build the plastic model. While tradition dictates that the structure cost is typically considered part of the spacecraft bus cost estimate, the SDL continues to follow the modularity philosophy by separating the structure cost. Because of the size of the ARMADILLO spacecraft, the structural components outlined in Table 5.3 are used for all modules of the spacecraft and cannot be individually accounted for in each module. The summary costs listed in Table 5.3 represent the development costs as of February 2012. For the expanded contents of Table 5.3, see Appendix G. Because the Bevo-2 and ARMADILLO spacecraft are still in development, these costs represent only the current accumulated development costs. Some costs directly associated with fabricating the protoflight EDU unit, such as EDU wiring and machined parts, are yet to be listed in Table 5.3 as they have not been purchased as of February 2012.

Table 5.3 - Development costs associated with the satellite structure.

			Component		Subsystem		ARMADILLO Prototyping	ARMADILLO Protoflight
Subsystem Cost ($)			Prototype Section Total (USD)	Protoflight Section Total (USD)	Prototype Total	Protoflight Total		
Satellite structure							$ 2,703.98	$ 1,005.40
STR					$2,703.98	$1,005.40		
	Fasteners		$0.00	$212.62				
		Connectors and pins for wire harnesses						
		Reaction wheel cable harness						
		ADC fasteners						
	Cables/wiring		$0.00	$792.78				
		ADC cable						
		Wiring 1						
		Wiring 2 (for flight too)						
	Plastic Model		$2,703.98	$0.00				
		SLA						
		Fasteners and screws						
		Extra parts						

5.4 Payload Costs

As explained in the Assumptions section, the payloads are considered donated components. For the Bevo-2 spacecraft, the only payload is the DRAGON GPS receiver. This hardware is donated by NASA Johnson Space Center. The ARMADILLO payload module houses the Piezoelectric Dust Detector (PDD) being developed by Baylor University and the FOTON GPS receiver being developed in the Radionavigation Lab at UT-Austin.

All of these payloads are considered donated and thus do not incur any cost on the ARMADILLO budget. However, should the FOTON GPS receiver be added to any future mission, the current estimated retail price of the receiver is $50,000. These costs for both the Bevo-2 and ARMADILLO missions are summarized in Table 5.4.

Table 5.4 - Payload cost for ARMADILLO and Bevo-2 missions.

ARMADILLO Payload Costs			
Payload	**Cost (ea)**	**Quantity needed**	**Component Total (USD)**
PDD	$0.00	1	$0.00
FOTON GPS	$50,000.00	1	$50,000.00
		ARMADILLO Payload	$50,000.00
Bevo-2 Payload Costs			
Payload	**Cost (ea)**	**Quantity needed**	**Component Total (USD)**
DRAGON GPS	$0.00	1	$0.00
		Bevo-2 Payload	$0.00

5.5 Flight Unit/Recurring Costs

The flight hardware, or recurring, costs spreadsheet is set up almost identically to the development hardware spreadsheet. Once again, the SDL philosophy of 3U CubeSat modularity is applied with three subsets – Attitude Determination and Control (ADC), Spacecraft Bus and the Satellite Structure. Note that these distinctions are almost identical to the physical modules of the spacecraft – the ADC, bus and payload modules.

The ADC module flight unit summary costs are shown in Table 5.5, the spacecraft bus module summary costs in Table 5.6, and the satellite structure flight unit summary costs are listed in Table 5.7. For the full cost tables, see Appendix G. The majority of integration is done by the students and the labor cost is captured as the personnel hours tracked throughout the project duration. Thus, the cost of the machined parts and the integration components such as wiring and fasteners comprise the total integration costs experienced by the SDL as part of the ARMADILLO mission.

Table 5.5 - ADC module flight satellite costs.

		Component	Subsystem	Module
Subsystem Cost ($)		Flight Component Total (USD)	CBE ($)	
ADC module				$101,852.13
ADC			$97,123.28	
	Actuators	$63,000.00		
	Sensors	$24,924.28		
	Flight Computer	$9,199.00		
NVS	Camera	$1,804.50	$1,804.50	
THR			$2,924.35	
	Device	$1,133.00		
	Valve	$1,791.35		

Table 5.6 - Spacecraft bus module flight satellite costs.

		Component	Subsystem	Module
Subsystem Cost ($)		Flight Component Total (USD)	CBE ($)	
Spacecraft Bus module				$58,600.53
CDH			$9,199.00	
	Flight Computer	$9,199.00		
COM			$27,638.53	
	UHF/VHF Radio	$11,759.13		
	GPS	$74.80		
	S-band	$15,804.60		
EPS			$21,763.00	
	Electronics Board	$7,542.00		
	Battery	$3,221.00		
	Solar Power	$11,000.00		

Table 5.7 - Satellite structure flight unit costs.

		Component	Subsystem	Module
Subsystem Cost ($)		Flight Component Total (USD)	CBE ($)	
Satellite structure				$27,500.00
STR machining			$22,500.00	
	ADC Module	$7,500.00		
	Bus Module	$7,500.00		
	Payload			
		$7,500.00		
Integration		$5,000.00	$5,000.00	
	Wiring and Connectors			
	Fasteners			
	Chemicals (Elastomer, Staking, etc..)			

Note that the values in Table 5.7 represent estimates because as of February 2012, the structure drawings have not been sent to the machine shop and the actual costs have not been established. Because ARMADILLO has been selected for launch through the Educational Launch of Nanosatellites (ELaNA), a deployment mechanism will be provided by NASA. If this was not the case, the SDL estimates the cost of a deployment mechanism, such as the P-POD, at approximately $50,000. As part of the full flight unit cost tables which may be found in Appendix G, the number of flight components already purchased and in the SDL is noted along with the cost of each of these components. As of February 2012, the ARMADILLO spacecraft owns eight flight-quality components. These are: one reaction wheel, two sun sensors, one flight computer, one ADC computer, one UHF/VHF radio, and one spacecraft battery with the accompanying electronics board. Because of the expensive nature of picosatellite reaction wheels and sun sensors, these ARMADILLO flight-worthy components are currently considered Bevo-2 protoflight hardware. Together, all the ARMADILLO in-house and flight-worthy components cost approximately $60,000. With a total flight hardware cost of almost $188,000, the ARMADILLO spacecraft has about $128,000 of costs yet to purchase. These values are summarized in Table 5.8.

Table 5.8 - Summary of ARMADILLO flight hardware costs already purchased and the cost to complete the spacecraft.

ARMADILLO Flight HW Costs	
Flight HW CBE	$187,952.66
Total number of components in-house	8
Cost of in-house components	$60,061.00
ARMADILLO Completion Cost	**$127,891.66**

5.6 Recurring vs. Non-Recurring Hardware Costs

As explained in the Methodology section, non-recurring hardware costs are typically associated with the development costs while the recurring hardware costs are considered the flight unit costs. This distinction is important for the comparison to industry models which will take place in Chapter 6. Table 5.9 outlines the recurring and non-recurring costs associated with the ARMADILLO 3U CubeSat. Note that the non-recurring costs are broken down into non-recurring prototyping and non-recurring protoflight unit costs since the prototyping costs do not consist of hardware on the EDU spacecraft. Because the SDL is currently developing two 3U CubeSat spacecraft, funding obtained through one project is leveraged for the development of both satellites. This helps to alleviate the financial burden of the development of two independent spacecraft designs.

Table 5.9 - ARMADILLO Recurring vs. Non-recurring Hardware Costs.

ARMADILLO Recurring vs. Non-recurring Costs	
Recurring	$ 187,952.66
Non-recurring Prototyping	$ 78,728.19
Non-recurring Protoflight unit	$ 94,460.49
Flight Unit + EDU	**$ 282,413.15**
Total Cost (Flight unit + prototyping + EDU)	**$ 361,141.34**

5.7 Student Grassroots Approach Summary

The grassroots approach taken in the SDL for the Bevo-2 and ARMADILLO missions included listing out each piece of hardware and its associated price for both the Development/EDU satellite as well as the flight. Following the SDL modularity philosophy, the components were placed into their respective modules in order to obtain costs per module. Flight system integration costs are calculated based upon previous flight experience from fabricating the Bevo-2 satellite whereas the integration costs of the development satellite are based upon purchased items needed to fabricate the EDU. Because most of the mission-level tests will be completed at the expense of either NASA or the Air Force, the majority of Integration and Testing (I&T) costs do not need to be accounted for in the grassroots approach. The facilities cost estimate provided in Chapter 4 gives an idea of the costs accumulated at the University-level as of February 2012 when buying supplies necessary for integration and testing. The projected personnel costs contain the actual cost of the paid undergraduate and graduate research assistants (URAs and GRAs, respectively) in the SDL as well as the Principal Investigator (PI) cost to the projects. These total costs were based upon data dating back to the estimated beginning of both projects in September 2010 and are projected to the completion of both projects at the end of calendar year 2012.

There were many assumptions which went into the calculation of all these cost values, for a complete list see Appendix A. The key assumptions are:

- With the exception of a few "subcontractors", the satellites are managed, designed and built by students.
- Across both the Bevo-2 and ARMADILLO missions, only the Piezo-electric Dust Detector (PDD), FOTON and DRAGON GPS receivers are considered "donated" hardware. The other components are COTS.
- The cost of software engineering is assumed to be part of the personnel costs, as all the mission script programming is completed by students in the SDL. The student hours are tracked and are figured into the personnel costs. Since all team members work on computer code, it would be infeasible to separate the software costs from the computed personnel costs.

With these assumptions in mind and the cost breakdown structure shown in Figure 4.1, the grassroots cost approach is summarized in Table 5.10. Note that the total cost shown in Table 5.10 uses the actual personnel costs determined from the number of graduate and undergraduate research assistants as well as the Principal Investigator (PI) involvement and travel costs. Table 5.11 summarizes the government-like method employed to capture the personnel cost of the entire team, including the PI, and compares this method to the projected actual cost. See Chapter 4 for the calculations associated with these values. Recall that the recurring cost is based upon the percent reusability of systems engineering and deliverables – 48.13%.

Note that there is no cost for Mission Assurance (3.0) because these costs are already factored into the captured student labor hours cost. Also recall that since the science analysis will not be completed by SDL team members, the associated cost with Science (4.0) is \$0. Table 5.10 also shows no cost associated with Mission Operations (7.0) as of February 2012 because the Bevo-2 and ARMADILLO 3U CubeSat missions have not launched and no data is available. Once the spacecraft are launched and the missions begin, hours and costs specific to operations will be tracked. Finally, there is no cost of Launch Systems (8.0) for the ARMADILLO mission because the launch is provided by ELaNa. For the Bevo-2 mission, the UT-Austin team is responsible for the cost of the deployment mechanism, but the launch itself is provided through NASA-JSC.

Table 5.10 - ARMADILLO Grassroots Cost Summary.

ARMADILLO WBS		Cost ($)
1.0 Project Management		$273,296.63
	1.1 Project Management	$157,080.00
	1.2 Travel	$50,220.05
	1.3 Facilities	$65,996.58
2.0 Project Systems Engineering		$939,688.68
	2.1 Project Systems Engineering	$766,500.00
	2.2 Project Software Engineering	$0.00
	2.3 Project Hardware Engineering	$173,188.68
3.0 Mission Assurance		$0.00
	3.1 Mission Assurance Management	$0.00
	3.2 Hardware Quality Assurance	$0.00
	3.3 Software Quality Assurance	$0.00
4.0 Science		$0.00
	4.1 Science Management	$0.00
	4.2 Science Team	$0.00
	4.3 Science Data Support	$0.00
	4.4 Education and Outreach	$0.00
5.0 Payload		$50,000.00
	5.1 Payload Management and Systems Engineering	0
	5.2 FOTON GPS Receiver	$50,000.00
	5.3 Piezoelectric Dust Detector	$0.00
	5.4 Payload Integration and Testing	$0.00
6.0 Flight System		$187,952.66
	6.1 Attitude Determination Control Module	$101,852.13
	6.2 Bus Module	$58,600.53
	6.3 Satellite Structure	$27,500.00
7.0 Mission Operations		$0.00
	7.1 Mission Operations Management	$0.00
	7.2 Ground Facilities	$0.00
	7.3 Operations	$0.00
8.0 Launch Systems		$0.00
	8.1 Launch Services	$0.00
	Total 3U CubeSat Cost	**$1,450,937.96**

Table 5.11 - Personnel costs between measured and government method.

Total ($)	ARMADILLO Total	ARMADILLO Recurring	ARMADILLO Non-recurring
Total measured personnel cost	$923,580.00	$444,519.05	$479,060.95
Total government method cost	$590,058.68	$283,995.24	$306,063.44
Total government method cost w/ burdened labor rate of 50% + PI Cost	$1,042,168.02	$501,595.47	$540,572.55

With the summaries given in Table 5.10 and Table 5.11, the breakdown of ARMADILLO recurring and non-recurring costs is listed in Table 5.12. Note that the support non-recurring costs of Table 5.12 include the facilities costs listed in Table 5.10 and the government method personnel non-recurring costs of Table 5.11 because the government method accounts for all team members as well as the PI and better represents the personnel costs of the ARMADILLO mission. Similarly, the support recurring costs include the travel costs from Table 5.10 and the government method personnel recurring costs. Spacecraft non-recurring costs are assumed to only consist of the development expenses while the recurring value is the flight system cost.

Table 5.12 - ARMADILLO Mission Cost Summary.

ARMADILLO	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$ 173.19
Total S/C Re Costs	$ 237.95
Total spacecraft costs	$ 411.14
Total Support NR Costs	$ 606.57
Total Support Re Costs	$ 551.82
Total support costs	$ 1,158.38
TOTAL NR	$ 731.07
TOTAL Re	$ 789.77
TOTAL	$ **1,569.53**

This total mission cost of approximately $1.6 Million for the ARMADILLO 3U CubeSat will next be compared to typical industry cost models such as the Aerospace Corporation's Small Satellite Cost Model and the NASA/Air Force Cost Model. These models outline mission costs as the ARMADILLO cost is detailed in Table 5.12 – in terms of spacecraft and support costs, both recurring and non-recurring. Thus, Table 5.12 will be used in Chapter 6 comparisons to the industry cost models.

Chapter 6: Comparing Student Cost with Industry Models

6.1 Introduction and Purpose

The cost analysis method used for the Bevo-2 and ARMADILLO projects is a grassroots, or "bottom-up" approach to determining the total cost of a mission. The SDL grassroots approach accounts for all hardware, personnel and integration and testing costs as they apply to student projects. Many of these costs are minimal to non-existent when compared to the associated costs in industry. It is the goal of this chapter to provide a summary of the student grassroots cost approach and compare this analysis with typical industry models.

The industry models may be broken down into subcategories of Cost Models and Instrument Models. Cost models are used to estimate the cost of the spacecraft, payload excluded, and encompass the entire mission – from design, to fabrication to operations. The cost models used in this chapter have been selected to encompass unmanned spacecraft missions. Should this technique be used for human-rated spacecraft, these models will be irrelevant. The instrument models are typically only used in the designing, building and scientific operations of the instrument itself as opposed to the entire spacecraft. For the purposes of this thesis, and because the SDL is building two spacecraft rather than two instruments, only the spacecraft cost models are used. Specifically, this thesis uses two spacecraft cost models – Small Satellite Cost Model (SSCM) and NASA/Air Force Cost Model (NAFCOM) – and applies these models with input values based upon a 3U CubeSat design in an effort to determine the feasibility of using these industry models to accurately estimate costs of student-built small satellite projects.

6.2 Industry Model Methodology and Assumptions

According to Wertz, when estimating cost, there are four major engineering and program requirements which influence the total mission cost – size, complexity, technology availability and schedule.[22] These four mission parameters determine the class of the mission, drive the procurement approach and the level of government oversight. Industry cost models tend to rely upon a top-down approach called parametric cost estimating in which these four characteristics help establish Cost Estimating Relationships (CERs) for each subsystem of the satellite. These CERs are a mathematical equation with input variables such as mass, volume, power output, etc and yield an output of the total cost for that subsystem. The CERs are different for each model and sometimes vary within the specific model depending upon the input variable. For example, some of the models have different CERs if the total spacecraft mass is between 0 and 100 kg versus a total mass between 100 and 1000 kg. The CER equations themselves are based upon historical data from previous missions. Thus, as more and more space missions take place, these CERs are updated to more accurately reflect growing trends in space mission costs. Because these CERs are based upon actual data, the relationships reflect the impact of schedule and engineering changes as well as other programmatic issues which typically arise during mission planning and executing. Many CERs require an input variable of the system, subsystem or component mass.

In each of the following sections, the respective models will be explained and the CERs (if available) will be given along with the input and output values. In some cases, the CERs are not available due to the proprietary nature of the models. Instead, the cost model is a type of computer program where the input variables are entered and the program calculates and displays the total cost for that subsystem of the satellite.

Each model has its own set of assumptions and rules. These rules and assumptions typically deal with what each component or subsystem of the satellite encompasses. Naturally, each cost model is only as good as the database of satellites used to determine the CERs. The newest available version of the industry cost models was used in an effort to gather the most accurate cost information. Additionally, models tend to differ on their definitions of "recurring", "non-recurring" and other cost definitions. These descriptions as they apply to the specific model will be given in the model's analysis section.

Finally, many of the models calculate the total cost in a year which is not 2011. Thus, the U.S. inflation calculator and Consumer Price Index (CPI) were used in order to determine the cost in current year dollars.[23] The CPI values are listed for each month and the inflation value may be calculated by finding the ratio of the current month to the month of the cost value. For comparison sake, all CPI values were taken in the month of August for each year. In other words, all calculations to 2011 dollars used the CPI value for August 2011 and the August in whichever year the model calculated the cost.

6.3 Small Satellite Cost Model (SSCM)

6.3.1 SSCM General Information

The Small Satellite Cost Model (SSCM) was created by The Aerospace Corporation to estimate the costs associated with small satellites (less than 1000 kg).[24] Access to this model is currently restricted to U.S. citizens. Though an attempt was made to request the newest version of SSCM – SSCM10 released in October 2010 – a response was never received and SSCM05 – released in September 2005 – was used in the following sections instead. This simply means that the CERs may not be as accurate as in the SSCM10 edition, but still provide the general trends of small satellite cost estimation.

6.3.2 SSCM Assumptions and Scope

The SSCM model describes its methodology and assumptions as:

1. Estimates assume the cost of developing and producing one spacecraft, the phase known among NASA users as Phases C/D and for DoD users as fits within Phases B/C. Concept development and operations are not included. Also, the emphasis is on spacecraft bus costs; payload, launch vehicles, upper stages, associated GSE are not included.
2. All costs estimated by CERs are contractor costs.
3. CER estimates are in FY05 $K.
4. Non-recurring and recurring costs can be estimated separately, using the provided factors. Non-recurring costs include all efforts associated with design, drafting, engineering unit IA&T, GSE, and program management / systems engineering costs that can be identified as non-recurring. This includes all costs associated with design verification and interface requirements. Recurring costs cover all efforts associated with flight hardware manufacture, IA&T, program management and systems engineering that can be identified as recurring.
5. Spacecraft system-level cost estimates for program management, systems engineering, integration, assembly and checkout, GSE, and system test operations are separate from the subsystem level.
6. CERs are statistical fits to data derived from actual costs of recent small satellite programs. Use of CERs to estimate costs of future programs relies on the assumption that historical trends will accurately reflect future costs.
7. Most costs in the small satellite database are actual program costs at completion, gathered from the spacecraft operators. In a few cases,

however, cost data provided was for satellites that were nearly complete but had not yet been launched. In those cases, contractor estimate at complete (EAC) costs were used.

8. CERs estimate burdened costs including direct labor, material, overhead, and general administrative costs.
9. Most programs in the database rely on some degree of hardware commonality to previous units, but limited quantitative data were available. CERs therefore yield costs that represent a mathematical average amount of heritage, level of technology complexity, and amount of schedule delays and engineering changes. Cost estimates derived from the CERs should therefore be accompanied by a comprehensive cost-risk assessment to estimate potential effects of a level of complexity below or beyond average.

A few assumptions made when applying this model to the ARMADILLO and Bevo-2 missions are:

1. Development time is taken to be for ARMADILLO, a set amount of design/development given the timeline of the University Nanosatellite Program. Development began in January 2011 and will finish in January 2013, yielding a development time of 2 years which equals 24 months. This timeframe is applied to the cost drivers in the 1.3 Integration Assembly & Test, 3.0 Program Level and 4.0 Operations CERs.
2. Spacecraft dry mass is taken as the total allowable mass for a 3U CubeSat released via the PPOD deployment system – 4 kg – less the mass of the ARMADILLO thruster propellant – approximately 80 grams.

3. The TT&C/C&DH SSCM CER uses the number of instruments aboard the spacecraft. The number of instruments aboard ARMADILLO not already accounted for in the ADCS, TT&C/C&DH, EPS, Structure, or Thermal categories is three – the Thruster, PDD, and Camera.
4. Some cost drivers are taken from the component selection and requirements satisfaction, these include:
    a. Pointing knowledge of five degrees for the ADCS CER.
    b. Transmit power of one Watt for the TT&C/C&DH CER.
    c. Use of a Nickel-Cadmium (NiCd) battery for the EPS CER.
    d. Aluminum as the structure material for the Structure CER.
    e. Beginning of Life (BOL) power assumed to be 5.1 Watts, the estimated maximum obtained in full sunlight.
5. The majority of the remaining cost drivers typically use masses of subsystems. These mass values may be obtained via the mass budget in Appendix D.

6.3.3 SSCM Results and Analysis

The Small Satellite Cost Model includes two models. The first is for spacecraft which have a mass less than 100 kg and the second model is for those small satellites with masses between 100 and 1000 kg. With a 4 kg satellite, Bevo-2 and ARMADILLO technically fit within the <100 kg model. Table 6.1 gives the CERs for the SSCM <100 kg model and the input values associated with each WBS element. Note that Table 6.1 does not include a CER for the propulsion unit. The ARMADILLO thruster cost is not accurately captured in this method. Even though the <100 kg model includes WBS element titled “Thruster”, there is no CER to help estimate the thruster cost. Because the ARMADILLO thruster is being developed in-house, considering it another instrument and including its cost as part of the cost driver for TT&C/C&DH does not accurately reflect the cost data which the ARMADILLO team possesses.

Table 6.1 also separates the total spacecraft non-recurring and recurring costs from the support non-recurring and recurring costs according to the percent values given in their respective CERs. Table 6.2 then gives the total cost for the WBS elements in both FY05 and FY11 dollars. Table 6.2 also summarizes the spacecraft and support non-recurring and recurring costs. Note that the CER for Operations (4.0) is set to $0 in order to more accurately compare with the grassroots approach of Chapter 5, where operations cost has not yet been factored into the analysis. The Integration and Testing (I&T) cost as captured in the SSCM model typically refers to the testing prior to integration with the launch vehicle. In the university setting, this I&T cost refers to the costs associated with the testing in the university lab. With respect to the SDL, the integration and testing with the launch provider are completed by the integrator and at no cost to the university. For Bevo-2 the launch integrator is NASA while for ARMADILLO it is AFRL. For these reasons, it is acknowledged that the I&T costs greatly differ for student-built spacecraft than in industry.

Table 6.1 - SSCM (<100 kg) CERs and value calculations.

WBS Element	CER (FY05 $K)	Cost Driver (X)	NRe %	Re %	X1	X2	CER value (FY05 $K)	CER NR (FY05 $K)	CER Re (FY05 $K)
1.1.1 ADCS	Y = 193.28*X1^1.672*X2^-1.799	X1 = Payload mass (kg); X2 = pointing control (deg)	0.58	0.42	0.52	5	$3.58	$2.08	$1.50
1.1.2 TT&C/C&DH	Y = 392.67*X1^0.834	X1 = number of instruments	0.49	0.51	3	--	$981.63	$481.00	$500.63
1.1.4 EPS	Y = 150.05*X1^0.161*X2^0.491	X1 = Solar array area (m^2); X2 = power subsystem mass (kg)	0.48	0.52	0.136	0.73	$93.25	$44.76	$48.49
1.1.5 Structure	Y = 29.28*X1^0.774	X1 = BOL Power (W)	0.58	0.42	5.1	--	$103.33	$59.93	$43.40
1.1.5 Thermal	Y = 386.41*X1^0.719	X1 = thermal subsystem mass (kg)	0.55	0.45	0	--	$0.00	$0.00	$0.00
1.1.6 Thruster	N/A	N/A	N/A	N/A	--	--	--	--	--
								Total s/c NR cost	**Total s/c Re cost**
								$587.76	$594.02
1.3 Integration, Assembly & Test	Y = 0.140*X1^1.471*X2^1.023	X1 = development time (months); X2 = BOL Power (W)	0.31	0.69	24	5.1	$79.48	$24.64	$54.84
3.0 Program level	Y = 1.42*X1^1.514*X2^0.438	X1 = development time (months); X2 = BOL Power (W)	0.54	0.46	24	5.1	$356.32	$192.41	$163.91
4.0 Operations	Y = 0.047*X1^2.352*x2^0.465	X1 = development time (months); X2 = BOL Power (W)	0	1	24	5.1	$0.00	$0.00	$0.00
								Total support NR cost	**Total support Re cost**
								$217.05	$218.75

Table 6.2 - SSCM (< 100 kg) total cost breakdown in FY05 and FY11 dollars.

WBS Element	Total cost (development + flight unit, FY05 $K)	Total cost (development + flight unit, FY11 $K)
1.1.1 ADCS	$3.58	$4.13
1.1.2 TT&C/C&DH	$981.63	$1,132.30
1.1.4 EPS	$93.25	$107.56
1.1.5 Structure	$103.33	$119.19
1.1.5 Thermal	$0.00	$0.00
1.1.6 Thruster	$0.00	$0.00
Total S/C NR Costs	$587.76	$677.98
Total S/C Re Costs	$594.02	$685.20
Total spacecraft costs	$1,181.78	$1,363.17
1.3 IA&T	$79.48	$91.68
3.0 Program level	$356.32	$411.01
4.0 Operations	$0.00	$0.00
Total Support NR Costs	$217.05	$250.37
Total Support Re Costs	$218.75	$252.33
Total support costs	$612.56	$502.69
TOTAL	**$1,617.59**	**$1,865.87**
TOTAL NR	**$804.82**	**$928.35**
TOTAL Re	**$812.77**	**$937.52**

The costs outlined through the SSCM <100 kg model as shown in Table 6.1 and Table 6.2 are simplistic with regards to the level of detail the ARMADILLO spacecraft can provide. While the <100 kg model is a good starting place for estimating small satellite costs, the 100-1000 kg model provides a more detailed CER approach. Despite having a mass of 4 kg and thus being out of range to apply the 100-1000 kg model, Table

6.3 and Table 6.4 show the results of the SSCM 100-1000 kg model as applied to the ARMADILLO spacecraft. Note that these CERs are much more detailed and are even specialized to Earth Orbiting (EO) and Planetary missions. Since Bevo-2 and ARMADILLO are designed for Low Earth Orbit, the EO equations are applied. The 100-1000 kg model also characterizes the ADCS as either spin stabilized versus 3-Axis stabilized – the ARMADILLO spacecraft is 3-Axis stabilized. The power system options consist of body-mounted, deployed-fixed or deployed-articulated – ARMADILLO has body-mounted solar panels and power supply boards. These more elaborated categories help to more accurately capture the costs associated with a very detailed small satellite design. Furthermore, the 100-1000 kg model includes a thruster CER which helps to capture the development and production costs associated with the ARMADILLO cold-gas thruster. Table 6.4 then gives the cost breakdown summary for each WBS element in terms of recurring, non-recurring and FY05 and FY11 dollars. See Appendix H for the full cost model table, including the percent values for NR and Re calculations.

Table 6.3 - SSCM (100-1000kg) CERs and value calculations.

WBS Element	Category	CER (FY05 $K)	Cost Driver (X)	CER value (FY05 $K)	CER NR (FY05 $K)	CER Re (FY05 $K)
1.1.1 ADCS	Spin stabilized	Y = 0.613*X1^1.584*X2^(-1.316)	X1 = Satellite wet mass (kg); X2 = pointing control (deg)	--	--	--
	3-Axis stabilized	Y = 1567.03*X1^(-0.260)*X2^0.069	X1 = pointing knowledge (deg); X2 = ADCS subsystem mass (kg)	$ 1,016.32	$589.47	$426.85
1.1.2 TT&C/C&DH	EO	Y = 247.41*X1^0.418*X2^1.369	X1 = CDH subsystem mass (kg); X2 = transmit power (W)	$165.11	$80.90	$84.20
	Planetary	Y = 4061.72*X1^0.622	X1 = CDH subsystem mass (kg)	--	--	--
1.1.4 EPS	Body-mounted	Y = 2994.97*X1^0.0269*2.157^X2	X1 = EPS mass (kg); X2 = battery type (0 = NiCd, 1 = NiH2)	$ 2,969.72	$ 1,425.47	$ 1,544.26
	Deployed-fixed	Y = 281.58*X1^0.484	X1 = BOL Power (W)	--	--	--
	Deployed-articulated	Y = 45.93*X1^0.689*1.598^X2	X1 = BOL Power (W); X2 = Solar Cell Type (0=Si; 1 = GaAs)	--	--	--
1.1.5 Structure	All	Y = 183.99*X1^0.540*1.742^X2*X3^0.412	X1 = Structure mass (kg); X2 = Structure material (0 = Aluminum, 1 = composite); X3 = solar array area (m^2)	$85.85	$49.80	$36.06
1.1.5 Thermal	All	Y = 72.37*X1^0.931*X2^0.084	X1 = thermal subsystem mass (kg); X2 = BOL power (W)	$0.00	$0.00	$0.00
1.1.6 Thruster	All	Y = 324.17*X1^0.446*1.781^X2*2.253^X3	X1 = propulsion subsystem dry mass (kg); X2 = propellant type (0 = cold gas; 1 = Hydrazine); X3 = Monoprop (=0) or Biprop (=1)	$189.48	$94.74	$94.74
					Total s/c NR cost $2,240.37	**Total s/c Re cost** $2,186.11
1.3 Integration, Assembly & Test	All	Y = 141.16*X1^0.302*X2^0.475	X1 = design life (months); X2 = bus dry mass (kg)	$705.26	$218.63	$486.63
3.0 Program level	EO	Y = 205.80*X1^0.524*X2^0.173*1.435^X3	X1 = Bus dry mass (kg); X2 = design life (months); X3 = stabilization type (0 = spin, 1 = 3-axis)	$1,047.02	$565.39	$481.63
	Planetary	Y = 84.56*X1^1.398	X1 = Development time (months)	--	--	--
4.0 Operations	All	Y = 0.136*X1^1.510*3.019^X2	X1 = Satellite wet mass (kg); X2 = stabilization type (0 = spin, 1 = 3-axis)	$0.00	$0.00	$0.00
					Total s/c NR cost $784.02	**Total s/c Re cost** $968.26

Table 6.4 - SSCM (100-1000kg) total cost breakdown in FY05 and FY11 dollars.

WBS Element	**Total cost (development + flight unit, FY05 $K)**	**Total cost (development + flight unit, FY11 $K)**
1.1.1 ADCS	$1,016.32	$1,172.31
1.1.2 TT&C/C&DH	$165.11	$190.45
1.1.4 EPS	$2,969.72	$3,425.54
1.1.5 Structure	$85.85	$99.03
1.1.5 Thermal	$0.00	$0.00
1.1.6 Thruster	$189.48	$218.57
Total S/C NR Costs	$2,240.37	$2,584.24
Total S/C Re Costs	$2,186.11	$2,521.66
Total spacecraft costs	$4,426.49	$5,105.90
1.3 IA&T	$705.26	$813.50
3.0 Program level	$1,047.02	$1,207.73
4.0 Operations	$0.00	$0.00
Total Support NR Costs	$784.02	$904.36
Total Support Re Costs	$968.26	$1,116.87
Total Support Costs	$1,752.28	$2,021.23
TOTAL	**$6,178.76**	**$7,127.13**
TOTAL NR	**$3,024.39**	**$3,488.60**
TOTAL Re	**$3,154.37**	**$3,638.53**

The two SSCM models are summarized in Table 6.5 for later comparison to the NASA/Air Force Cost Model (NAFCOM). As might be expected, the <100 kg model estimates a lower cost than the 100-1000 kg model by factor of approximately 3.8. Section 6.6 of this chapter compares the industry-used models to the cost model developed in the SDL.

Table 6.5 - Summary of two SSCM versions.

SSCM <100 kg	Total cost (development + flight unit, FY05 $K)	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$587.76	$677.98
Total S/C Re Costs	$594.02	$685.20
Total spacecraft costs	$1,181.78	$1,363.17
Total Support NR Costs	$217.05	$250.37
Total Support Re Costs	$218.75	$252.33
Total support costs	$435.80	$502.69
TOTAL NR	$804.82	$928.35
TOTAL Re	$812.77	$937.52
TOTAL	$1,617.59	$1,865.87

SSCM 100-1000 kg	Total cost (development + flight unit, FY05 $K)	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$2,240.37	$2,584.24
Total S/C Re Costs	$2,186.11	$2,521.66
Total spacecraft costs	$4,426.49	$5,105.90
Total Support NR Costs	$784.02	$904.36
Total Support Re Costs	$968.26	$1,116.87
Total Support Costs	$1,752.28	$2,021.23
TOTAL NR	$3,024.39	$3,488.60
TOTAL Re	$3,154.37	$3,638.53
TOTAL	$6,178.76	$7,127.13

6.3.4 SSCM Lessons Learned

As most university satellite design projects have spacecraft masses of less than 100 kg, the <100 kg Small Satellite Cost Model provides an effective tool for initially estimating the costs of a student-built small satellite. However, with CubeSats becoming highly capable spacecraft by including systems like propulsion units, this <100 kg model will need to reflect the spacecraft capability by having more detailed input variables as with the 100-1000 kg model. Only by developing a more detailed <100 kg cost model will student-built micro- and pico-satellites obtain accurate cost information.

Both SSCM models require that the spacecraft be within the range of spacecraft data accumulated from previous missions. Specifically, this data yields minimum and maximum values for the CER input variables of Table 6.1 and Table 6.3. These minimum and maximum range values are shown together with the associated value for the Bevo-2 and ARMADILLO 3U CubeSat missions in Table 6.6. For the majority of values, the 3U bus fits within the range. But for certain values, the most obvious ones are the masses, the 3U CubeSat is out of range. Because of these range values, it is suggested that the SSCM <100 kg model include CubeSat designs in future iterations of the cost model.

Table 6.6 - SSCM range parameters for both <100 kg and 100-1000 kg models.

Technical Parameter	Range		3U CubeSat Value
	Minimum	Maximum	
Development Time (months)	13	40	24
Design Life (months)	6	96	24
Satellite Wet Mass (kg)	113	877	4
Bus Dry Mass (kg)	45	674	3.02
Payload Mass (kg)	2.8	22.2	0.520
Number of Instruments	1	14	3
Power Subsystem Mass (kg)	2	19.7	0.73
BOL Power (W)	20	231	5.1
Solar Array Area (m^2)	0.124	1.5	0.136
Structure Subsystem Mass (kg)	6.7	182.9	1.117
ADCS Subsystem Mass (kg)	5.8	58.5	0.81
Pointing Control (deg)	3	10	5
Pointing Knowledge (deg)	0.01	1.5	5
Propulsion Subsystem Dry Mass (kg)	9	118.2	0.3
C&DH Subsystem Dry Mass (kg)	10.3	18.7	0.38
Transmit Power (W)	1.5	5.5	1
Thermal Subsystem Mass (kg)	0.2	1	0

6.4 NASA/AIR FORCE COST MODEL (NAFCOM)

6.4.1 NAFCOM General Information

NASA and the United States Air Force created the NAFCOM cost model and released the newest version in 2011. The cost model is a computer program which must be installed with a short list of other programs in order to be fully operational. Additionally, government regulations require the user to be a US citizen and contain the program on their personal computer rather than install it on public-access computers such as in a laboratory setting. In order to gain access, one must contact the NAFCOM representative with valid paperwork and a government sponsor willing to vouch for appropriate use of the NAFCOM program.[25]

6.4.2 NAFCOM Assumptions and Scope

The NAFCOM cost model is based upon historical data from previous missions and may be divided into several different categories:

- D&D represents the design and development cost.
- STH is the cost of the System Test Hardware.
- Flight Unit corresponds to the costs associated with the flight unit effort including the period beginning with the start of production initiated by long lead procurements and ending with the delivery of the first unit. Flight unit costs represent only the cost of the first unit to fly.
- Design, Development, Test and Evaluation (DDT&E) encompasses the design and development through the factory checkout of the first flight article. This value is determined by adding the D&D and STH values.

- Production refers to the cost of a flight unit multiplied by the quantity. In the ARMADILLO and Bevo-2 missions, all quantities in the NAFCOM model are one.
- Total reflects the total development and production cost of all systems required for the program. This value is obtained by adding the DDT&E and Production costs.

The NAFCOM model refers often to the Technology Maturity Index (TMI) which is based upon the Technology Readiness Level (TRL). The TMI values range from 1 to 12 and is based upon experience with the technology, flight experience, test experience, and the application of the technology. The TMI scale, applied in the calculations for each subsystem or WBS category, is defined by the NAFCOM model as:

1. Technology research has begun to be translated into applied research and development.
2. Technology is in the conceptual or application formulation phase.
3. Technology has been subjected to extensive analysis, experimentation, and/or a characteristic proof of concept, but has no flight experience.
4. Technology has been validated in a lab/test environment, but has no flight experience.
5. Technology has experience, but not in a space environment.
6. Technology has flight experience, but not recent flight experience.
7. Technology has recent flight experience (< 5 years) and the application of technology is at the edge of experience.
8. Technology has recent flight experience (< 5 years) and the application of technology within realm of experience.

9. Technology is approaching maturity (5-10 years) of flight experience encompassing at least 3 missions and the application of technology is at the edge of experience.
10. Technology is approaching maturity (5-10 years) of flight experience encompassing at least 3 missions and the application of technology within realm of experience.
11. Technology is mature (> 10 years) of flight experience encompassing at least 5 missions and the application of technology is at the edge of experience.
12. Technology is mature (>10 years) of flight experience encompassing at least 5 missions and the application of technology within realm of experience.

The NAFCOM model has very specific questions which the user must answer. In order to fully understand the following list of answers and assumptions made, the NAFCOM model must be downloaded and explored. The assumptions made when applying the NAFCOM model to the Bevo-2 and ARMADILLO missions are:

- The mission uses the Uncrewed Earth Orbiting Spacecraft template model.
- Assume FY2011 for the proper inflation.
- An Engineering Labor Hourly Rate of 48.
- A Manufacturing Labor Hourly Rate of 44.
- Overhead Rate of 50% to correspond with the university overhead at the University of Texas at Austin.
- General & Administrative (G&A) Rate of 10%.

- Several inputs were general to all WBS elements. The following common inputs were selected from a drop-down menu in the NAFCOM program:
  - Manufacturing methods are assumed to be a TMI (3) with moderate manufacturing technology
  - Engineering management is assumed to be a TMI (3) with moderate design changes.
  - New Design is assumed to be a TMI (8) with a new design, but components validated in a lab environment.
  - Funding availability is assumed to be a TMI (2) with some infrequent delays.
  - Test approach is assumed to be a TMI (2) with moderate testing and qualification at the prototype/protoflight level.
  - Integration complexity is assumed to be a TMI (1) of minimal major interfaces involving multiple contractors.
  - Pre-devleopment Study is assumed to be a TMI (3) with less than 9 months of pre-phase C/D study.
- Assumptions specific to the Structures and Mechanisms category are:
  - Mass is 1.118 kg.
  - There are no large inert structures, thus model input is (2). which is no.
  - There are no significant deployables, thus model input is (2).
- There is no thermal control aboard Bevo-2 or ARMADILLO.
- There is no reaction control subsystem, instead the reaction wheels are contained within the ADC subsystem.
- Assumptions specific to the Electrical Power Subsystem category are:

    - Mass is 0.730 kg.
    - Operational/design life is 24 months.
- Assumptions specific to the Communications / Command and Data Handling category are:
    - Mass is 0.38 kg.
    - A partially redundant system (2).
    - TMI (7) is recent flight experience (< 5 years) but at the edge of experience.
    - There are two transmitters aboard – the UHF/VHF and S-band radios.
    - Number of frequency bands is three (UHF, VHF and S-band).
    - Bevo-2 and ARMADILLO are neither a lander nor a probe.
    - Scientific mission (2).
- Assumptions specific to the Attitude Determination and Control module are:
    - Mass of 0.81 kg.
    - TMI is (4) which is no flight experience but extensive testing in a lab environment.
    - A partially redundant system (2).
    - 3-axis stabilization (2).
    - NAFCOM asks the user to select ADC components. The components available in NAFCOM and selected for the ARMADILLO mission are: a computer, sun sensors, star tracker, gyroscopes and magnetometers.
- Some assumptions specific to the structure and testing are:

    - System level testing with limited university resources yields a 1.50 value for System Test Operations (STO).
    - The 3U CubeSat is easy to assemble but still needs tools and teaching yielding a 0.25 value for GSE-Tooling.
    - The 3U CubeSat is easy to assemble and transport yielding a 0.1 value for GSE – ME/GSE.
- Since no fee, contingency or vehicle level integration is applied in the grassroots approach, the NAFCOM input is set to 0%.
- The lowest suggested values was taken for Program Support – 10 %

The above assumptions were specific to the input variables. The NAFCOM model, like many parametric cost models, bases the CERs on previous mission data. Furthermore, the NAFCOM model lets the user select which missions to use in the calculations. Additionally, the database provides an explanation of each mission so the user may select missions which are similar to their own. For the Bevo-2 and ARMADILLO cost estimates, all of the Unmanned, Earth-Orbiting, Scientific Explorer-class missions are selected. These missions are listed in Table 6.7 and may be researched for more information.

Table 6.7 - List of missions used in NAFCOM model analysis.

Mission Acronym	Mission Full Name
AE-3	Atmosphere Explorer – 3
AEM-HCMM	Application Explorer Missions – Heat Capacity Mapping Mission
AMPTE	Active Magnetospheric Particle Tracer Explorers – Charge Composition Explorer
COBE	Cosmic Background Explorer
DE-1	Dynamic Explorer - 1
DE-2	Dynamic Explorer – 2
FAST	Fast Auroral Snapshot Explorer
IBEX	Interstellar Boundary Explorer
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SME	Solar Mesosphere Explorer
SNOE	Student Nitric Oxide Explorer

6.4.3 NAFCOM Results and Analysis

Unfortunately, because of government regulations, the NAFCOM model does not publish its Cost Estimating Relationships (CERs) in the contractor version of the cost model. Thus, this section provides only the output costs associated with the Work Breakdown Structure (WBS) element. The previous assumption section details the input variables entered into the NAFCOM model. Given this lack of visibility into the model, the analysis lacks a level of fidelity by only giving costs according to WBS element instead of according to subsystem, as with the SSCM costs.

The cost of a 3U CubeSat mission according to the NAFCOM model is summarized in Table 6.8. See Appendix H for the fully detailed NAFCOM report. The

NAFCOM model does not break the costs down into specifically recurring and non-recurring costs. Though, according to the definitions, the Production costs are the costs associated with producing one flight unit. This could be assumed to be the recurring cost while the DDT&E cost is the development, or non-recurring cost. These costs are summarized in Table 6.9.

Table 6.8 - NAFCOM model results summary by NAFCOM WBS element.

WBS Element	**D&D**	**STH**	**Flight Unit**	**DDT&E**	**Production**	**Total (FY2011 $K)**
Uncrewed Earth Orbiting Spacecraft	$2,007.71	$518.52	$ 553.94	$ 4,238.85	$ 553.94	$ 4,792.79
1.0 Spacecraft Bus	$2,007.72	$518.52	$ 395.36	$ 2,526.23	$ 395.36	$ 2,921.59
				Total s/c NR cost	**Total s/c Re cost**	**Total s/c cost**
				$ 2,526.23	**$ 395.36**	**$ 2,921.59**
2.0 Spacecraft Bus System Integration	$ -	$ -	$ 108.22	$ 1,330.48	$ 108.22	$ 1,438.70
3.0 Fee	$ -	$ -	$ -	$ -	$ -	$ -
4.0 Program Support	$ -	$ -	$ 50.36	$ 382.14	$ 50.36	$ 432.50
5.0 Contingency	$ -	$ -	$ -	$ -	$ -	$ -
6.0 Vehicle Level Integration	$ -	$ -	$ -	$ -	$ -	$ -
				Total support NR cost	**Total support Re cost**	**Total support cost**
				$ 1,712.62	**$ 158.58**	**$ 1,871.20**

Table 6.9 - NAFCOM recurring and non-recurring cost breakdown.

NAFCOM	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$2,526.23
Total S/C Re Costs	$395.36
Total spacecraft costs	$2,921.59
Total Support NR Costs	$1,712.62
Total Support Re Costs	$158.58
Total support costs	$1,871.20
TOTAL NR	$4,238.85
TOTAL Re	$553.94
TOTAL	$4,792.79

6.4.4 NAFCOM Lessons Learned

In order to properly compare NAFCOM with other cost models, the following lessons are noted for future reference:

- NAFCOM does not have a recurring vs. non-recurring breakdown. Thus, the DDT&E cost is assumed to be non-recurring while Production cost is assumed to be recurring.
- Missions selected from the database were considered “explorer” Earth-Orbiting missions in an effort to use a similar class of missions as Bevo-2 and ARMADILLO in the CER database, but these missions still have masses much larger than the 3U CubeSat mission modeled. It would be advantageous to update NAFCOM to capture CubeSat missions. It is acknowledged that there is a large disparity in the mass of the missions used in NAFCOM calculations and the mass of a 3U CubeSat mission. The goal of this analysis was to understand the use and application of parametric models as they apply to student-built spacecraft.

- In some cases, inputs were qualitative – such as with the TMI and redundancy. Even with a set scale defined by NAFCOM, these selections were based upon knowledge of the spacecraft design and not quantitative in nature.

6.5 Models Not Used

The models discussed in the previous sections represent the most common government cost models that are used for many spacecraft missions. There are, however, a multitude of other cost models in existence. These models can be classified into two categories: mission cost models and instrument cost models. Each model initially investigated and eventually not used is listed below with rationales as to why the model was not used.

1. Mission cost models:
    a. Unmanned Space Vehicle Cost Model, 8th edition (USCM8) was not applied to the 3U CubeSat mission because the CubeSat cost drivers inputs were considered outside the database ranges. The USCM8 model is managed by the Air Force Space Command and access may be requested by visiting their website.[26]
    b. Planetary Data Systems Archiving Cost Analysis (PDS) may be found online but is mainly meant for planetary missions.[27]
    c. Space Operations Cost Model (SOCM) may be found online but could not seem to run on the computer on which all data was calculated and stored. The version downloaded was out of date and

no contact was listed to whom a request could be made for additional information and/or the newest version.[28]

d. Systems Evaluation and Estimation of Resources (SEER) is an industry-used cost model which is not based upon flown space systems. Moreover, there was a fee required to use the software which was outside the scope of this research.[29]

e. Parametric Review of information for Costing and Evaluation (PRICE) is widely used in industry, but not primarily based upon space missions and requires a fee to use.[30]

2. Instrument cost models do not accurately reflect the complexity of designing, building, testing and operating a small satellite. Rather, these models exist purely for modeling the costs associated with developing the instruments placed on spacecraft. Instrument models are widely used in industry. The most common models are:
   a. NASA Instrument Cost Model (NICM). [31]
   b. Scientific Instrument Cost Model (SICM). [32]
   c. Multi-variable Instrument Cost Model (MICM). [33]
   d. Passive Sensor Cost Model (PSCM). [34]

6.6 Industry Model Comparison to Grassroots Approach

After having applied the SSCM and NAFCOM models to a student-built 3U CubeSat, these industry cost models are compared to the SDL grassroots approach. Table 6.10 summarizes the ARMADILLO recurring and non-recurring costs. Recall the distinction between recurring and non-recurring costs: the support non-recurring costs include the facilities and the "government method" personnel non-recurring costs, the support recurring costs include the travel costs and the "government method" personnel recurring costs. Spacecraft non-recurring costs are assumed to only consist of the development expenses while the recurring value is the flight system cost.

Recall that the SDL is currently building two spacecraft – Bevo-2 and ARMADILLO. Some of the costs are leveraged between the two missions. These non-recurring shared costs typically consist of computer software, prototyping equipment and hardware testing devices such as the vacuum chamber. Personnel costs, non-recurring and recurring alike, are shared between the two missions since tasks accomplished for one mission are applicable to the other – see Chapter 3 for reusability analysis and Chapter 4 for personnel cost analysis. The two missions, however, have different hardware costs based upon the components selected for the respective missions – see Chapter 5 for discussion on the ARMADILLO hardware costs. Based upon the level of funding and the financial burden of building a 3U CubeSat, the SDL would not be able to build either the Bevo-2 or the ARMADILLO spacecraft without sharing the development costs between both missions.

Table 6.10 - Grassroots approach summarized in recurring and non-recurring costs.

ARMADILLO	**Total cost (development + flight unit, FY11 $K)**
Total S/C NR Costs	$ 173.19
Total S/C Re Costs	$ 237.95
Total spacecraft costs	$ 411.14
Total Support NR Costs	$ 606.57
Total Support Re Costs	$ 551.82
Total support costs	$ 1,158.38
TOTAL NR	$ 779.76
TOTAL Re	$ 789.77
TOTAL	**$ 1,569.53**

Note that the total cost of the entire mission – spacecraft and support, recurring and non-recurring – is approximately $1.6 Million. This price tag yields the entire development – prototyping and fabricating a protoflight EDU – as well as the fabrication of the flight spacecraft. Recall that the personnel costs captured in Table 6.10 represent the projected costs according to the "government method" employed in the SDL. This method catalogues the labor costs of all the students working on the 3U CubeSat project, accounts for the PI cost to the program as well as the associated university overhead for all personnel. It is the best representation of the labor required to build a 3U CubeSat.

Of the three cost models used, the Small Satellite <100 kg Cost Model best represents this student-built satellite design project, but still overestimates the total cost at a price of approximately $1.9 Million. In the previous sections for each industry cost model, a summary table was provided at the conclusion of the section. All these summary tables are summarized in Table 6.11. Recall that the Operations cost associated with the two SSCM models and the NAFCOM model was removed in order to better capture the costs as laid out in the grassroots approach. The Integration and Testing costs are also acknowledged to be different in an industry setting as opposed to a student-built spacecraft. Because of the nature of student-built spacecraft and the launch opportunities available, a majority of the integration and testing with the launch provider are arranged at no cost by the spacecraft integrators such as NASA and AFRL.

Table 6.11 - Summary of all industry cost models.

SSCM <100 kg	Total cost (development + flight unit, FY05 $K)	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$587.76	$677.98
Total S/C Re Costs	$594.02	$685.20
Total spacecraft costs	$1,181.78	$1,363.17
Total Support NR Costs	$217.05	$250.37
Total Support Re Costs	$218.75	$252.33
Total support costs	$435.80	$502.69
TOTAL NR	$804.82	$928.35
TOTAL Re	$812.77	$937.52
TOTAL	$1,617.59	$1,865.87

SSCM 100-1000 kg	Total cost (development + flight unit, FY05 $K)	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$2,240.37	$2,584.24
Total S/C Re Costs	$2,186.11	$2,521.66
Total spacecraft costs	$4,426.49	$5,105.90
Total Support NR Costs	$784.02	$904.36
Total Support Re Costs	$968.26	$1,116.87
Total Support Costs	$1,752.28	$2,021.23
TOTAL NR	$3,024.39	$3,488.60
TOTAL Re	$3,154.37	$3,638.53
TOTAL	$6,178.76	$7,127.13

NAFCOM	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$2,526.23
Total S/C Re Costs	$395.36
Total spacecraft costs	$2,921.59
Total Support NR Costs	$1,712.62
Total Support Re Costs	$158.58
Total support costs	$2,913.08
TOTAL NR	$4,238.85
TOTAL Re	$553.94
TOTAL	$4,792.79

Note that the models include different assumptions. For these assumptions, see the individual cost model section. Directly comparing the two industry models – the

NAFCOM and SSCM <100 kg models – which give a total cost including the development and one flight unit, notice that the NAFCOM cost prediction is over twice as expensive than the SSCM (<100 kg) estimate but about $2M less than the SSCM (100-1000 kg) estimate. It is expected that the SSCM <100 kg model would more accurately estimate a 3U CubeSat mission because the SSCM model is specifically targeted for small satellites. While the NAFCOM model allows the user to select missions for CER calculations, very few microsatellite-class or smaller missions are available to select. Despite choosing, for the NAFCOM database, Explorer-class missions which more closely resemble the ARMADILLO mission, this NAFCOM estimate is closer to the estimate provided via the SSCM 100-1000 kg model. Thus, because the ARMADILLO mission fits within most of the SSCM <100 kg model parameters, it is expected that the results would more closely mirror the grassroots estimate.

While the SSCM <100 kg model provides a good estimation tool for student-built 3U CubeSat projects, the model still over-estimated by approximately 20%. Because CubeSat and small satellite projects are becoming more prevalent in industry and university settings, a cost model is needed which can accurately predict the costs associated with these missions. It is suggested that this CubeSat cost model use a combination of features from both SSCM and NAFCOM. Namely, use CERs with the ability to select which missions in a CubeSat database are used as a basis for these CERs. Furthermore, use a NAFCOM-like TMI scale to indicate the level of technology maturity in the satellite project. Finally, separate the payload costs from the subsystem-level CERs since small satellite payloads are not all created equally and may be better represented by instrument cost models such as NICM.

Chapter 7: Conclusion and Recommendations

Systems engineering is vital to the design of any spacecraft mission. As former NASA administrator, Dr. Michael Griffin, explains:

> Properly understood, the core purpose of the discipline of system engineering, and the primary responsibility of the system engineer, is the fielding of an elegant design. An elegant design is one which produces the intended result, is both robust and efficient, and generates a minimum of unintended consequences.[8]

At a university-level, the systems engineering team is responsible for ensuring the spacecraft meet all requirements, tracking the satellite costs, developing schedules and organizing the integration of the satellite. Furthermore, based upon a philosophy of modularity, the University of Texas at Austin (UT-Austin) Satellite Design Lab (SDL) systems engineering (SYS) team monitors the spacecraft design reusability. By developing the concept of design modularity, future missions may use any combination of individual 3U CubeSat modules, being developed for the Bevo-2 and ARMADILLO missions, as part of their spacecraft design.

This thesis was created out of a need to track the spacecraft costs and design reusability based upon a mission objective of the ARMADILLO mission. The research also benefits future designs by providing a quick estimate of a similar-class mission, defining a process of common spacecraft design deliverables and identifying the general systems engineering and configuration management practices of a student-led satellite design laboratory. Finally, the thesis serves applications desiring rapid response capability by providing a proven and well-documented reusable bus design which allows quicker access to space.

7.1 SUMMARY OF RESULTS

Design reusability is outlined in three ways – by hardware, software and systems engineering practices. Hardware reusability is calculated by comparing component mass and quantity on the bus design. Furthermore, for a component to be considered reusable, it must meet a set of performance parameters listed in Section 3.3.3. While a method for determining the software reusability of this 3U CubeSat design is outlined in Section 3.4.3, the ARMADILLO and Bevo-2 spacecraft designs are not yet mature enough to apply this methodology and obtain any preliminary results. The systems engineering reusability was calculated in two ways – based upon deliverables required by AFRL as part of the UNP competition as well as based upon the systems processes implemented throughout the course of the ARMADILLO design. The reusability calculations are detailed in Chapter 3 and summarized in Table 3.7. The reusability methods implemented in Chapter 3 yield an average hardware reusability of 87.89% and an average systems engineering reusability of 48.13%.

Personnel cost at the university-level is highly leveraged. Only Graduate and Undergraduate Research Assistants (GRAs and URAs, respectively) get paid for the time they spend working on the satellite projects. These costs, along with the cost of the Principal Investigator, are shown in Table 4.10 as the "Total measured personnel cost". Because not all students receive paid positions, an effort was made to capture the labor costs of a 40 person team by implementing a government-like pay grade method. For this method to be effective, hours were tracked starting in the fall 2011 semester and the associated hourly wage of each student accumulates to the total personnel cost shown in Table 4.10. The University of Texas at Austin burdened labor rate of 50% is used to more directly compare this government method with typical industry models and the "Total measured personnel cost". For more information on how the government method and actual personal costs were determined, see Chapter 4.

The total number of hours tracked during the fall 2011 semester is approximately 3130 amounting to a personnel cost of $73,588.39. For spring 2012, as of February 19th, 1449 labor hours have been recorded costing a total of $33,029.11. It should be noted that not all students submit their hours every two weeks. But the approximately 20 students who do record their hours represent the core of the team and provide a good estimate of the hours and labor costs associated with designing the Bevo-2 and ARMADILLO spacecraft.

The calculation of 3U CubeSat hardware costs was straightforward and consisted of listing each component according to subsystem and module in which the subsystem is located. Both the prototyping and protoflight costs are included in the EDU cost for the sake of documenting all the development costs associated with a 3U CubeSat mission. Prototyping uses any device to learn how to interface with components. Protoflight components are those which are interfaced with on a regular basis but will ultimately be part of the EDU spacecraft. Flight costs are only the components and integration costs associated with the flight unit. In other words, the flight costs are the costs of the components which will be ultimately launched, whereas the EDU cost is comprised of both the prototyping and protoflight expenses. All costs are explained and identified in Chapter 5 with the full detailed tables in the Appendix.

To compare with industry cost models, recurring and non-recurring costs were identified. Recurring costs are assumed to be the flight unit costs while the non-recurring costs were calculated based upon the combination of the prototyping and protoflight development costs. These recurring and non-recurring costs, summarized in Table 5.9, amount to a total 3U CubeSat hardware cost of approximately $360,000. The Bevo-2 mission experienced no payload costs, as the primary DRAGON GPS Receiver payload is supplied by NASA-JSC. The ARMADILLO mission receives its payloads at no cost as well – though in future non-UT missions, the FOTON GPS receiver will cost roughly $50,000.

To effectively compare the two industry-used satellite cost models which were applied to the 3U CubeSat design, it was necessary to organize the 3U CubeSat mission into a Work Breakdown Structure, shown in Figure 4.1. This cost breakdown is given in Table 5.10. Some entries are associated with a $0 cost because of the nature of student-built spacecraft missions. Many of these costs, such as the Mission Assurance (3.0) and Mission Operations (7.0), have already been captured in the student labor cost because the students will accomplish these tasks as part of the hours captured in the personnel cost analysis. Other costs like the Science (4.0) or Launch Systems (8.0) are not the responsibility of the UT-Austin SDL and are thus a zero-cost item for this analysis.

Table 7.1 shows the total cost, using the government method personnel cost calculation, of the entire mission – personnel, one flight satellite and all the prototyping and protoflight equipment – as approximately $1.5 Million. This price tag and the recurring (Re) and non-recurring (NR) costs are then compared to the industry model summaries of Table 6.11. Note that the support non-recurring costs of Table 7.1 include the facilities and the government method personnel non-recurring costs, while the support recurring costs include the travel costs and the government method personnel recurring costs. Spacecraft non-recurring costs are assumed to only consist of the development expenses while the recurring value is the flight system cost.

Table 7.1 - Total ARMADILLO mission costs listed in spacecraft and support recurring and non-recurring costs.

ARMADILLO	Total cost (development + flight unit, FY11 $K)
Total S/C NR Costs	$ 173.19
Total S/C Re Costs	$ 237.95
Total spacecraft costs	$ 411.14
Total Support NR Costs	$ 557.89
Total Support Re Costs	$ 551.82
Total support costs	$ 1,109.70
TOTAL NR	$ 731.07
TOTAL Re	$ 789.77
TOTAL	$ **1,520.84**

The Small Satellite Cost Model for spacecraft less than 100 kg, developed by the Aerospace Corporation, most accurately portrays the mission cost of a student-built 3U CubeSat as approximately $2 Million. This value is still approximately 27.67% higher than the total mission cost estimated by the grassroots approach. The grassroots approach accounts for more detail in the system design than the SSCM <100 kg model, which estimates the entire satellite mission cost with a handful of CERs. Note that both the NAFCOM and SSCM models, with results detailed in Table 6.11, have their own sets of assumptions and both models must clearly be understood before being applied to a given mission. For example, NAFCOM and the SSCM 100-1000 kg models both assume a certain spacecraft mass in order to accurately model the mission cost. Because most CubeSats have masses ranging from 1 kg (1U CubeSats) to 4 kg (3U CubeSats), these two cost models are out of range for CubeSat missions. See Chapter 6 for information on each of these models as well as more detailed analysis of each model as it applies to a 3U CubeSat design.

7.2 Concluding Remarks and Recommendations for Future Applications

There is a crucial gap in the cost estimating of small satellites which may be seen by comparing two widely-used cost models, the Small Satellite Cost Model (SSCM <100 kg) and the NASA/Air Force Cost Model (NAFCOM) as they apply to a 3U CubeSat project, with the grassroots methods which were developed in this thesis. While each of these models provides a basic understanding of the elements which go into cost estimating, the Cost Estimating Relationships (CERs) do not have enough historical data of picosatellites and nanosatellites (<50 kg) to accurately reflect the mission costs. Thus, the most important recommendation of this thesis is to develop a nanosatellite/CubeSat cost model with which university and industry developers alike can determine their mission costs during the design, development and operational stages. This is a long and interscholastic endeavor which would require the cooperation of many university and industry small satellite programs in order to gather all the required historical data. It is important, then, to start this process now at the beginning of the nanosatellite/CubeSat boom.

For the cost models used in this thesis, it is advised for future cost estimating projects to more fully delve into the missions in each model database. For the purposes of this research, missions were selected to be included in the model based upon the parameters of the mission being an Unmanned, Earth-Orbiting, Explorer-class spacecraft. It would be desirable to have greater visibility into and better understand the NAFCOM CERs as well as the scope of the database. For a more detailed analysis, it is also suggested to run Monte Carlo simulations on the cost estimates to yield a probability distribution of the most likely costs associated with the mission being analyzed.

The personnel costs captured in Chapter 4 are not accurately reflected by personnel cost models used throughout industry. Thus, it is suggested that future cost models include activity-based personnel cost estimation as the grassroots approach implemented on a basic level with the labor hours tracking and analysis. This more accurately outlines the university lab environment where students do not necessarily work the standard 40 hour work weeks.

This thesis serves an immediate use for the design analysis of the Bevo-2 and ARMADILLO 3U CubeSat projects as well as provides a foundation for future SDL missions. The thesis has provided an overview of the systems engineering practices necessary to design and fabricate future 3U CubeSat missions via describing the methodology applied for the reusability and cost analyses. Comparisons between future missions and this thesis may then be established which tell the true reusability of the satellite design, software implementation, deliverables and systems engineering processes.

Future SDL leaders should continuously refine the “government-like” personnel cost methodology based upon the experiences of the lab. In other words, more “additional steps” as identified in Chapter 4 should be included as the experience of team members changes. Furthermore, to make the reusability calculations more robust, it is suggested to implement an activity-based cost modeling system where the hours tracked are associated with the task being accomplished. For example, one would define the core activities which recur for each mission and record the hours charged to those activities such as procuring hardware and software, testing the hardware and software, writing documentation, etc. A similar process may be done with the non-recurring tasks such as initial trade studies, initial analyses, and preliminary structural designs. By specifically tracking these periods of time, it is possible to learn how much of each student’s time is spent on each portion of the design reusability implementation. This will give a much better estimate of how much time is saved when using the 3U CubeSat reusable design and deliverables.

This thesis documents the level of reusability and associated costs of the UT-Austin 3U CubeSat design as of Critical Design Review status. Because the Bevo-2 CubeSat will not be delivered until August 2012 and the ARMADILLO spacecraft will not arrive at the UNP Flight Competition Review (FCR) until January 2013, the spacecraft and personnel costs are projected to completion. It should be clarified that the life cycle costs for the ARMADILLO project begin when the mission design begins and ends at delivery. Because this analysis is only intended to determine mission costs through flight unit delivery, the analysis did not explore post-delivery integration and test, launch, or operations costs. The 3U CubeSat costs were compared with typical industry models and the results showed that existing cost models significantly overestimated the actual mission costs in the university lab setting. Given the rising interest of nanosatellites, the conclusion of this research emphasizes a vital need for new cost models which are better suited to lower cost, student developed university satellites.

Appendix A: Assumptions

MISSION AND/OR LAB ASSUMPTIONS:

1. The only contributed or donated hardware components on the ARMADILLO mission are the Piezo-electric Dust Detector (PDD) being developed, designed and delivered by Baylor University and the FOTON GPS Receiver being developed by the Radionavigation Laboratory at UT-Austin. For the Bevo-2 mission, the only donated hardware is the DRAGON GPS receiver from NASA Johnson Space Center (NASA-JSC).
2. As mentioned in the first assumption, the PDD, DRAGON and FOTON are not being built by the students in the SDL. These devices are considered donated by a subcontractor and are evaluated as a zero cost for the flight units. Because students are not developing these devices, there is no associated development cost. Both the flight and development cost methodology will be detailed in the hardware cost analysis of Chapter 5.
3. Two additional devices, the Kraken interface board and the cold-gas thruster, are being manufactured by a subcontractor. Students develop the designs and test the prototypes, but the physical fabrication, or in the case of the thruster - the printing of the device is left to a professional company. These costs are reflected in both the development and flight unit costs as detailed in the cost analysis of Chapter 5.
4. With the exception of these few subcontractors, the entire satellite is designed and built by students at UT-Austin. Additionally, the SDL itself is student managed. Further discussion on this is explored in the previous section (2.1).

5. Because UT-Austin is designing a 3U CubeSat and desires to fly on a multitude of launch vehicles, the SDL chose to follow the 3U design specifications put forth by the CubeSat community and developed by Cal Poly.[14] Following these standards allows for easier flight qualification and potentially more launch opportunities.
6. The SDL is able to apply lessons learned from past experiences in the design, fabrication, and operation of small satellites during the past ten years. In fact, lessons are gathered on a daily basis from the two spacecraft which make up the FASTRAC mission– Emma and Sara Lily– which are currently in orbit about the Earth. Further discussion of these experiences is provided in the "Past Missions" section (2.3).
7. Most of the current SDL work is not restricted in any way. However, the Bevo-2 and ARMADILLO missions do have some components which have restricted access according to the International Traffic in Arms Regulations (ITAR). ITAR policies require that some hardware may not be accessed by non-US citizens and may not be taken out of the country without explicit consent from the US Government. Because of the use of ITAR hardware, the SDL has a separate access-restricted room in which the ITAR-related hardware is stored and tested.
8. The SDL has a Class 100 Clean Bench which is used to integrate the EDU and flight satellites for both Bevo-2 and ARMADILLO.
9. While the SDL is responsible for preliminary testing of all components and subsystems as well as initial full system testing, the pre-launch integrators (NASA and AFRL) are responsible for flight qualifying the

satellite at their respective facilities. These test costs are not included in the cost estimates.

10. Given the iterative nature of designing a satellite, the values used throughout this thesis, such as the mass and number of components within a subsystem, may change over time. Thus, a data cut-off date is necessary in order to apply all the analyses in this thesis to a common set of data from a given point in time. Because it is a student lab, a data cut-off date was chosen to correspond with the end of the semester: December 11, 2011. This is the date where all data was saved in separate files and used for analysis. Because this data cut-off date is not reflective of the end of the project life cycle, costs are extrapolated based upon accumulated data. This extrapolation process is explained in Chapters 4 and 5.

HARDWARE REUSABILITY ASSUMPTIONS:

5. Hardware reusability is measured by the amount of necessary hardware the Bevo-2 and ARMADILLO 3U CubeSats have in common.
6. The definition of necessary hardware for each mission is based upon the hardware needed to satisfy mission requirements as stated in the requirements verification matrix for each mission.
7. Hardware reusability is calculated with respect to the spacecraft bus elements and does not include the Bevo-2 or ARMADILLO payloads. Thus, the analysis gives a hardware reusability value for the spacecraft bus as it applies to future missions.

8. Component refers to the piece-level of the subsystem. For instance, within the CDH subsystem, the flight computer is considered a single piece, or component. While the flight computer is comprised of resistors, capacitors, etc., the reusability analysis relies only upon comparison between the Bevo-2 and ARMADILLO components.

SOFTWARE REUSABILITY ASSUMPTIONS:

The SDL software design philosophy also follows the modularity approach. The satellite subsystems are each responsible for their respective sections of software. The main flight computer managed by the Command and Data Handling (CDH) team is then responsible for integrating all the subsystem code into the proper modes and formats.

It is the duty of the CDH team to ensure that all subsystems follow the software Interface Control Documents (ICD) established by the CDH team. Therefore, it is an assumption made for the methodology listed below that the subsystems have indeed followed this philosophy.

SYSTEMS ENGINEERING PROCESSES REUSABILITY ASSUMPTIONS:

4. The Systems Engineering deliverables produced during the development of ARMADILLO and Bevo-2 are primarily based upon the list of deliverables required by the University Nanosatellite Program competition run by the Air Force Research Lab.[20] These deliverables are standard for many government institutions. Therefore, the set provided by AFRL is used as the basis for determining reusability of the deliverables.

5. In addition to the deliverables required by the UNP competition, several other systems engineering processes were established by iterating upon the processes created by Garner and described in his thesis. These processes are directly applicable to future missions. These additional processes are identified separately from the design review deliverables with their respective percent reusability also identified.
6. The definition of systems engineering percent reusability applied in this thesis is not based upon the differences between Bevo-2 and ARMADILLO as it is with hardware and software reusability, because the two missions produce the same deliverables and processes dependent upon what is required by the mission technical support (NASA and AFRL).

HARDWARE COST ASSUMPTIONS:

This method is very clear-cut and simply consists of listing the spacecraft components, the quantities and the total costs. However, a few comments must be made regarding the payloads aboard the ARMADILLO and Bevo-2 spacecraft.

7. The only contributed or donated hardware on the ARMADILLO mission is the Piezo-electric Dust Detector (PDD), being developed by Baylor University, and the FOTON GPS Receiver, being developed in the Radionavigation Lab at UT-Austin. For the Bevo-2 mission, the only donated hardware is the DRAGON GPS receiver from NASA Johnson Space Center (JSC).
8. As mentioned in the first comment, the PDD, FOTON, and DRAGON are not being built by the students in the SDL and are assumed to arrive in the

SDL already space-qualified. These are considered to be "subcontracts" and the SDL simply purchases these devices as Commercial Off The Shelf (COTS) components.

9. The SDL will build as complete a protoflight unit as possible. This device is also known as the Engineering Design Unit (EDU). Because of the expense of the components, some subsystems of the protoflight unit may not completely represent the flight unit configuration. The hardware costs associated with developing and building this EDU are considered the non-recurring engineering costs.
10. The SDL purchases as many prototype units as is practical to give students the most possible interfacing opportunities.
11. Ultimately, only one flight unit is produced with the required number of components needed for full satellite functionality. The costs associated with fabricating this flight unit are considered to be the recurring costs.

Appendix B: Reusability Calculations

Hardware Reusability Calculations

Table B.1 - Hardware reusability calculations by number of component per subsystem.

			Bevo-2	ARMADILLO	On Both ?	Change	% change (B => A)	% non-reusable
ADC								**0.00%**
	Actuators							
		RW-0.01-4-I2C-2-0-0	3	3	1	0	0.00%	
		Magnetic Torque Rods	2	2	1	0	0.00%	
	Sensors							
		SS-411-VIS-RS485-3-0	2	2	1	0	0.00%	
		Honeywell HMR2003 Magnetometer	1	1	1	0	0.00%	
		Analog Devices ADIS16251 Gyros	3	3	1	0	0.00%	
		GPS Receiver	1	1	1	0	0.00%	
	Flight Computer							
		Phytec LPC3250 and Kraken	1	1	1	0	0.00%	
CDH								**0.00%**
	CDH Computer							
		Phytec LPC3250 and Kraken	1	1	1	0	0.00%	
COM								**50.00%**
	UHF/VHF							
		Radio	1	1	1	0	0.00%	
		Antenna	1	1	1	0	0.00%	
	S-band							
		Radio	0	1	0	1	50.00%	
		Antenna	0	1	0	1	50.00%	
	GPS Antenna							
		Antenna	1	1	1	0	0.00%	
	Cross-link							
		Radio	1	0	0	1	50.00%	
		Antenna	1	0	0	1	50.00%	
EPS						0		**0.00%**
	Main EPS							
		EPS	1	1	1	0	0.00%	

		Battery Board for EPS	1	1	1	0	0.00%	
	Solar Power							
		Solar Cell	23	23	1	0	0.00%	
		Solar Panel Triplet	5	5	1	0	0.00%	
		Solar Panel Couplet	2	2	1	0	0.00%	
		Solar Panel Singlet	4	4	1	0	0.00%	
NVS								**0.00%**
	Camera							
		Camera Body	1	1	1	0	0.00%	
		Lens	1	1	1	0	0.00%	
STR								**11.11%**
	Wall Shells							
		Payload Shell	1	1	1	0	0.00%	
		ADC Shell	1	1	1	0	0.00%	
		Bus Shell	1	1	1	0	0.00%	
	Connectors/Caps							
		Section Connectors	2	2	1	0	0.00%	
		ISIS End Cap	1	1	1	0	0.00%	
		ADC End Cap	1	1	1	0	0.00%	
	Component Mounting							
		Reaction Wheel Mount	1	1	1	0	0.00%	
		Magnetorquer Mounts	1	1	1	0	0.00%	
		GPS mount	1	1	1	0	0.00%	
		Electronic Stack Brackets	4	4	1	0	0.00%	
		Payload mount	0	1	0	1	11.11%	
		Camera Mount	1	1	1	0	0.00%	
	Integration							
		Fasteners	1	1	1	0	0.00%	
		Wiring	1	1	1	0	0.00%	
THR								**0**
	Pressurant							
		SLA Vessel	1	1	1	0	0.00%	
		R-236fa	1	1	1	0	0.00%	
		Reinforcing Plate	1	1	1	0	0.00%	
		Tank Lid	1	1	1	0	0.00%	
		Gasket	1	1	1	0	0.00%	
	Valve							
		Valves	3	3	1	0	0.00%	

	Valve Mounting Hardware	1	1	1	0	0.00%	
	Reinforcing Plate	1	1	1	0	0.00%	
						TOTAL %Non-reusable	**8.73%**
						TOTAL % Reusable	**91.27%**

Table B.2 - Hardware resuability by component mass in each subsystem.

mass in grams (g)			Bevo-2	ARMADILLO	On Both?	Change	Total Non-reusable mass
ADC							**265**
	Actuators						
		RW-0.01-4-I2C-2-0-0	368.1	368.1	1	0	
		Magnetic Torque Rods	60	60	1	0	
	Sensors						
		SS-411-VIS-RS485-3-0	66.4	66.4	1	0	
		Honeywell HMR2003 Magnetometer	23.4	23.4	1	0	
		Analog Devices ADIS16251 Gyros	14.1	14.1	1	0	
		GPS	100	365	0	265	
	Flight Computer						
		Phytec LPC3250 and Kraken	75.8	75.8	1	0	
CDH							**0**
	CDH Computer						
		Phytec LPC3250 and Kraken	75.8	75.8	1	0	
COM							**152.9**
	UHF/VHF						
		Radio	78	78	1	0	
		Antenna	130	130	1	0	
	S-band						
		Radio	0	42.9	0	42.9	
		Antenna	0	20	0	20	
	GPS Antenna						
		Antenna	10	10	1	0	
	Cross-link						
		Radio	50	0	0	50	
		Antenna	40	0	0	40	
EPS							**0**
	Main EPS						
		EPS	100.2	100.2	1	0	
		Battery Board for EPS	270.9	270.9	1	0	
	Solar Power						
		Solar Cell	51.428	51.428	1	0	
		Solar Panel	173.5	173.5	1	0	

		Triplet					
		Solar Panel Couplet	47.4	47.4	1	0	
		Solar Panel Singlet	50.8	50.8	1	0	
NVS							**0**
	Camera						
		Camera Body	58.3	58.3	1	0	
		Lens	58.3	58.3	1	0	
STR							**201.84**
	Wall Shells						
		Payload Shell	332.24	233.82	0	98.42	
		ADC Shell	190.78	190.78	1	0	
		Bus Shell	155.8	155.8	1	0	
	Connectors/Caps						
		Section Connectors	95.61	95.61	1	0	
		ISIS End Cap	58.64	58.64	1	0	
		ADC End Cap	37.16	37.16	1	0	
	Component Mounting						
		Reaction Wheel Mount	76.48	76.48	1	0	
		Magnetorquer Mounts	5.88	5.88	1	0	
		GPS Mount	86.14	63.94	0	22.2	
		Electronic Stack Brackets	9.77177	9.77177	1	0	
		Payload Mount	0	76.83	0	76.83	
		Camera Mount	23.97	19.58	0	4.39	
	Integration						
		Fasteners	20	20	1	0	
		Wiring	20	20	1	0	
THR							**0**
	Pressurant						
		SLA Vessel	200	200	1	0	
		R-236fa	84	84	1	0	
		Reinforcing Plate	1.6	1.6	1	0	
		Tank Lid	3	3	1	0	
		Gasket	0.04	0.04	1	0	
	Valve						
		Valves	15	15	1	0	
		Valve Mounting Hardware	60	60	1	0	
		Reinforcing Plate	4	4	1	0	

		Total NR mass	619.74
		Total mass limit	3600
		Total reusable mass	2980.26
		%NR	17.22%
		%R	82.79%

Systems Engineering Reusability Calculations

Table B.3 - Full list of deliverables, reusability values and weights.

Deliverables	ARMADILLO document	% Reusable	Difficulty weight	Weighted % resuable	%R rationale	Difficulty weight rationale
Presentation slides	SYS199-SCR_charts_Texas	25.00%	3.25	0.81	Template provides good idea of what should go into it; should be changed for specific mission	Lots of thought, effort and time required to specifically tailor document
	SYS199-PDR_Texas	25.00%	3.60	0.90		Lots of thought, effort and time required to specifically tailor document
Mission Overview	SYS197-Mission_overview	25.00%	3.00	0.75	Template provides good idea of what should go into it	Document requires some thought and lots of time but relatively simple to produce
Concept of Operatoins	SYS197-ConOps	50.00%	3.00	1.50	Template and graphics provides good idea of what should go into it and how to illustrate	Mainly thought goes into this document; easy to produce otherwise
Schedule	SYS191-Overall_Project_Timeline	50.00%	3.60	1.80		Mainly thought goes into this document; easy to produce otherwise
	SYS191-Project_gantt	50.00%	3.80	1.90	Template and graphics provides good idea of what should go into it and how to illustrate	Mainly thought goes into this document; easy to produce otherwise
	SYS491-Testing_&_Integration	50.00%	3.33	1.67		Mainly thought goes into this document; easy to produce otherwise
Block diagrams	SYS297-ARMADILLO_system_block_diagram	50.00%	2.50	1.25		Mainly thought goes into this document; easy to produce otherwise
	SYS297-ARMADILLO_software_block_diagram	50.00%	2.50	1.25	Template and graphics provides good idea of what should go into it and how to illustrate	Mainly thought goes into this document; easy to produce otherwise
	SYS297-Subsystem_Block_Diagram	50.00%	2.75	1.38		Mainly thought goes into this document; easy to produce otherwise

Personnel budget	SYS191-Personnel_budget	10.00%	1.40	0.14	Highly specific to current personnel and mission	Number crunching makes this document simple to produce, but still time consuming
RVM	SYS194-Mission_requirements_descope_options	25.00%	3.20	0.80	Template provides good idea of what should go into it; should be changed for specific mission	Lots of thought, effort and time required to specifically tailor document
	SYS194-Subsystem_rationales_requirements	25.00%	3.40	0.85		Lots of thought, effort and time required to specifically tailor document
Document Tree	SYS199-SRR_deliverables	25.00%	2.75	0.69		Document consists of list provided by customer, team must update to reflect additional documents as well as file names
	SYS199-SCR_deliverables	25.00%	2.75	0.69	Template provides good idea of what should go into it; should be changed for specific mission	Document consists of list provided by customer, team must update to reflect additional documents as well as file names
	SYS199-PDR_deliverables	25.00%	3.50	0.88		Document consists of list provided by customer, team must update to reflect additional documents as well as file names
Press Related Info	SYS191-Press_info	75.00%	1.75	1.31	Need not be altered, may be used as reference for future missions	Document consists of list provided by customer, team must update to reflect additional documents as well as file names
CAD of spacecraft	STR200 - Armadillo Main Assembly.STEP				**Defined by HW reusability	
Mass Budget	SYS192-Overall_Mass_Budget	50.00%	2.40	1.20	Template provides good starting point; dissimilar data needs to be replaces	Mainly thought goes into this document; easy to produce otherwise
Power Budget	SYS192-Overall_Power_Budgets	50.00%	3.00	1.50	Template provides good starting point; dissimilar data needs to be replaces	Mainly thought goes into this document; easy to produce otherwise
	SYS692-Power_Modes_and_Current_Budget_WIP	50.00%	3.00	1.50		Mainly thought goes into this document; easy to produce otherwise

Link Budget	SYS193-Link_Budget	50.00%	4.00	2.00	Template provides good starting point; dissimilar data needs to be replaces	Mainly thought goes into this document; easy to produce otherwise
Data Budget	SYS193-Data_budget	50.00%	3.50	1.75	Template provides good starting point; dissimilar data needs to be replaces	Mainly thought goes into this document; easy to produce otherwise
Board test results	SYS697-Subsystem_Status_Testing_Results	25.00%	4.25	1.06	Template provides good idea of what should go into it; should be changed for specific mission	Mainly thought goes into this document; easy to produce otherwise
Structural Analysis	STR697-Loads_Vibration_Analysis	25.00%	3.60	0.90	Template provides good idea of what should go into it; should be changed for specific mission	Document requires some thought and lots of time but relatively simple to produce
Thermal Analysis	STR697-Thermal_Analysis	25.00%	4.20	1.05	Template provides good idea of what should go into it; should be changed for specific mission	Document requires some thought and lots of time but relatively simple to produce
Materials List		50.00%	2.00	1.00	Template provides good starting point; dissimilar data needs to be replaces	Document requires some thought and lots of time but relatively simple to produce
Radiation Mitigation Design	SYS692-Radiation_Mitigation	50.00%	3.25	1.63	Template provides good starting point; dissimilar data needs to be replaces	Mainly thought goes into this document; easy to produce otherwise
EMC/EMI Mitigation Design	EPS697-EMI_Mitigation_Design_Plan	25.00%	2.80	0.70	Template provides good idea of what should go into it; should be changed for specific mission	Mainly thought goes into this document; easy to produce otherwise

Interface Control Documents	SYS798-0_Interface_Control_Document_Master_List	25.00%	2.25	0.56	Based upon calculation of how many ICDs change	Mainly thought goes into this document; easy to produce otherwise
	All ICDs	25.00%	2.75	0.69	Based upon calculation of how many ICDs change	Mainly thought goes into this document; easy to produce otherwise
Pressure Profile		25.00%	2.00	0.50	Template provides good idea of what should go into it; should be changed for specific mission	Document requires some thought and lots of time but relatively simple to produce.
Mechanical Drawing Package					**Defined by HW reusability	
Assembly Procedure	STR300-1-ADC_Module_Assembly_Procedure	90.00%	2.80	2.52		Mainly thought goes into this document; easy to produce otherwise
	STR300-2-Spacecraft_Bus_Assembly_Procedure	90.00%	2.60	2.34		Mainly thought goes into this document; easy to produce otherwise
	STR300-3-Payload_Module_Assembly_Procedure_ARMADILLO	50.00%	2.80	1.40	Since ADC, Bus modules are designed to be reusable, this assembly only requires new mission name;	Lots of thought, effort and time required to specifically tailor document
	STR300-ARMADILLO_Assembly_Procedure	90.00%	3.25	2.93		Mainly thought goes into this document; easy to produce otherwise
Software					**Defined by SW reusability	
Ground Support Design		50.00%	3.00	1.50	Template provides good starting point; dissimilar data needs to be replaces	Lots of thought, effort and time required to specifically tailor document
Frequency Allocation Paperwork		25.00%	3.67	0.92	Template provides good idea of what should go into it; should be changed for specific mission	Lots of thought, effort and time required to specifically tailor document
EDU/Flight satellite					**Defined by HW reusability	
System functional test results		50.00%	2.00	1.00	Template provides good starting point; dissimilar	Lots of thought, effort and time required to specifically tailor document

					data needs to be replaces	
Facilities and Resources	SYS798-Facilities_and_Resources	90.00%	2.00	1.80	Document need only be updated for new facilities and new mission name.	Document takes small amount of time and effort to produce
	SYS798-Ground_Station_Equipment	90.00%	2.00	1.80		Document takes small amount of time and effort to produce

Table B.4 - Systems processes developed by UT-Austin with associated reusability percent and weight.

SYS process	ARMADILLO document	% Reusable	Weight	Weighted %resuable	%R rationale	Weight rationale
Word Document Template	SYS100-Document_template	90.00%	1	0.9	Template only needs updated mission title	Simple outline is provided in template; Only basic thought goes into producing this document
Excel Document Template	SYS100-Excel_template	90.00%	1	0.9	Template only needs updated mission title	Simple outline is provided in template; Only basic thought goes into producing this document
Trade Study Template	SYS100-Trade_Study_Template	90.00%	1.4	1.26	Template only needs updated mission title	Simple outline is provided in template; Only basic thought goes into producing this document
Internal Review Plan	SYS195-Internal_Review_Plan	75.00%	1.6	1.2	Template needs minor modifications for new processes and new hardware	Mainly thought goes into this document; easy to produce otherwise
Documentation Plan	SYS195-Documentation_Plan	75.00%	1.8	1.35	Template needs minor modifications for new processes and new hardware	Mainly thought goes into this document; easy to produce otherwise
Organization Chart	SYS197-Org_chart	10.00%	2.2	0.22	Template provides good starting place; Highly specific to current personnel and mission	Document takes small amount of time and effort to produce
Preliminary Risk Analysis	SYS699-Risk_Analysis_and_Mitigation	25.00%	3	0.75	Template provides good idea of what should go into it; should be changed for specific mission	Lots of thought, effort and time required to specifically tailor document
Certification Logs	SYS797-Cert_log_blank	90.00%	1.6	1.44	Template only needs updated mission title and any additional updates	Simple outline is provided in template; Only basic thought goes into producing this document
Hardware Control Plan		90.00%	1.75	1.575	Template needs updated title and any additional new	Mainly thought goes into this document; easy to produce

					processes and new hardware	otherwise
Mission calendars	Google calendars	10.00%	2.6	0.26	Template provides good starting place; Highly specific to current personnel and mission	Simple outline is provided in template; Only basic thought goes into producing this document
Action item logs	SYS191-Action_Item_Log	10.00%	3	0.3	Template provides good starting place; Highly specific to current personnel and mission	Document consists of list provided by customer, team must update to reflect additional documents as well as file names
Contact lists	Google spreadsheets	10.00%	1.6	0.16	Template provides good starting place; Highly specific to current personnel and mission	Simple outline is provided in template; Only basic thought goes into producing this document
Lessons Learned documents	Lessons Learned Google Doc	100.00%	2	2		Simple outline is provided in template; Only basic thought goes into producing this document
	PDR/Small Sat notes	100.00%	1.8	1.8	Serves as a reference for future missions; nothing need change.	Simple outline is provided in template; Only basic thought goes into producing this document
Hours tracking	Google Form	90.00%	1.4	1.26	Form needs updated title	Simple outline is provided in template; Only basic thought goes into producing this document
Subsystem updates	Google doc	10.00%	2.8	0.28	Template provides good starting place; Highly specific to current personnel and mission	Simple outline is provided in template; Only basic thought goes into producing this document
Subsystem development plans	Google doc	50.00%	2.8	1.4	Template provides good starting point; dissimilar data needs to be replaces	Simple outline is provided in template; Only basic thought goes into producing this document
Personnel questionnaire form	Google Form	90.00%	1.6	1.44	Form need not change; vital information already	Document takes small amount of time and effort to produce

				included	
SYS795-Physical_electronics_ICD_template	90.00%	2	1.8	Template only needs updated mission title;	Simple outline is provided in template; Only basic thought goes into producing this document
SYS795-Physical_hardware_ICD_template	90.00%	2.2	1.98	Template only needs updated mission title;	Simple outline is provided in template; Only basic thought goes into producing this document
SYS795-Software_ICD_template	90.00%	2.25	2.03	Template only needs updated mission title;	Simple outline is provided in template; Only basic thought goes into producing this document

Appendix C: Personnel Costs

Table C.1 - Fall 2011 breakdown of total hours per student.

Alias:	Grade/ step	Hourly wage	22 Aug - 4 Sept	5 Sept - 18 Sept	19 Sept - 2 Oct	3 Oct - 16 Oct	17 Oct - 30 Oct	31 Oct - 13 Nov	14 Nov - 27 Nov	28 Nov - 11 Dec	12 Dec - 25 Dec	26 Dec - 8 Jan	Total hours	Cost
Student 1	GS-5/5	$17.00	--	--	--	--	--	--	0	6	--	--	6	$102.00
Student 2	GS-4/10	$17.43	24	15.75	10.25	8	24.25	23.25	21.5	1.25	--	21.5	149.75	$2,610.14
Student 3	GS-4/6	$15.65	2	6.75	2.25	--	8.5	--	0	--	--	0	19.5	$305.18
Student 4	GS-5/6	$17.50	--	--	--	--	--	--	--	--	--	--	0	$0.00
Student 5	GS-5/7	$18.00	--	2.5	--	--	3.5	--	--	--	--	--	6	$108.00
Student 6	GS-5/3	$16.00	--	--	--	--	--	--	--	--	--	--	0	$0.00
Student 7	GS-4/5	$15.20	--	5.	--	--	--	14	--	--	--	--	19	$288.80
Student 8	GS-4/3	$14.31	--	5.5	4	--	12.5	16	--	0	--	--	38	$543.78
Student 9	GS-5/10	$19.50	30	17	35	30	17	--	32	--	--	--	161	$3,139.50
Student 10	GS-4/4	$14.75	3	2.5	2.5	5	2	--	2	0.5	--	--	17.5	$258.13
Student 11	GS-4/7	$16.09	4.5	10.5	4	2.5	9.5	21	2	0	--	0	54	$868.86
Student 12	GS-9/8	$28.04	35	20	17	--	30	--	--	15	--	5	122	$3,420.88
Student 13	GS-1/2	$10.06	5	5.25	--	3	2.75	--	--	--	--	--	16	$160.96
Student 14	GS-5/6	$17.50	32.5	27	10	20	11	15	15	0	--	0	130.5	$2,283.75
Student 15	GS-3/2	$12.74	--	--	2.5	11	--	4	--	0	0	--	17.5	$222.95
Student 16	GS-11/10	$35.76	70	70	86	82	80	85	55	50	--	10	588	$21,026.88
Student 18	GS-5/3	$16.00	--	--	1.5	--	--	--	--	--	--	--	1.5	$24.00
Student 20	GS-5/6	$17.50	2	2	5	6	7	--	--	--	--	--	22	$385.00
Student 21	GS-3/7	$14.34	10	13.5	6	--	--	27	17	10	--	--	83.5	$1,197.39
Student 22	GS-3/2	$12.34	--	--	--	--	--	6	--	--	3	--	9	$111.06
Student 23	GS-10/10	$32.55	45.5	45.25	37.5	30	55.25	52	45.25	23	39	22.5	395.25	$12,865.39
Student 25	GS-6/7	$20.07	24.5	31.5	14.5	15	17.5	16	12	12	--	--	143	$2,870.01
Student 46	GS-4/3	$14.31	--	--	--	--	--	--	--	--	--	--	0	$0.00
Student 27	GS-4/5	$15.20	--	--	--	7	15	24	15	3	0	6	70	$1,064.00
Student 28	GS-4/10	$17.43	--	--	--	--	--	--	--	--	--	--	0	$0.00
Student 29	GS-5/5	$17.00	--	--	8	9	--	15	--	--	0	0	32	$544.00
Student 30	GS-3/6	$13.94	0.75	2	4	4	3.5	5	3	0	9	0	31.25	$435.63
Student 31	GS-5/5	$17.00	--	12.25	10	3.25	10	5.25	0	3.5	4.5	--	48.75	$828.75
Student 32	GS-4/6	$15.65	30.25	10.5	6.25	11.75	11	--	11	2.25	--	0	83	$1,298.95
Student 33	GS-7/7	$22.31	--	--	--	13	36.75	20.5	25	11.5	0	--	106.75	$2,381.59
Student 34	GS-4/2	$13.86	--	--	--	1	--	--	--	--	--	--	1	$13.86

Student 35	GS-7/5	$21.07	5.5	17	--	14.5	--	--	26	10	--	22	95	$2,001.65
Student 36	GS-5/6	$17.50	--	10	10	11	11.5	11.5	10	10	--	--	74	$1,295.00
Student 37	GS-7/8	$22.92	--	--	--	--	--	--	--	--	--	--	0	$0.00
Student 38	GS-4/10	$17.43	19.25	18.5	20.75	25	25	35	17	11	9	--	180.5	$3,146.12
Student 39	GS-4/4	$14.75	0	1.5	3.5	6.25	4.25	25.5	2	2	--	0	45	$663.75
Student 40	GS-4/4	$14.74	0	--	3	0	--	--	--	--	--	--	3	$44.22
Student 41	GS-3/3	$12.74	--	3	8	6	0	7	6	6	--	13	49	$624.26
Student 43	GS-6/8	$20.63	--	27	42	44	38	31.5	16	26	--	24	248.5	$5,126.56
Student 44	GS-7/5	$21.07	2	--	--	5	11	15	--	30	--	--	63	$1,327.41
Student 45	GS-4/4	$14.75	9	14	14	8.75	17.25	12.25	13.5	7.25	--	--	96	$1,416.00
Student 47	GS-4/1	$13.41	--	--	--	--	--	--	--	4	0	0	4	$53.64
Student 48	GS-5/4	$16.50	--	--	--	--	--	--	--	--	--	--	0	$0.00

Table C.2 - Actual and Projected personnel costs (shown in italicized red) through the end of ARMADILLO and Bevo-2 missions.

3U CubeSat Actual/Projected Personnel budget							
		Level 3			**Level 2**	**Level 1**	
Subcategory cost ($)		Cost (ea)	Quantity	Total (USD)	Total ($)	ARMADILLO Total ($)	Bevo-2 Total ($)
Undergraduate Research Assistants						$88,500.00	$88,500.00
Fall 2010		$1,500.00	0	$0.00	$0.00		
Spring 2011		$1,500.00	5	$7,500.00	$7,500.00		
Summer 2011		$6,000.00	4	$24,000.00	$24,000.00		
Fall 2011		$1,500.00	6	$9,000.00	$9,000.00		
Spring 2012		$1,500.00	5	$7,500.00	$7,500.00		
Summer 2012		$6,000.00	4	$24,000.00	$24,000.00		
Fall 2012		$1,500.00	6	$9,000.00	$9,000.00		
Spring 2013		$1,500.00	5	$7,500.00	$7,500.00		
Graduate Research Assistants						$678,000.00	$678,000.00
Fall 2010		$20,000.00	5	$100,000.00	$100,000.00		
Spring 2011		$20,000.00	5	$100,000.00	$100,000.00		
Summer 2011		$13,000.00	3	$39,000.00	$39,000.00		
Fall 2011		$20,000.00	5	$100,000.00	$100,000.00		
Spring 2012		$20,000.00	5	$100,000.00	$100,000.00		
Summer 2012		$13,000.00	3	$39,000.00	$39,000.00		
Fall 2012		$20,000.00	5	$100,000.00	$100,000.00		
Spring 2013		$20,000.00	5	$100,000.00	$100,000.00		
Faculty PI Involvement						$157,080.00	$157,080.00
2010-2011 School year		$52,360.00	1	$52,360.00	$52,360.00		
2011-2012 School year		$52,360.00	1	$52,360.00	$52,360.00		
2012-2013 School year		$52,360.00	1	$52,360.00	$52,360.00		
Travel						$50,220.05	$9,835.64
Bevo-2					$9,835.64		
	Bevo-2 SCR :: 9/10/2010	$900.00	1	$1,386.00			
	Bevo-2 PDR :: 8/26/2011	$580.54	1	$894.03			
	Bevo-2 CDR :: 11/14/2011	$1,226.56	1	$1,888.90			
	Additional review	$1,226.56	1	$1,888.90			
	Launch support	$1,226.56	2	$3,777.80			

ARMADILLO					$50,220.05		
	UNP Kick-off :: 1/16/11 - 1/18/11	$2,400.00	1	$3,696.00			
	CubeSat workshop:: 4/19/11 - 4/23/11	$2,000.00	1	$3,080.00			
	SHOT1 :: 6/8/11 - 6/11/11	$1,170.00	1	$1,801.80			
	PDR/Small Sat :: 8/6/11 - 8/14/11	$6,342.92	1	$9,768.10			
	Satellite Fabrication :: 11/9/11-11/12/11	$1,527.50	1	$2,352.35			
	CubeSat workshop April 2012	$2,000.00	1	$3,080.00			
	SHOT2	$1,170.00	1	$1,801.80			
	PQR/Small Sat	$8,000.00	1	$12,320.00			
	FCR	$8,000.00	1	$12,320.00			
					Total personnel cost	$973,800.05	$933,415.64

Appendix D: Mass Budgets

ARMADILLO Mass budget								
Subsystem Mass (g)			Level 3	Level 2 CBE (g)	Contingency	Allocated (g)	Level 1	Configuration as Measured
ADC							810.075	
	Actuators			428.1	5.00%	449.505		
	15	RW-0.01-4-l2C-2-0-0 (3)	368.1					Flight
	16	Magnetic Torque Rods (2)	60					
	Sensors			267.6	5.00%	280.98		
	12	SS-411-VIS-RS485-3-0 (2)	66.4					Flight
	13	Honeywell HMR2003 Magnetometer	23.4					EDU with DB9
	14	Analog Devices ADIS16251 Gyros (3)	14.1					EDU on PCB
	17	FOTON GPS Receiver	163.7					EDU Module
	Flight Computer			75.8	5.00%	79.59		
	11	Phytec LPC3250 and Kraken	75.8					EDU
CDH							79.59	
	CDH Computer			75.8	5.00%	79.59		
		Phytec LPC3250 and Kraken	75.8					
COM							294.945	
	UHF/VHF Radio			208	5.00%	218.4		
		Radio	78					Li-1 EDU
		Antenna	130					
	S-band Radio			62.9	5.00%	66.045		
		Radio	42.9					Radio Module
		Antenna	20					
	GPS Antenna			10	5.00%	10.5		
EPS							728.9394	
	Main EPS			371.1	5.00%	389.655		EDU with standoffs
		EPS	100.2					Measured as unit
		Battery Board for EPS	270.9					Measured as unit
	Solar Power			323.128	5.00%	339.2844		
		Solar Cell (23)	51.428					
		Solar Panel Triplet (5)	173.5					2nd iteration of each of the solar panels measured
		Solar Panel Couplet (2)	47.4					
		Solar Panel Singlet (4)	50.8					
NVS	Camera			116.6	5.00%	122.43	122.43	
		Camera Body	58.3					EDU (they weigh the same)
		Lens	58.3					EDU (they weigh the same)
STR							1117.506359	1

	Wall Shells			580.4	5.00%	609.42			
		Payload Shell	233.82						
		ADC Shell	190.78						
		Bus Shell	155.8						
	Connectors/Caps			191.41	5.00%	200.9805			
		Section Connectors (2)	95.61						
		ISIS End Cap	58.64						
		ADC End Cap	37.16						
	Component Mounting			252.4818	5.00%	265.1058585			
		Reaction Wheel Mount	76.48						
		Magnetorquer Mounts	5.88						
		FOTON Mount	63.94						
		Electronic Stack Brackets (4)	9.77177						
		PDD Mount	76.83						
		Camera Mount	19.58						
	Fasteners			20	5.00%	21			
	Wiring			20	5.00%	21			
THR							386.022		
	Pressurant			288.64	5.00%	303.072			
		SLA Vessel	200						
		R-236fa	84						
		Reinforcing Plate	1.6						
		Tank Lid	3						
		Gasket	0.04						
	Valve			79	5.00%	82.95			
		Valves (3)	15						
		Valve Mounting Hardware	60						
		Reinforcing Plate	4						
PDD				400	0.00%	400	400		

TOTALS	CBE	Allocated	Level 1	Design Limit	Margin
	3770.96	3939.507759	3939.507759	4000	1.51%

Bevo-2 Mass Budget

Subsystem Mass (g)			Level 3	Level 2 CBE (g)	Contingency	Allocated (g)	Level 1	Configuration as Measured
ADC							869.19	
	Actuators			548.1	5.00%	575.505		
		RW-0.01-4-I2C-2-0-0 (3)	368.1					Flight
		Magnetic Torque Rods (3)	180					
	Sensors			203.9	5.00%	214.095		
		SS-411-VIS-RS485-3-0 (2)	66.4					Flight
		Honeywell HMR2003 Magnetometer	23.4					EDU with DB9
		Analog Devices ADIS16251 Gyros (3)	14.1					EDU on PCB
		Dragon GPS Receiver	100					EDU Module
	Flight Computer			75.8	5.00%	79.59		
		Phytec LPC3250 and Kraken	75.8					EDU
CDH							79.59	
	CDH Computer			75.8	5.00%	79.59		
		Phytec LPC3250 and Kraken	75.8					
COM							389.445	
	UHF/VHF Radio			208	5.00%	218.4		
		Radio	78					Li-1 EDU
		Antenna	130					
	S-band Radio			62.9	5.00%	66.045		
		Radio	42.9					Radio Module
		Antenna	20					
	Xbee Crosslink			90	5.00%	94.5		
		Radio	50					
		Antenna	40					
	GPS Antenna			10	5.00%	10.5		
EPS							733.635	
	Main EPS			371.1	5.00%	389.655		EDU with standoffs
		EPS	100.2					Measured as unit
		Battery Board for EPS	270.9					Measured as unit
	Solar Power			327.6	5.00%	343.98		
		Solar Cell (25)	55.9					
		Solar Panel Triplet (5)	173.5					2nd iteration of each of the solar panels measured
		Solar Panel Couplet (3)	47.4					

		Solar Panel Singlet (4)	50.8					
NVS	Camera			116.6	5.00%	122.43	122.43	
		Camera Body	58.3					EDU (they weigh the same)
		Lens	58.3					EDU (they weigh the same)
STR							1168.095359	
	Wall Shells			678.82	5.00%	712.761		
		Payload Shell	332.24					
		ADC Shell	190.78					
		Bus Shell	155.8					
	Connectors/Caps			191.41	5.00%	200.9805		
		Section Connectors (2)	95.61					
		ISIS End Cap	58.64					
		ADC End Cap	37.16					
	Component Mounting			202.2418	5.00%	212.3538585		
		Reaction Wheel Mount	76.48					
		Magnetorquer Mounts	5.88					
		Electronic Stack Brackets (4)	9.77177					
		Dragon Mount	86.14					
		Camera Mount	23.97					
	Fasteners			20	5.00%	21		
	Wiring			20	5.00%	21		
THR							386.022	
	Pressurant			288.64	5.00%	303.072		
		SLA Vessel	200					
		R-236fa	84					
		Reinforcing Plate	1.6					
		Tank Lid	3					
		Gasket	0.04					
	Valve			79	5.00%	82.95		
		Valves (3)	15					
		Valve Mounting Hardware	60					
		Reinforcing Plate	4					

TOTALS	**CBE**	**Contingency**	**Allocated**	**Level 1**	**Design Limit**	**Margin**
	3569.912	0.05	3748.407359	3748.407359	4000	6.29%

Appendix E: Requirements Verification Matrix

Bevo-2 Requirements Verification Matrix

ID	LONESTAR Program Overview
LPO	LONESTAR, Low earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and docking, is a programmatic partnership among the University of Texas at Austin, Texas A&M University and NASA-JSC aimed at exploring and developing alternative Autonomous Rendezvous and Docking (ARD) systems for use on cost effective, low power microsatellite infrastructures. Over the course of four missions, the University of Texas at Austin and Texas A&M University will design and build four pairs of cooperative satellites to test and implement systems to ultimately demonstrate ARD on the fourth and final mission.

ID	Mission 2 Objectives : "The LONESTAR-2 mission shall..."	Source
M2O-1	Evaluate sensors including but not limited to: GPS receivers, IMUs, rate gyros, accelleromaters	LPO
M2O-2	Evaluate Reaction Control System (RCS).	LPO
M2O-3	Evaluate GN&C system including guidance algorithms, absolute navigation, and relative navigation.	LPO
M2O-4	Evaluate communications capabilities between two spacecraft and from each spacecraft to their ground stations.	LPO
M2O-5	Evaluate the capability to take video.	LPO

ID	Mission 3 Objectives : "The LONESTAR-3 mission shall..."	Source
M3O-1	Evaluate RCS.	LPO
M3O-2	Demonstrate ability to maintain relative velocity and attitude within TBD requirements.	LPO
M3O-3	Evaluate Autonomous Flight Manager (AFM).	LPO
M3O-4	Demonstrate docking system	LPO

ID	Mission 4 Objectives : "The LONESTAR-4 mission shall..."	Source
M4O-1	Demonstrate full Autonomous Rendezvous and Docking (ARD) capability using GN&C, RCS and AFM	LPO

ID	Mission Requirements : "The LONESTAR-2 mission shall…"	Source
MR-1	The entire LONESTAR envelope is not to exceed the maximum dimensions of the NASA Deployment System for the JAXA JEM Airlock on the ISS	
MR-2	The entire LONESTAR mass is not to exceed 100 kg.	
MR-3	AggieSat 4 shall not exceed 50 kg	

MR-4	Bevo-2 shall not exceed 35 kg	
MR-5	This project will follow the standard project management schedule.	
MR-6	Each University Team will select two members to create and organize an interface monitoring function in order to maintain robust and productive communications between the university teams and oversight members: NASA and MEI.	
MR-7	Each Spacecraft will have three-axis stabilization capability and demonstrate it.	M2O-1, M2O-2, M20-3
MR-8	Both teams will work together to evaluate any GN&C system interfaces and compatibility and the testing required for these systems.	M2O-1, M2O-2, M20-3
MR-9	Each team will evaluate and test an additional component that will be needed for the next generation of their spacecraft and final mission.	M3O-1, M3O-2, M3O-3, M3O-4, M4O-1
MR-10	Each team will evaluate and test portions of their future generation control system algorithms	M2O-3, M3O-1, M3O-2, M3O-3, M3O-4
MR-11	Each spacecraft will communicate with the ground station, both directions	M2O-4
MR-12	Each spacecraft will communicate with each other when separated.	M2O-4
MR-13	Each satellite will exchange its GPS solution with the other satellite	M2O-1, M2O-4
MR-14	Each spacecraft will evaluate the viability and capability of downloading captured visual evidence	M2O-5
MR-15	Each spacecraft will carry a GPS system for use in determining the viability of navigation solutions for the final mission	M2O-1, M4O-1
MR-16	Each spacecraft will downlink GPS data for the NASA team to be able to evaluate the operation of the receiver	M2O-1
MR-17	The two spacecraft will separate from each other.	
MR-18	Each spacecraft will take and downlink video or still photographs	M2O-5
MR-19	Once separated, each spacecraft will provide Relative Navigation solutions	M2O-1, M2O-4, M3O-2
MR-20	Each spacecraft will downlink satellite health data and sensor data during ground passes.	M2O-4

ID	**System Requirements: "The Bevo-2 satellite shall…"**	
S1	Have a mass of no more than 35 kg	MR-4
S2	Provide independent verification of ADC module through the use of a miniaturized star-tracker.	MR-7, MR-8, MR-9, MR-10, MR-18
S3	Operate an ADC module capable of satisfying the most stringent subsystem pointing requirements.	MR-7, MR-8, MR-9, MR-10, MR-18
S4	Provide a space of 1U (TBR) in the payload module for any military, scientific or commercial payload.	MR-12, MR-13, MR-14, MR-15, MR-18
S5	Demonstrate a cold-gas thruster capable of small orbit maneuvers for payload requested orbit maintenance.	MR-9, MR-10, MR-17
S6	Be operational for at least 4 (TBR) months in order to gain as much scientific data as possible and satisfy payload mission success criteria.	MR-5, MR-9, MR-10, MR-14
S7	De-orbit within 25 years after end of mission.	MR-5, MR-9, MR-10, MR-14

S8	Accept and manage ground commands	MR-9, MR-10, MR-11, MR-14, MR-16, MR-18, MR-20
S9	Meet all NASA safety structural, electrical and testing requirements.	MR-5, MR-9, MR-10, MR-14
S10	Contain a flight computer capable of handling payload and satellite subsystem data.	MR-9, MR-10, MR-11, MR-12, MR-13, MR-14, MR-15, MR-16, MR-18, MR-19, MR-20
S11	Communicate vital health and scientific data with ground stations	MR-9, MR-10, MR-11, MR-12, MR-13, MR-14, MR-15, MR-16, MR-18, MR-19, MR-20
S12	Meet all Interface Control Specifications w/ AggieSat 4 satellite	MR-1, MR-2, MR-3, MR-4, MR-5, MR-6, MR-17
S13	Evaluate photo and video capability	MR-14
S14	Capture and downlink photos of each satellite	MR-14
S15	Capture video of each satellite or a secondary object	MR-14
S16	Downlink video as a secondary objective	MR-14

ADC Requirements: "The ADC subsystem shall…"

ADC-1	Perform rotational maneuvers at a minimum rate of 0.1 deg/s. (TBR)	S3
ADC-2	Perform rotational maneuvers at a maximum rate of 80 deg/s. (TBR)	S3
ADC-3	Maintain a pointing accuracy of better than 5 degrees (eigenaxis angle, 1-sigma) (TBR)	S3
ADC-4	Hold steady pointing for at least 20 minutes during science operations.	S3
ADC-5	Determine its position to within 1000 m. (TBR)	S3

CDH Requirements: "The CDH subsystem shall…"

CDH-1	Provide 1 or 2 GB (TBR) data storage with double redundancy	S10
CDH-2	Receive, process and execute commands within the window of an Austin ground station pass	S8, S10
CDH-3	Activate and begin executing commands upon "hot-start" separation from AG-4	S9
CDH-4	Accept and execute a command to reprogram satellite software	S8, S10
CDH-5	Manage all commands governing the state and actions of the satellite	S8, S9, S10

COM Requirements: "The COM subsystem shall…"

COM-1	Transmit data on a high-bandwidth at a frequency of TBR	S8, S11
COM-2	Receive data on a high-bandwidth at a frequency of TBR	S8, S11
COM-3	Uplink commands from ground stations at a frequency of TBR	S8, S11
COM-4	Downlink commands from ground stations at a frequency of TBR	S8, S11

EPS Requirements: "The EPS subsystem shall…"

EPS-1	Provide the spacecraft up to 2.5 A at 3.3 V	S6
EPS-2	Provide the spacecraft up to 2.5 A at 5 V	S6
EPS-3	Monitor and distribute power provided by AG-4 of 5 V at 0.5 A upon release from AG-4	S12

NVS Requirements: "The NVS subsystem shall…"

NVS-1	Take at least 1 (TBR) images of celestial objects	S2, S13
NVS-2	Determine the angular position of the satellite to within 50 arcsec (TBR) with a goal of 1 arcsec (TBR)	S2, S13
NVS-3	Determine the angular velocity of the satellite to within 10 arcsec/sec (TBR) with a goal of 5 arcsec/sec (TBR)	S2, S13
NVS-4	Take images with at least .78 megapixel (Final) resolution	S2, S13

STR Requirements: "The Bevo-2 structure shall…"

STR-1	Maintain a satellite mass budget of less than 35 kg	S1
STR-2	Maintain a width and depth of 113.0 +/- 0.1 mm	S12
STR-3	Maintain a length of 340.5 +/- 0.3 mm	S12
STR-4	Employ non-hazardous materials	S9, CubeSat Specs
STR-5	Use the coordinate system as defined by LONESTAR ICD Specifications	S12
STR-6	Have a center of gravity located within a 2 cm sphere from the geometric center	S12
STR-7	Use materials as stated in the CubeSat Design Specifications	S12
STR-8	Maintain a Class 100000 level cleanliness	S9

THR Requirements: "The THR subsystem shall…"

THR-1	Provide at least 10 m/s of deltaV	S3, S5, S6, S7
THR-2	Perform translational maneuvers with a minimum acceleration of 0.001 m/s^2	S3, S5, S6, S7
THR-3	Operate in cooperation with launch vehicle constraints	S9, S12
THR-4	Maintain an operating tank pressure of under 1.2 standard atmospheres	S9
THR-5	Contain stored chemical energy of no more than 100 Watt-Hours	S9

ARMADILLO Requirements Verification Matrix

ID	Mission Overview
MO	Enable new capabilities to assess space debris risks and improve space weather forecasting using low cost rapidly deployable CubeSat technologies.

ID	Mission Statements/Objectives : "The ARMADILLO mission shall…"	Source
MS1	Characterize unknown sub-millimeter level dust and debris particles to improve atmosphere models and assess operational risks in Low Earth Orbit.	MO
MS2	Enable future global real-time space weather monitoring by demonstrating an innovative dual frequency GPS receiver capable of centimeter level orbit determination and ionospheric radio-occultation within a single CubeSat volume (10 cm x 10 cm x 10 cm).	MO
MS3	Facilitate ease of production for future missions by measuring and tracking satellite life cycle costs and lead times for military, scientific, and commercial uses of a highly capable reusable 3U CubeSat bus design.	MO

ID	Mission Requirements : "The ARMADILLO mission shall…"	
M1	Gather information on space debris particles by measuring the mass, velocity and direction of impact in order to classify the particle as man-made or natural.	MS1
M2	Monitor space debris particles in Low Earth Orbit at various altitudes and in various directions for greatest scientific return.	MS1
M3	Pass all scientific data gathered on-orbit to scientists on the ground for analysis.	MS1, MS2, MS3
M4	Demonstrate a dual-frequency GPS receiver through a radio occultation experiment designed to help improve knowledge of atmospheric properties.	MS2
M5	Validate first generation attitude determination and control technology capable of six degree-of-freedom, 3-axis stabilization on a maneuverable 3U CubeSat spacecraft.	MS1, MS2, MS3
M6	Adhere to all programmatic guidelines and standards for greatest possibility of mission success.	MS1, MS2, MS3
M7	Have a goal of determining a mass percentage of spacecraft components whose design can be reused for rapid fabrication of future missions.	MS3
M8	Have a goal of determining a percentage of reusable, modular code which will allow future missions ease of programming and faster launch readiness.	MS3
M9	Employ systems engineering practices and design methods for ease of measuring and tracking the rapid development of 3U spacecraft missions.	MS3

ID	System Requirements: "The ARMADILLO satellite shall…"	
S1	Provide independent verification of ADC module through the use of a miniaturized star-tracker.	M5
S2	Operate an ADC module capable of satisfying the most stringent subsystem pointing requirements.	M5
S3	Provide a space of 1U (TBR) in the payload module for any military, scientific or commercial payload.	M1, M2, M4, M7, M9
S4	Demonstrate a cold-gas thruster capable of small orbit maneuvers for payload requested orbit maintenance.	M2, M4, M5
S5	Be operational for at least 4 (TBR) months in order to gain as much scientific data as possible and satisfy payload mission success criteria.	M1, M2, M4

S6	De-orbit within 25 years after end of mission.	M6
S7	Accept and manage ground commands	M1, M2, M3, M4, M5, M6, M8, M9
S8	Meet all University Nanosatellite Program structural, electrical and testing requirements.	M6
S9	Contain a flight computer capable of handling payload and satellite subsystem data.	M1, M2, M3, M4, M5, M6, M8, M9
S10	Communicate vital health and scientific data with ground stations	M3, M5
S11	Place debris/dust sensor(s) on the satellite exterior to gather in-situ measurements of space debris particles.	M1, M2
S12	Meet all CubeSat Design Specifications	M6

ADC Requirements: "The ADC subsystem shall…"

ADC-1	Perform rotational maneuvers at a minimum rate of 0.1 deg/s. (TBR)	S2
ADC-2	Perform rotational maneuvers at a maximum rate of 80 deg/s. (TBR)	S2
ADC-3	Maintain a pointing accuracy of better than 5 degrees (eigenaxis angle, 1-sigma) (TBR)	S2
ADC-4	Hold steady pointing for at least 20 minutes during science operations.	S2
ADC-5	Determine its position to within 1000 m. (TBR)	S2

CDH Requirements: "The CDH subsystem shall…"

CDH-1	Provide 2 GB (TBR) data storage with triple (TBR) redundancy	S9
CDH-2	Receive, process and execute commands within the window of an Austin ground station pass	S7, S9
CDH-3	Activate and begin executing commands upon separation from launch vehicle	S8
CDH-4	Accept and execute a command to reprogram satellite software	S7, S9
CDH-5	Manage all commands governing the state and actions of the satellite	S7, S8, S9

COM Requirements: "The COM subsystem shall…"

COM-1	Transmit data on a high-bandwidth at a frequency of TBR	S7, S10
COM-2	Receive data on a high-bandwidth at a frequency of TBR	S7, S10
COM-3	Uplink commands from ground stations at a frequency of TBR	S7, S10
COM-4	Downlink commands from ground stations at a frequency of TBR	S7, S10
COM-5	Wait 30 minutes after deployment switches are activated from PPOD ejection to begin transmitting	S12 (2.4.3)
COM-6	Provide documentation of frequency allocations and licenses	S12 (2.4.4)

COM-7	Be capable of receiving a transmitter shutdown command per FCC regulation	S12 (2.4.1)
COM-8	Wait 30 minutes after deployment switches are activated from PPOD ejection to deploy antennas	S12 (2.4.2)

EPS Requirements: "The EPS subsystem shall…"

EPS-1	Provide the spacecraft up to 2.5 A at 3.3 V	S5
EPS-2	Provide the spacecraft up to 2.5 A at 5 V	S5
EPS-3	Prevent activation of the spacecraft prior to separation from launch vehicle	S12 (2.3.1)
EPS-4	Provide a "Remove Before Flight pin" located in an accessible port	S12 (2.3.1, 2.3.4)
EPS-5	Include at least one deployment switch as designated in CubeSat Design Specifications (which shall be depressed while inside the PPOD)	S12 (2.3.2)
EPS-6	Have a resistance of less than 2.5 milli-Ohm between any point on the CubeSat and the satellite interface plane	S8 (6.6.3)

GSE Requirements: "The GSE subsystem shall…"

GSE-1	Charge and discharge the battery while the satellite is inhibited	S8 (6.6.4)
GSE-2	Employ at least three high-side and one ground-side inhibits installed to prevent unwanted power distribution	S8 (6.6.1)
GSE-3	Power and monitor the satellite's health while the satellite is inhibited	S8 (6.6.4)
GSE-4	Support functional testing of satellite	S8 (6.6.4)
GSE-5	Develop a transportation system to encapsulate the satellite and all necessary connections	S8 (6.6.4)
GSE-6	Be capable of command and control of the satellite while the satellite is inhibited	S8 (6.6.4)
GSE-7	Employ a main power switch with indicator light	S8 (6.6.4)
GSE-8	Employ circuit protection methods via fuses or circuit breakers on the load lines	S8 (6.6.4)
GSE-9	Use copper wiring	S8 (6.6.4)
GSE-10	Employ scoop-proof connectors in harnessing between satellite and EGSE	S8 (6.6.4)
GSE-11	Use standard 120 V, 60 Hz, 3 prong "household" power	S8 (6.6.4)
GSE-12	Meet all safety requirements prescribed by the UNP User's Guide references	S8 (6.6.4)

NVS Requirements: "The NVS subsystem shall…"

NVS-1	Take at least 1 (TBR) images of celestial objects	S1
NVS-2	Determine the angular position of the satellite to within 50 arcsec (TBR) with a goal of 1 arcsec (TBR)	S1
NVS-3	Determine the angular velocity of the satellite to within 10 arcsec/sec (TBR) with a goal of 5 arcsec/sec (TBR)	S1

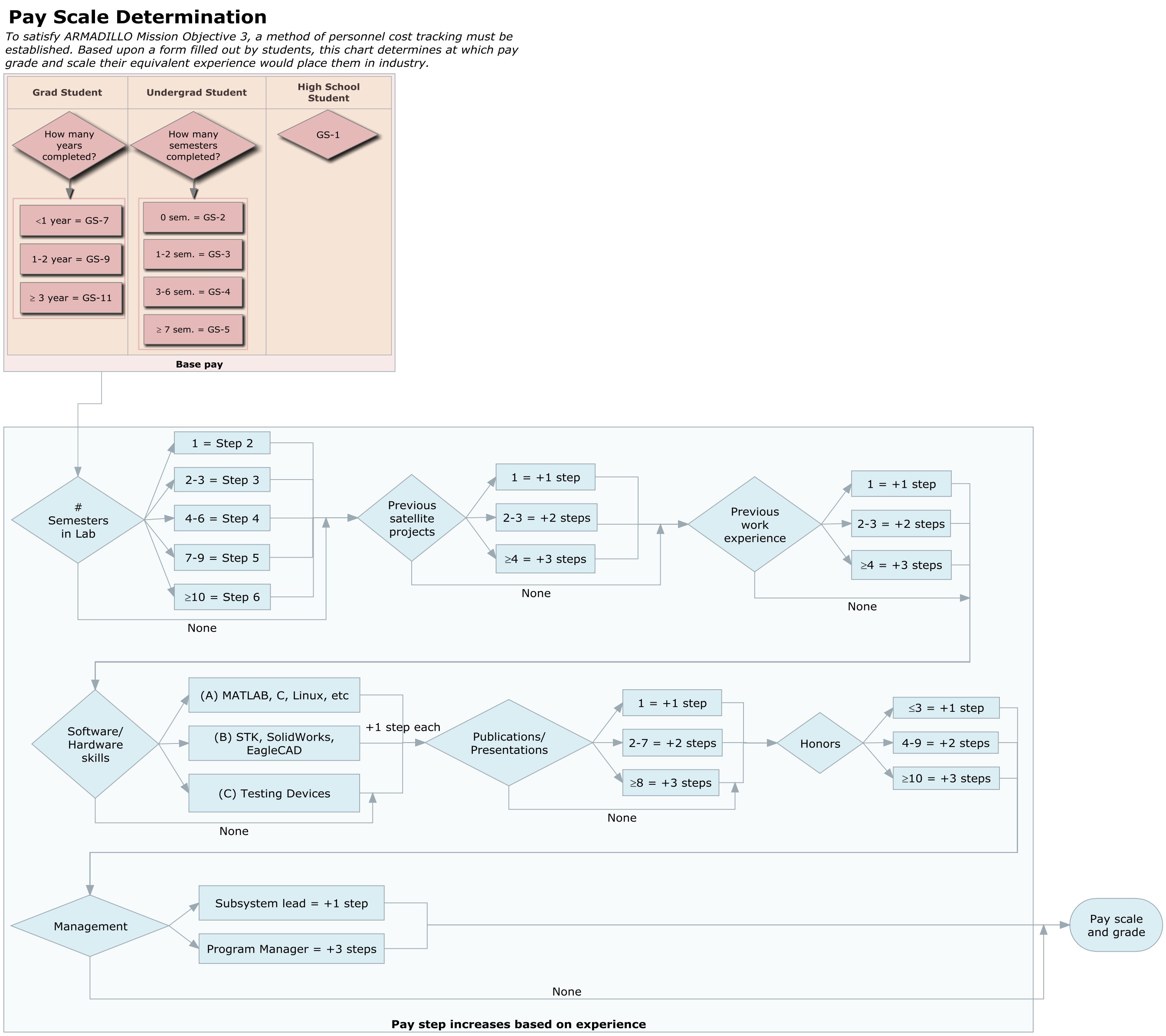
NVS-4	Take images with at least .78 megapixel (Final) resolution	S1
	PLD Requirements: "The PLD subsystem shall…"	
PDD-1	Obtain measurements of space dust size	S5, S11
PDD-2	Obtain measurements of space dust velocity and direction	S5, S11
PDD-3	Determine whether space dust is man-made or natural	S5, S11
PDD-4	Contain an "on/off" switch	S11
PDD-5	Conform to CubeSat size constraints	S11
PDD-6	Conform to standards of ARMADILLO spacecraft	S1 - S12
	STR Requirements: "The ARMADILLO structure shall…"	
STR-1	Maintain a satellite mass budget of less than 4 kg	S12 (2.2.16)
STR-2	Maintain a width and depth of 113.0 +/- 0.1 mm	S12 (2.2.5)
STR-3	Maintain a length of 340.5 +/- 0.3 mm	S12 (2.2.5.1)
STR-4	Employ non-hazardous materials	S12 (2.1.3, 2.1.6)
STR-5	Use materials which follow CubeSat and UNP outgassing criterion	S8 (6.3.2), S12 (2.1.7)
STR-6	Constrain all deployables	S12 (2.2.8)
STR-7	Follow rail guildelines as stated in CubeSat specifications	S12 (2.2.9-2.2.13)
STR-8	Allow for diagnostics and/or battery charging by concientiously building around access ports	S12 (2.3.3)
STR-9	Have a fundamental frequency above 100 Hz	S8 (6.3.1)
STR-10	Have design limit load factors of at least +/- 20G's along each axis	S8 (6.3.3.1)
STR-11	Have a structural design yield Factor of Safety of at least 2.0	S8 (6.3.3.2)
STR-12	Have a structural design yield Ultimate FOS of at least 2.6	S8 (6.3.3.2)
STR-13	Have a test FOS for the operating torque margin of at least 1.0	S8 (6.3.3.3)
STR-14	Have an analysis operating torque FOS of at least 2.0	S8 (6.3.3.3)
STR-15	Have a test FOS for the holding torque margin of at least 1.0	S8 (6.3.3.3)
STR-16	Have a holding torque analysis FOS of at least 2.0	S8 (6.3.3.3)
STR-17	Use the coordinate system as defined by CubeSat Design Specifications	S12 (2.2.2, 2.2.3)
STR-18	Have a center of gravity located within a 2 cm sphere from the geometric center	S12 (2.2.17)

STR-19	Use materials as stated in the CubeSat Design Specifications	S12 (2.2.19, 2.2.20)
STR-20	Sustain a maximum depressurization of 0.5 psi/second	S8 (6.3.3.6)
STR-21	Maintain a Class 100000 level cleanliness	S8 (6.4)

THR Requirements: "The THR subsystem shall…"

THR-1	Provide at least 10 m/s of deltaV	S2, S4, S5, S6
THR-2	Perform translational maneuvers with a minimum acceleration of 0.001 m/s^2	S2, S4, S5, S6
THR-3	Operate in cooperation with launch vehicle constraints	S8, S12
THR-4	Maintain an operating tank pressure of under 1.2 standard atmospheres	S12 (2.1.4)
THR-5	Contain stored chemical energy of no more than 100 Watt-Hours	S12 (2.1.5)

Appendix F: Full Pay Scale Determination Flow Chart



Appendix G: ARMADILLO Hardware Costs

Table G.1 - ADC module development costs.

	Component							Subsystem		ARMADILLO Prototyping	ARMADILLO Protoflight
Subsystem Cost ($)	Cost (ea)	Prototype Quantity	Protoflight quantity	Prototype Component Total (USD)	Protoflight Component Total (USD)	Prototype Section Total (USD)	Protoflight Section Total (USD)	Prototype Total	Protoflight Total		
ADC module										$ 7,390.05	$ 42,294.07
ADC								$3,652.50	$37,924.28		
Actuators						$0.00	$13,000.00				
RW-0.01-4-I2C-2-0-0	$10,000.00	0	1	$0.00	$10,000.00						
CubeSat Magnetorquer Rod	$1,500.00	0	2	$0.00	$3,000.00						
Sensors						$3,652.50	$24,924.28				
SS-411-VIS-RS485-3-0	$12,000.00	0	2	$0.00	$24,000.00						
Sun sensor testing light source	$457.00	1	0	$457.00	$0.00						
Honeywell HMR2003 Magnetometer	$700.00	0	1	$0.00	$700.00						
Magnetometer Analog Dip	$210.00	1	0	$210.00	$0.00						
Magnetometer development kit	$795.00	1	0	$795.00	$0.00						
Analog Devices ADIS16251 Embedded Gyros	$74.76	3	3	$224.28	$224.28						
EDU Gyros	$103.31	3	0	$309.93	$0.00						
Gyro	$281.25	1	0	$281.25	$0.00						

		development kit											
		Analog Devices IMU	$635.54	1	0	$635.54	$0.00						
		IMU development kit	$739.50	1	0	$739.50	$0.00						
NVS	Camera						$0.00	$2,080.20	$1,804.50	$2,080.20	$1,804.50		
		Aptina Development Kit	$1,240.20	1	0	$1,240.20	$0.00						
		Network Vision 5MP grey camera mvBlueFOX	$297.00	1	0	$297.00	$0.00						
		Network Vision C-Mount lens holder	$124.00	2	0	$248.00	$0.00						
		Networ Vision 1MP BlueFOX camera	$1,065.00	0	1	$0.00	$1,065.00						
		Matrix Vision USB cable	$20.00	0	1	$0.00	$20.00						
		Edmund Optics Lens	$295.00	1	0	$295.00	$0.00						
		C-Mount Xenoplan compact Lens	$719.50	0	1	$0.00	$719.50						
THR										$1,657.35	$2,565.29		
	Device							$1,537.53	$973.94				
		Rev 1	$299.00	1	0	$299.00	$0.00						
		Rev 2	$363.00	1	0	$363.00	$0.00						
		Rev 3	$501.00	1	0	$501.00	$0.00						
		Rev 4	$606.05	0	1	$0.00	$606.05						
		R-236fa	$330.00	0	1	$0.00	$330.00						
		Tank screws rev 2	$5.72	1	0	$5.72	$0.00						
		Tank screws rev 3	$11.32	1	0	$11.32	$0.00						
		O-rings rubber	$6.21	1	0	$6.21	$0.00						
		Parts 1	$59.98	1	0	$59.98	$0.00						
		Parts 2	$17.40	8	0	$139.20	$0.00						
		Electronic parts	$37.89	0	1	$0.00	$37.89						

	NI DAQ	$152.10	1	0	$152.10	$0.00		
Valve						$0.00	$119.82	$1,591.35
	Clippard mini valves	$20.95	5	0	$104.75	$0.00		
	Valve screws rev 2	$10.00	1	0	$10.00	$0.00		
	Valve screws rev 3	$5.07	1	0	$5.07	$0.00		
	Lee valves	$530.45	0	3	$0.00	$1,591.35		

Table G.2 - Spacecraft bus module development costs

	Component					Subsystem				ARMADILLO Prototyping	ARMADILLO Protoflight
Subsystem Cost ($)	Cost (ea)	Prototype Quantity	Protoflight quantity	Prototype Component Total (USD)	Protoflight Component Total (USD)	Prototype Section Total (USD)	Protoflight Section Total (USD)	Prototype Total	Protoflight Total		
Spacecraft Bus module										$ 68,634.16	$ 51,161.02
CDH								$22,369.53	$9,199.00		
Flight Computer						$22,109.65	$9,199.00				
phyCore MPC5200 SOM	$499.00	1	0	$499.00	$0.00						
phyCore MPC5200 Dev Kit	$799.00	1	0	$799.00	$0.00						
Phytec LPC3250	$199.00	3	1	$599.99	$199.00						
Phytec LPC3250 Dev Kit	$499.00	2	0	$998.00	$0.00						
Kraken	$9,000.00	0	1	$9,000.00	$9,000.00						
Host development	$5,000.00	1	0	$5,000.00	$0.00						
MicroSys MPX5200 Core Module	$714.00	2	0	$1,428.00	$0.00						
CRX02 Carrier board	$445.00	1	0	$445.00	$0.00						
MicroSys Development Kit	$80.00	1	0	$80.00	$0.00						
MPX Boot module	$380.00	1	0	$380.00	$0.00						
MPX Header Pin Adapter Board	$60.00	2	0	$120.00	$0.00						
MPX I/O Adapter	$195.00	1	0	$195.00	$0.00						
ARM11 Linux rapid development kit	$879.00	1	0	$879.00	$0.00						
ARM9 LPC3250 Linux Rapid development kit	$599.99	2	0	$1,199.98	$0.00						
DigiKey SPI-I2C bridge	$2.80	5	0	$14.00	$0.00						
Demo Board I2C	$59.50	1	0	$59.50	$0.00						

		PCB connectors, switches, resistors	$79.96	1	0	$79.96	$0.00				
		PC104 board	$4.75	8	0	$38.00	$0.00				
		PCB switches	$5.14	8	0	$41.12	$0.00				
		Kraken screws and standoffs	$13.12	1	0	$13.12	$0.00				
		LPC3250 router and card reader	$39.98	1	0	$39.98	$0.00				
		2 GB SD cards	$40.40	3	0	$121.20	$0.00				
		1 GB SD cards	$26.60	3	0	$79.80	$0.00				
	Cables/fasteners						$0.00	$259.88	$0.00		
		USB to RS485 converter w/ cable	$30.00	1	0	$30.00	$0.00				
		USB to RS485 converter	$25.00	4	0	$100.00	$0.00				
		Pins, connectors	$87.88	1	0	$87.88	$0.00				
		Crimp tin	$0.14	300	0	$42.00	$0.00				
COM							$0.00			$19,348.55	$20,199.02
	UHF/VHF Radio						$0.00	$0.00	$10,150.00		
		Helium 100 Radio	$4,900.00	0	1	$0.00	$4,900.00				
		ISIS Deployable UHF/VHF Antenna	$5,250.00	0	1	$0.00	$5,250.00				
	GPS						$0.00	$21.06	$44.42		
		SMT Patch Antenna	$7.02	3	2	$21.06	$14.04				
		GPS/WIFI/ISM Patch antenna	$30.38	0	1	$0.00	$30.38				
	Development/Prototyping						$0.00	$19,309.09	$0.00		
		DigiKey Antenna	$8.82	2	0	$17.64	$0.00				
		DigiKey Breadboard	$8.98	4	0	$35.92	$0.00				
		DigiKey Toggle Switch	$8.89	2	0	$17.78	$0.00				
		Li-1 UHF half duplex radio	$4,900.00	2	0	$9,800.00	$0.00				
		Li-1 Pumpkin breakout board	$100.00	2	0	$200.00	$0.00				
		Pumpkin header breakout board	$250.00	1	0	$250.00	$0.00				
		CubeSat/MSP430 3U skeletonized	$8,750.00	1	0	$8,750.00	$0.00				
		Overo Earth	$149.00	1	0	$149.00	$0.00				

		computer-in-module											
		Chestnut expansion board	$79.00	1	0	$79.00	$0.00						
		Logic Level converter	$1.95	5	0	$9.75	$0.00						
	S-Band						$0.00	$18.40	$10,004.60				
		Microhard MHX2420 Radio	$10,000.00	0	1	$0.00	$10,000.00						
		Taoglas Antenna	$4.60	4	1	$18.40	$4.60						
EPS							$0.00			$26,916.08	$21,763.00		
	Electronics Board		7542	2	1	15084	$7,542.00	$ 15,084.00	$ 7,542.00				
	Battery		3221	2	1	6442	$3,221.00	$ 6,442.00	$ 3,221.00				
	Solar Power							$5,355.02	$11,000.00				
		Solar Cell	$300.00	14	25	$4,200.00	$7,500.00						
		Solar Panel Singlet	$96.25	4	0	$385.00	$0.00						
		Solar Panel Couplet	$64.17	6	0	$385.02	$0.00						
		Solar Panel Triplet	$96.25	4	0	$385.00	$0.00						
		Solar Cell PCB	$350.00	0	10	$0.00	$3,500.00						
	Banana plugs		$35.06	1	0	$35.06	$0.00	$35.06	$0.00				

Table G.3 - Spacecraft structure development costs.

			Component							Subsystem		ARMADILLO Prototyping	ARMADILLO Protoflight
Subsystem Cost ($)			Cost (ea)	Prototype Quantity	Protoflight quantity	Prototype Component Total (USD)	Protoflight Component Total (USD)	Prototype Section Total (USD)	Protoflight Section Total (USD)	Prototype Total	Protoflight Total		
Satellite structure												$ 2,703.98	$ 1,005.40
STR										$2,703.98	$1,005.40		
	Fasteners							$0.00	$212.62				
		Connectors and pins for wire harnesses	$55.66	0	1	$0.00	$55.66						
		Reaction wheel cable harness	$16.74	0	1	$0.00	$16.74						
		ADC fasteners	$140.22	0	1	$0.00	$140.22						
	Cables/wiring			0				$0.00	$792.78				
		ADC cable	$40.11	0	1	$0.00	$40.11						
		Wiring 1	$135.93	0	1	$0.00	$135.93						
		Wiring 2 (for flight too)	$616.74	0	1	$0.00	$616.74						
	Plastic Model			0				$2,703.98	$0.00				
		SLA	$2,418.00	1	0	$2,418.00	$0.00						
		Fasteners and screws	$150.98	1	0	$150.98	$0.00						
		Extra parts	$135.00	1	0	$135.00	$0.00						

Table G.4 - ADC module flight unit costs.

			Component						Subsystem	Module
Subsystem Cost ($)			Cost (ea)	Quantity needed	Component Total (USD)	Flight Quantity in-house	Flight Costs Purchased	Flight Component Total (USD)	CBE ($)	
ADC module										$101,852.13
ADC									$97,123.28	
	Actuators							$63,000.00		
		RW-0.01-4-l2C-2-0-0	$20,000.00	3	$60,000.00	1.	$20,000.00			
		Magnetic Torque Rods	$1,500.00	2	$3,000.00		$0.00			
	Sensors							$24,924.28		
		SS-411-VIS-RS485-3-0	$12,000.00	2	$24,000.00	2.	$24,000.00			
		Honeywell HMR2003 Magnetometer	$700.00	1	$700.00		$0.00			
		Analog Devices ADIS16251 Gyros	$74.76	3	$224.28		$0.00			
	Flight Computer							$9,199.00		
		Phytec LPC3250	$199.00	1	$199.00	1.	$199.00			
		Kraken	$9,000.00	1	$9,000.00		$0.00			
NVS	Camera							$1,804.50	1804.5	
		Matrix Vision BlueFOX camera	$1,065.00	1	$1,065.00		$0.00			
		Matrix Vision USB cable	$20.00	1	20		0			
		Schneider Optics Lens	$719.50	1	719.5		0			
THR									$2,924.35	
	Device							$1,133.00		
		SLA Vessel	$700.00	1	$700.00		$0.00			
		R-236fa	$333.00	1	$333.00		$0.00			

		Misc Hardware	$100.00	1	$100.00		$0.00			
	Valve							$1,791.35		
		Valves	$530.45	3	$1,591.35		$0.00			
		Valve Mounting Hardware	$200.00	1	$200.00		$0.00			

Table G.5 - Spacecraft bus flight unit costs.

			Component						Subsystem	Module
Subsystem Cost ($)			Cost (ea)	Quantity needed	Component Total (USD)	Flight Quantity in-house	Flight Costs Purchased	Flight Component Total (USD)	CBE ($)	
Spacecraft Bus module										$58,600.53
CDH									$9,199.00	$44,841.77
	Flight Computer							$9,199.00		
		Phytec LPC3250	$199.00	1	$199.00	1.	$199.00			
		Kraken	$9,000.00	1	$9,000.00		$0.00			
COM									$27,638.53	ARMADILLO
	UHF/VHF Radio							$11,759.13	$12,075.27	Bevo-2
		Helium 100 Radio	$4,900.00	1	$4,900.00	1.	$4,900.00			
		ISIS Deployable UHF/VHF Antenna	€ 5,250.00	1	$6,859.13		$0.00			
	GPS							$74.80		
		SMT Patch Antenna	$7.02	2	$14.04		$0.00			
		GPS/WIFI/ISM Adhesive Mount	$30.38	2	$60.76		$0.00			

	S-band								$15,804.60	ARMADILLO		
		*in pounds	Clyde Space S-band	£ 10,000.00	1	$15,800.00		$0.00				
			Taoglas Antenna	$4.60	1	$4.60		$0.00				
	Cross-link (Bevo-2 only)								$241.34	Bevo-2		
			XBee XTend Radio	$230.00	1	$230.00		$0.00				
			Crosslink Antenna	$11.34	1	$11.34		$0.00				
EPS											$21,763.00	
	Electronics Board			$7,542.00	1	$7,542.00	1.	$7,542.00	$7,542.00			
	Battery			$3,221.00	1	$3,221.00	1.	$3,221.00	$3,221.00			
	Solar Power								$11,000.00			
			Solar Cell	$300.00	25	$7,500.00		$0.00				
			Solar Cell PCB	$350.00	10	$3,500.00		$0.00				

Table G.6 - Spacecraft structure flight unit costs.

			Component						Subsystem	Module
Subsystem Cost ($)			Cost (ea)	Quantity needed	Component Total (USD)	Flight Quantity in-house	Flight Costs Purchased	Flight Component Total (USD)	CBE ($)	
Satellite structure										$27,500.00
										$25,000.00
STR machining									$22,500.00	ARMADILLO
	ADC Module							$7,500.00	$20,000.00	Bevo-2
		Estimate			$7,500.00		$0.00			
					$0.00		$0.00			
					$0.00		$0.00			
	Bus Module						$0.00	$7,500.00		
		Estimate			$7,500.00		$0.00			
					$0.00		$0.00			
					$0.00		$0.00			
	Payload						$0.00			
		ARMADILLO ESTIMATE			$7,500.00		$0.00	$7,500.00		ARMADILLO
		BEVO-2 ESTIMATE			$5,000.00		$0.00	$5,000.00		BEVO-2
Integration							$0.00	$5,000.00	$5,000.00	
	Wiring and Connectors				$3,000.00		$0.00			
	Fasteners				$1,000.00		$0.00			
	Chemicals (Elastomer, Staking, etc..)				$1,000.00		$0.00			

Appendix H: Cost Model Tables

Table H.1 - SSCM 100-1000 kg full model

WBS Element	Category	CER (FY05 $K)	Cost Driver (X)	NRe %	Re %	X1	X2	X3	CER value (FY05 $K)	CER NR (FY05 $K)	CER Re (FY05 $K)
1.1.1 ADCS	Spin stabilized	Y = 0.613*X1^1.584*X2^(-1.316)	X1 = Satellite wet mass (kg); X2 = pointing control (deg)	58.00 %	42.00%	--	--	--	--	--	--
	3-Axis stabilized	Y = 1567.03*X1^(-0.260)*X2^0.069	X1 = pointing knowledge (deg); X2 = ADCS subsystem mass (kg)	58.00 %	42.00%	5	0.81	--	$1,016.32	$589.47	$426.85
1.1.2 TT&C/C&DH	EO	Y = 247.41*X1^0.418*X2^1.369	X1 = CDH subsystem mass (kg); X2 = transmit power (W)	49.00 %	51.00%	0.38	1		$165.11	$80.90	$84.20
	Planetary	Y = 4061.72*X1^0.622	X1 = CDH subsystem mass (kg)	49.00 %	51.00%	--	--	--	--	--	--
1.1.4 EPS	Body-mounted	Y = 2994.97*X1^0.0269*2.157^X2	X1 = EPS mass (kg); X2 = battery type (0 = NiCd, 1 = NiH2)	48.00 %	52.00%	0.73	0	--	$2,969.72	$1,425.47	$1,544.26
	Deployed-fixed	Y = 281.58*X1^0.484	X1 = BOL Power (W)	48.00 %	52.00%	--	--	--	--	--	--
	Deployed-articulated	Y = 45.93*X1^0.689*1.598^X2	X1 = BOL Power (W); X2 = Solar Cell Type (0=Si; 1 = GaAs)	48.00 %	52.00%	--	--	--	--	--	--
1.1.5 Structure	All	Y = 183.99*X1^0.540*1.742^X2*X3^0.412	X1 = Structure mass (kg); X2 = Structure material (0 = Aluminum, 1 = composite); X3 = solar array area (m^2)	58.00 %	42.00%	1.117	0	0.136	$85.85	$49.80	$36.06
1.1.5 Thermal	All	Y = 72.37*X1^0.931*X2^0.	X1 = thermal subsystem mass (kg); X2 = BOL	55.00 %	45.00%	0	5.1		$0.00	$0.00	$0.00

		084	power (W)								
1.1.6 Thruster	All	Y = 324.17*X1^0.446*1.781^X2*2.253^X3	X1 = propulsion subsystem dry mass (kg); X2 = propellant type (0 = cold gas; 1 = Hydrazine); X3 = Monoprop (=0) or Biprop (=1)	50.00 %	50.00%	0.3	0	0	$189.48	$94.74	$94.74
										Total s/c NR cost $2,240.37	**Total s/c Re cost** $2,186.11
1.3 Integration, Assembly & Test	All	Y = 141.16*X1^0.302*X2^0.475	X1 = design life (months); X2 = bus dry mass (kg)	31.00 %	69.00%	24	3.92	--	$705.26	$218.63	$486.63
3.0 Program level	EO	Y = 205.80*X1^0.524*X2^0.173*1.435^X3	X1 = Bus dry mass (kg); X2 = design life (months); X3 = stabilization type (0 = spin, 1 = 3-axis)	54.00 %	46.00%	3.92	24	1	$1,047.02	$565.39	$481.63
	Planetary	Y = 84.56*X1^1.398	X1 = Development time (months)	54.00 %	46.00%	--	--	--	--	--	--
4.0 Operations	All	Y = 0.136*X1^1.510*3.019^X2	X1 = Satellite wet mass (kg); X2 = stabilization type (0 = spin, 1 = 3-axis)	0.00%	100.00 %	4	1	--	$0.00	$0.00	$0.00
										Total s/c NR cost $784.02	**Total s/c Re cost** $968.26

Table H.2 - NAFCOM Full Cost Table

WBS Element		**D&D**	**STH**	**Flight Unit**	**DDT&E**	**Production**	**Total (FY2011 $K)**
Uncrewed Earth Orbiting Spacecraft		$2,007.71	$518.52	$ 553.94	$ 5,124.10	$ 675.25	$ 5,799.35
1.0 Spacecraft Bus		$2,007.72	$518.52	$ 395.36	$ 2,526.23	$ 395.36	$ 2,921.59
	Structures & Mechanisms	$ 443.59	$147.28	$ 113.96	$ 590.87	$ 113.96	$ 704.83
	Thermal Control	$ -	$ -	$ -	$ -	$ -	$ -
	Reaction Control Subsystem	$ -	$ -	$ -	$ -	$ -	$ -
	Electrical Power and Distribution	$ 164.99	$ 38.44	$ 28.93	$ 203.43	$ 28.93	$ 232.36
	Command, Control & Data Handling	$ 126.79	$ 81.20	$ 61.13	$ 207.99	$ 61.13	$ 269.12
	Attitude Determination & Control	$1,272.35	$251.59	$ 191.34	$ 1,523.95	$ 191.34	$ 1,715.29
	Apogee Kick Motor	$ -	$ -	$ -	$ -	$ -	$ -
					Total s/c NR cost	**Total s/c Re cost**	**Total s/c cost**
					$ 2,526.23	**$ 395.36**	**$ 2,921.59**
2.0 Spacecraft Bus System Integration		$ -	$ -	$ 108.22	$ 1,330.48	$ 108.22	$ 1,438.70
	Integration, Assembly and Checkout (IACO)	$ -	$ -	$ -	$ -		$ -
	System Test Operations (STO)	$ -	$ -	$ -	$ 603.41	$ -	$ 603.41
	Ground Support Equipment (GSE)	$ -	$ -	$ -	$ 35.32	$ -	$ 35.32
	Tooling	$ -	$ -	$ -	$ 7.68	$ -	$ 7.68

	ME GSE	$ -	$ -	$ -	$ 27.64	$ -	$ 27.64
	System Engineering & Integration (SE&I)	$ -	$ -	$ 51.26	$ 329.26	$ 51.26	$ 380.52
	Program Management	$ -	$ -	$ 56.96	$ 327.17	$ 56.96	$ 384.13
	Launch & Orbital Operations Support (LOOS)	$ -	$ -	$ -	$ -	$ -	$ -
3.0 Fee		$ -	$ -	$ -	$ -	$ -	$ -
4.0 Program Support		$ -	$ -	$ 50.36	$ 382.14	$ 50.36	$ 432.50
5.0 Contingency		$ -	$ -	$ -	$ -	$ -	$ -
6.0 Vehicle Level Integration		$ -	$ -	$ -	$ -	$ -	$ -
					Total support NR cost	**Total support Re cost**	**Total support cost**
					$ 1,712.62	**$ 158.58**	**$ 1,871.20**

Glossary

Acronym	Meaning
ADC	Attitude Determination and Control subsystem
AFRL	Air Force Research Lab
ARMADILLO	Attitude Related Maneuvers and Debris Instrument in Low (L) Orbit
ARTEMIS	Autonomous Rendezvous and rapid Turnaround Experiment Maneuverable Inspection Satellite
BLR	Burdened Labor Rate
BOL	Beginning of Life
CAD	Computer Aided Drafting
CBE	Current Best Estimate
CDH	Command and Data Handling subsystem
CDR	Critical Design Review
CER	Cost Estimating Relationship
COM	Communications subsystem
COTS	Commercial Off The Shelf
CPI	Consumer Price Index
D&D	Design and Development
DDT&E	Design Development Test and Evaluation
DRAGON	Dual RF Astrodynamic GPS Orbital Navigator
DSMC	Defense Systems Management College
EDU	Engineering Design Unit
EIA	Electronic Industries Alliance
EPS	Electrical Power System subsystem
FASTRAC	Formation Autonomy Spacecraft with Thrust, RelNav, Attitude and Crosslink
FCR	Flight Competition Review
FOTON	Fast, Orbital, TEC, Observables, and Navigation
G&A	General & Administrative
GPS	Global Positioning System
GRA	Graduate Research Assistant
GS	General Schedule
HW	Hardware
I&T	Integration & Testing
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ITAR	International Traffic in Arms Regulation
JAPDTSICM	JPL Advanced Projects Design Team Spacecraft Instrument Cost MOdel
JSC	Johnson Space Center
LEO	Low Earth Orbit
LOC	Lines of Code

LONESTAR	Low Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and docking
MA	Mission Assurance
NAFCOM	NASA/Air Force COst Model
NICM	NASA Instrument Cost Model
NR	Non-Reusable
NVS	Navigation Visual subsystem
PARADIGM	Platform for Autonomous Rendezvous and Docking with Innovative GN&C Methods
PDD	Piezo-electric Dust Detector
PDR	Preliminary Design Review
PI	Principal Investigator
PRA	Probabilistic Risk Assessment
PQR	Proto-Qualification Review
Q&A	Quality and Assurance
RVM	Requirements Verification Matrix
SDL	Satellite Design Lab
SE	Systems Engineering
SSCM	Small Satellite Cost Model
STH	System Test Hardware
STR	Structures/integration subsystem
SW	Software
SYS	Systems engineering subsystem
THR	Thruster subsystem
TMI	Technology Maturity Index
TRL	Technology Readiness Level
UNP	University Nanosatellite Program
URA	Undergraduate Research Assistant
USCM8	Unmanned Space vehicle Cost Model version 8
UT-Austin	University of Texas at Austin
WBS	Work Breakdown Structure

References

[1] NASA. “Edison Small Satellite Flight Demonstration Missions.” Office of the Chief Technologist. 2 February 2012. OMB Number 2700-0085.

[2] Nugent, R., Munakata, R., Chin, A., Coelho, R., Puig-Suari, J., “The CubeSat: The Picosatellite Standard for Research and Education.” AIAA paper 2008-7734. AIAA Space 2008 Conference. September 9-11 2008. San Diego, California.

[3] Johnson, C. “Shoe box-size satellites one of the next big things.” *Boston Globe*. 28 November 2011.

[4] Klamper, A. “NRO Embraces CubeSats for Testing Advanced Technologies.” *SpaceNews*. 13 August 2009. Web. 18 June 2011.

[5] Jorgenson, Therese Moretto. Personal Interview. 28 June 2011.

[6] Ryschkewitsch, M., Schaible, D., Larson, W., “The Art and Science of Systems Engineering.” 18 January 2009.

[7] Blanchard, B. S. and Fabrycky, W. J. *Systems Engineering and Analysis Fourth Edition*. New Jersey: Pearson Prentice Hall, 2006. Print.

[8] Griffin, M. D. “How Do We Fix Systems Engineering?” AIC Paper IAC-10.D1.5.4. 61st International Astronautical Congress. 27 September – 1 October 2010. Prague, Czech Republic.

[9] Guerra, L. *Space Systems Engineering, version 1.0.* [PowerPoint slides]. Retrieved from L. Guerra. Spring 2008.

[10] “SYS197-Mission_overview.” Satellite Design Laboratory. The University of Texas at Austin. Last updated: 2 December 2011.

[11] Yee, T. “Key Elements of Rapid Integration and Test.” AIAA 2005-6830. AIAA Space 2005. August 30 – Sept 1, 2005. Long Beach, California.

[12] Department of Defense. “Plan for Operationally Responsive Space.” *A Report to Congressional Defense Committees*. National Security Space Office, 2007. Web. 26 June 2011.

[13] Dillow, C. “The Air Force's New Cheap, Simple Spy Sat Will (Hopefully) Head into Orbit Tonight.” *Popular Science*. 29 June 2011. Web. 29 June 2011.

[14] Muñoz, S., Greenbaum, J., Lightsey, E.G., Campbell, T., Holt, G., & Stewart, S. (2011, August) The FASTRAC Mission: Operations Summary and Preliminary Experiment Results. 25th Annual AIAA/USU Conference on Small Satellites, Logan Utah, SSC11-III-4.

[15] “CubeSat Design Specifications Rev. 12.” The CubeSat Program, California Polytechnic State University. 1 August 2009.

[16] CubeSat Program, "Poly Picosatellite Orbital Deployer Mk III ICD." California Polytechnic State University. San Luis Obispo, CA.

[17] Fenton, N. *Software Measurement: A Necessary Scientific Basis*. IEEE Transactions on Software Engineering. Vol. 20. No. 3. March 1994.

[18] Krasner, H. *Software System Measurement and Metrics – EE382V.* [PowerPoint slides]. Retrieved from students in class. Fall 2011.

[19] Department of Defense. (2002). *Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs*. (DoD 5000.2-R). Washington, DC: U.S. Government Printing Office.

[20] Garner, D. *Systems Engineering Processes for a Student-based Design Laboatory*. Master's thesis. The University of Texas at Austin. December 2009. Print.

[21] "Nanosat-7 User's Guide." Air Force Research Laboratory Space Vehicles Directorate. UN7-0001. February 2011. Print.

[22] Larson, W. J. and Wertz, J. R. *Space Mission Analysis and Design Third Edition.* California: Microcosm Press, 1999. Print.

[23] "Consumer Price Index Data from 1913 to 2012." U.S. Department of Labor Bureau of Labor Statistic. Retrieved from http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/. Date Accessed: 20 April 2012.

[24] "Small Satellite Cost Model." The Aerospace Corporation. Retrieved from http://www.aero.org/capabilities/sscm/index.html. Date Accessed 20 April 2012.

[25] Winn, Sharon. *NASA/Air Force Cost Model (NAFCOM)*. (NASA Technical Document 20020048607). Marshall Space Flight Center.

[26] "Unmanned Space Vehicle Cost Model." United States Air Force Space Command. Retrieved from www.uscm8.com. Date accessed: 13 March 2012.

[27] "PDS: Planetary Data System." NASA. Retrieved from http://pds.nasa.gov/tools/cost-analysis-tool.shtml. Date Accessed: 13 March 2012.

[28] "Space Operations cost Model (SOCM)." NASA. Retrieved from http://cost.jsc.nasa.gov/SOCM/SOCM.html. Date accessed: 13 March 2012.

[29] "SEER by Galorath." Galorath. Retrieved from http://www.galorath.com/. Date accessed: 13 March 2012.

[30] "PRICE." PRICE Systems. Retrieved from http://www.pricesystems.com. Date accessed: 13 March 2012.

[31] Habib-Agahi, H.; Mrozinski, J.; Fox, G. "NASA Instrument Cost/Schedule Model." Jet Propulsion Laboratory. IEEEAC paper #1158. 29 October 2010.

[32] PRC System Services, "Scientific Instrument Cost Model (SICM)," Technical Brief 125, PRC D-2327-H, February 1990.

[33] Dixon, B. and Villone, P., "Goddard Multi-Variable Instrument Cost Model (MICM)," RAO Note #90-1, May 1990.

[34] Parametric Cost Estimating Handbook. NASA. 14 September 1995. Retrieved from http://cost.jsc.nasa.gov/pcehhtml/pceh.htm. Date accessed 13 March 2012.

Vita

Katharine Mary Brumbaugh was born in Burnsville, MN. After graduating from Apple Valley High School in 2006, she attended Purdue University to study Aeronautical/Astronautical Engineering. During her undergraduate career, Katharine interned for The Aerospace Corporation and The Boeing Company working on missions ranging from Air Force launches to the Space Shuttle and International Space Station. In May 2010, Katharine received the degree of Bachelor of Science and moved to Austin, Texas to continue her study of Aerospace Engineering at the University of Texas at Austin. Katharine quickly became involved in the Satellite Design Laboratory as the Lead Systems Engineer on the Bevo-2 and ARMADILLO missions. In January 2011, she assumed the role of Student Program Manager for the ARMADILLO mission.

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