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Configuration, manufacture, assembly, and integration of a university microsatellite

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CONFIGURATION, MANUFACTURE, ASSEMBLY, AND INTEGRATION
OF A UNIVERSITY MICROSATELLITE

by

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ABSTRACT

Since the launch of Sputnik over fifty years ago, satellites, large and small, have been designed, developed, and launched. Due to recent reductions in design, development and launch costs, these activities have permeated the realm of academia. As a result, universities have become small satellite developers thus giving students exposure to realistic systems engineering.

The Space Systems Engineering Team at the University of Missouri - Rolla (UMR), in conjunction with a number of Air Force, NASA, and industry mentors, is working toward the design, development, and launch of its first satellite, UMR SAT (University of Missouri - Rolla Satellite). This thesis documents the design of the UMR SAT satellites, specifically focusing attention on the layout of all components, component boxes designed for containment and protection from electromagnetic interference and the attachment of components inside the boxes and the boxes to the structure. This thesis also discusses the development of UMR SAT with challenges faced in manufacturing and prototyping including integration and wiring practice along with assembly and integration procedures including necessary equipment and facilities. The resulting configuration was assembled for the Air Force Research Lab University Nanosat Program Flight Competition Review.

This thesis concludes with a discussion of lessons learned in designing for manufacture, preparing for assembly, designing and using ground support equipment, and performing assembly. Many of the challenges met by the UMR SAT team are likely typical to those of any small satellite program.

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1. INTRODUCTION

The Space Systems Engineering Team at the University of Missouri - Rolla (UMR), in conjunction with a number of Air Force, NASA, and industry mentors, is working toward the design, construction, and launch of its first satellite, UMR SAT (University of Missouri - Rolla Satellite). UMR SAT consists of two microsatellites, named MR SAT (Missouri - Rolla Satellite) and MRS SAT (Missouri - Rolla Second Satellite), which will fly a close formation flight technology demonstration mission. The team was recently part of the University Nanosat Program competition, which is described in detail below. This thesis presents the design and implementation of a microsatellite configuration as completed by the author as the UMR SAT Integration lead.

1.1. UNIVERSITY NANOSAT PROGRAM

The University Nanosat Program (UNP) is a two-year cyclic competition sponsored by the Air Force Research Laboratory (AFRL), Air Force Office of Scientific Research (AFOSR), and American Institute of Aeronautics and Astronautics (AIAA). The program focuses on the education of university students in the design, fabrication, integration and test of satellites as well as enabling small satellite research and development. The two-year program cycle includes the design and build of a protoflight small satellite by each of the participating university teams.

The program is administered by a Program Manager and a Systems Engineer employed by AFRL. There are many other AFRL and industry personnel who assist with the program, mainly during design reviews, but also as mentors to the students. The program releases a User’s Guide to the schools that includes most of the requirements and constraints for the duration of the project. The User’s Guide also includes a listing of items due at design reviews as well as encouraged and discouraged practices in many subsystem areas. The program also provides a web-based forum for students from all universities involved to post questions relating to their project. The questions posted are then answered by AFRL personnel and available for all students to view.

In addition, the UNP sponsors several workshops during the two-year cycle. The Student Hands on Training (SHOT) workshops are held in Boulder, CO and include flying an experiment on a high altitude balloon, recovering the payload, and analyzing the results. SHOT I involves building a satellite kit that takes pictures and records the pressure and temperature as it rises in altitude, while SHOT II allows the schools to include hardware from their project satellite to be tested in the high altitude environment. The Satellite Fabrication (Sat Fab) course takes place roughly nine months into the two-year cycle. Each school sends four students to AFRL at Kirtland Air Force Base, Albuquerque, NM. The students learn procedures in building a satellite and many "do's and don'ts" along the way. They also receive hands-on soldering and other electrical training.

Over the course of the two years, several design reviews are held and the University teams are evaluated by AFRL and other industry personnel. The first design review occurs within the first three months of the program and is the System Concept Review (SCR). This review requires the University teams to present their mission statement, design concepts, requirements, preliminary schedule and budgets. SCR is usually a teleconference review.

The next review follows eight to nine months into the cycle and is the Preliminary Design Review (PDR). The PDR reviews the university's satellite design versus the design requirements. System and subsystem level designs are considered. Preliminary system analyses are evaluated at this design review.

The Critical Design Review (CDR) is held roughly 15 months into the two-year cycle. CDR is held at each university and is a full day review. The AFRL reviewers expect that the design will be near completion and design drawings will be submitted. The review covers detailed design, assembly procedures, system and subsystem analyses and the results of any subsystem level testing.

The last review before the Flight Competition Review is the Proto-Qualification Review (PQR). This review is held four to five months before the end of the competition. The purpose of this review is to evaluate an engineering design unit (EDU) of the nanosat. Along with the EDU, all analyses, drawings, and assembly procedures are expected to be complete. Testing procedures should be established as well.

The Flight Competition Review (FCR) is held roughly two years after the start of the program. All Universities submit their completed designs, analyses, tests and a proto-flight nanosat at this review. After a 15-minute briefing by each university and short demonstrations of hardware for AFRL and industry reviewers, the winner is chosen and announced.

The winner of the competition is expected to deliver a flight satellite to AFRL for final integration and test, within a year after the end of the competition. The AFRL personnel then present the winning spacecraft mission to the Department of Defense (DoD) Space Experiment Review Board (SERB). This is in an effort to secure a launch opportunity through the Space Test Program (STP). The fourth round of the UNP competition, Nanosat-4, began in January, 2005 and ended in March, 2007 with the Flight Competition Review [1].

1.2. UMR SAT

The objectives of UMR SAT are to test new technologies for Distributed Space Systems missions [2], including the study of the dynamics of satellites flying in tightly controlled formations and the development of a low-cost wireless communication link between the satellite pair. Data obtained during the close formation flight phase will be evaluated for the benefit of future missions. As a consequence of the modest budget that accompanies a university level project, UMR SAT also requires the use of innovative, low-cost solutions to meet the stated objectives [3].

The UMR SAT proposal was accepted into the Nanosat-4 competition in January, 2005. The team finished third out of eleven universities in the competition and received the Most Improved Team Award in March, 2007.

1.2.1. Mission. The objectives of the UMR SAT mission include conducting autonomous free formation flight to maintain a fifty-meter separation, and using technology demonstrations to show the potential of new approaches to formation control, intersatellite communication, and attitude and orbit determination and control [3]. The UMR SAT mission is organized using a Modes of Operation plan. Once the satellites have been integrated into the launch vehicle, the Modes of Operation dictate the following chronological events: Launch, Initialization, Power-up, Detumble, Pre-deploy, Separation, Formation Flight, Range Test, and Extended Mission [4]. During the launch, power-up, detumble, and pre-deploy modes, the satellites will be in a docked configuration. A three dimensional Computer Aided Design (CAD) model of the satellites in the docked configuration, with MRS SAT on top, is presented in Figure 1.1. The satellites are shown just after separation in Figure 1.2.

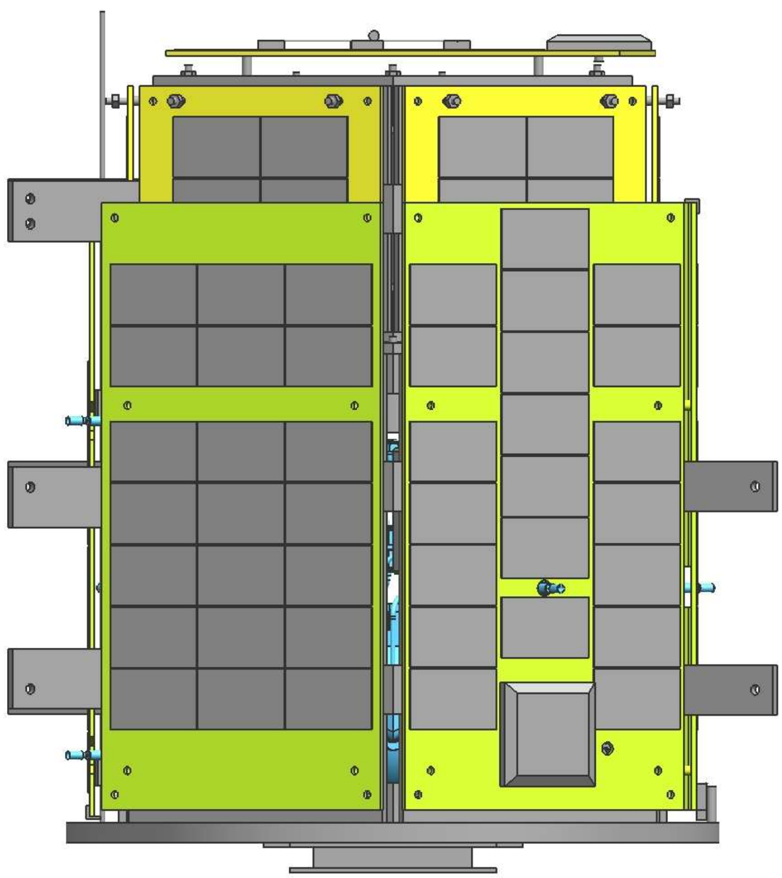


Figure 1.1 MR and MRS SAT Docked Configuration

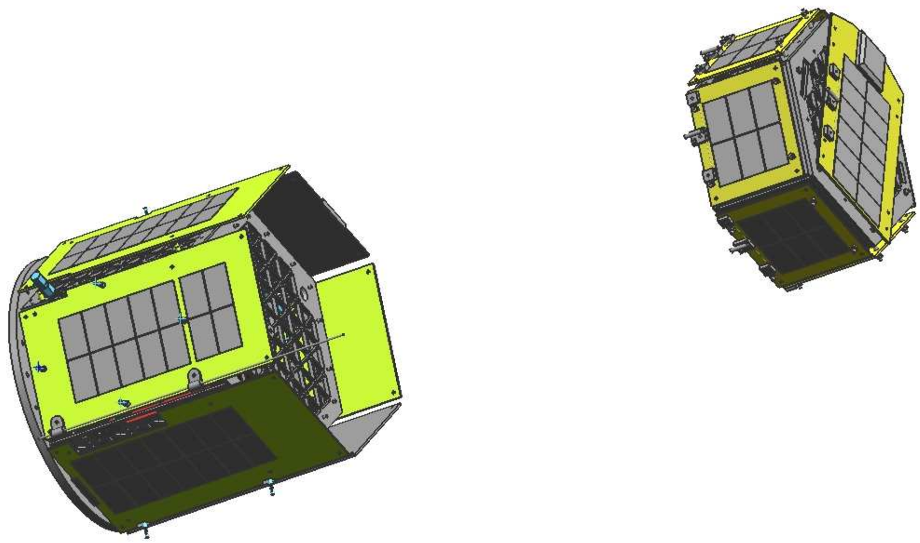


Figure 1.2 MR and MRS SAT After Separation

1.2.2. Subsystems. Small satellites, like large complex satellites, are often broken down into subsystems. A subsystem is a group of components that supports a common function [5]. The subsystems of the UMR SAT mission include the following:

- Structure
- Attitude Determination and Control (ADAC)
- Orbit
- Propulsion
- Command and Data Handling (C&DH)
- Power
- Communication
- Thermal
- Ground Support Equipment (GSE)
- Ground Station

- Documentation
- Testing
- Outreach
- Integration

In order to better understand how these subsystems physically fit together, the Structure and Integration subsystems are discussed in detail below. The Structure subsystem is responsible for supporting all other subsystems while withstanding launch loads and the Integration subsystem is responsible for configuring and assembling all subsystems within the satellites.

1.2.2.1. Structure. The UMR SAT mission involves adherence to requirements for the structure of the satellites. A sturdy structural design with sufficient capacity to carry all necessary components is essential to a spacecraft's mission success. It is also essential to limit the mass and size of the spacecraft in order to lower the costs associated with placing it in orbit. These primary constraints drive the overall structural design of most spacecraft. The University Nanosat Program placed several additional constraints on the structure of the satellites [6]. Some of these were not "hard" constraints, but were instead "very strong suggestions" to make launch possibilities more likely. These constraints included:

- Total mass of less than 30 kg
- Must fit within a prescribed cylindrical envelope of 47.498 cm (18.7 in) diameter by 47.498 cm (18.7 in) tall
- The center of gravity (CG) of the system shall be less than 0.635 cm (0.25 in) from the centerline and less than 30.48 cm (12.0 in) above the separation plane
- Must be capable of withstanding a limit load of 20 g's in all directions (i.e. x, y, and z) with a factor of safety of 2.0 for yield and 2.6 for ultimate
- Have a fundamental frequency above 100 Hz given a fixed base condition at the satellite interface plane

Additional constraints placed on the structure by the UMR SAT Program include:

- Use low-cost solutions for structural components
- Design the two satellites with the capability to launch in a docked configuration until commanded to deploy
- Design the satellite pair with as much commonality as possible

The structural design includes many aspects, including the size, shape, materials, and attachment methods. The overall size of the structure was limited by the above constraints.

To maximize the available volume, a shape most similar to a sphere or cylinder would be best. On the other hand, to make assembly and attachment of components inside the structure possible, a structure more resembling a cube-like shape would be desirable. Another important factor to consider was the surface area of solar panels facing the Sun at any given time. For simplicity, the structure includes surface mounted, non-deployable solar panels, so the amount of structural surface facing the Sun is directly proportional to the amount of energy the solar panels will be able to capture.

After conducting trade studies and basic analysis, it was decided that a hexagonal shape would be a good compromise. This limits the number of sides to six while allowing most of the available volume to be used. More surface area would face the Sun than in the cubic shape and the number of fasteners and attachments points would be less than that of an octagon. The bottom panel of MR SAT accommodates attachment to the launch vehicle separation mechanism and was thus designed as a circular plate. This plate is attached directly to the side panels of the structure.

A shelf in the middle of the hexagonal structure of MR SAT was considered, but the idea was discarded in preference to attaching components on the side panels, which leaves room for the propulsion tank and other propulsion components in the middle of the satellite. MRS SAT is also built in a hexagonal shape and was too short in height to consider adding a shelf. The resulting MR SAT and MRS SAT structures are presented in Figure 1.3 and Figure 1.4.

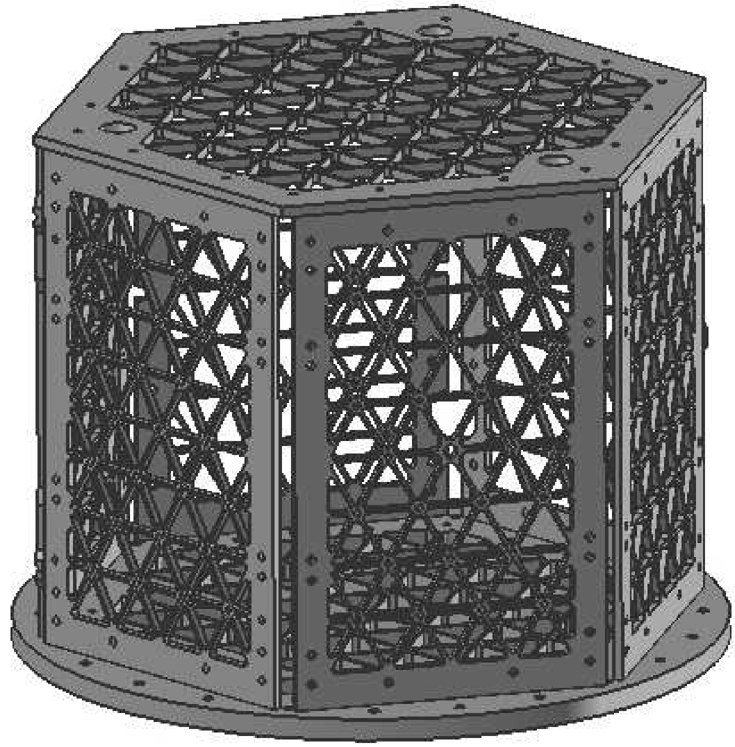


Figure 1.3 MR SAT Structure

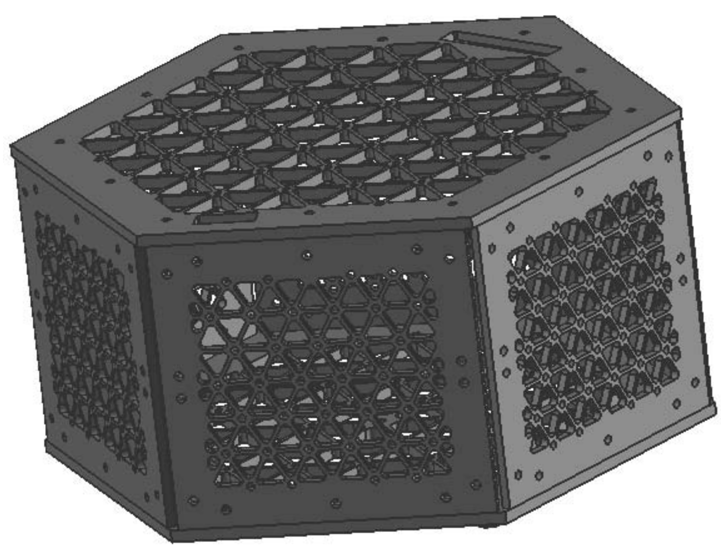


Figure 1.4 MRS SAT Structure

The material chosen for the primary structure of MR and MRS SAT was aluminum 6061-T6. Aluminum is a standard material for spacecraft as it offers high specific strength (i.e. strength per unit mass). The 6061-T6 alloy and temper was chosen because it combines relatively high strength, good workability, and high resistance to stress corrosion cracking. It is also relatively inexpensive and widely available.

The panels of the structure were designed with an isogrid pattern, as seen in Figure 1.5 and Figure 1.6. The isogrid pattern can be modeled as an isotropic material and reduces the mass of the structure while maintaining strength and stiffness. This design allows the isogrid nodes to be used for component attachment and the outer bands to be used for panel attachment to the rest of the structure.

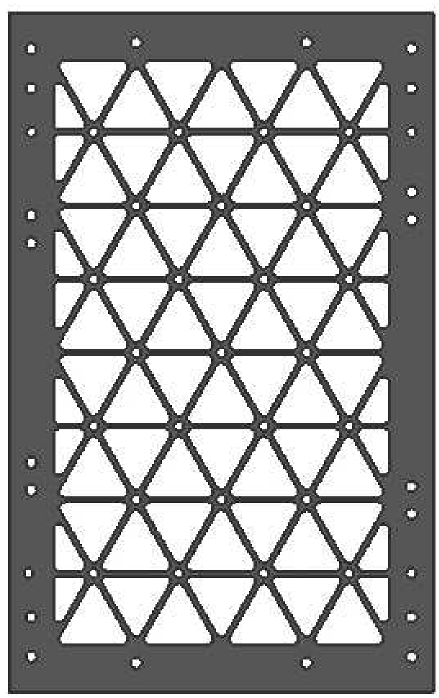


Figure 1.5 MR SAT Isogrid Panel

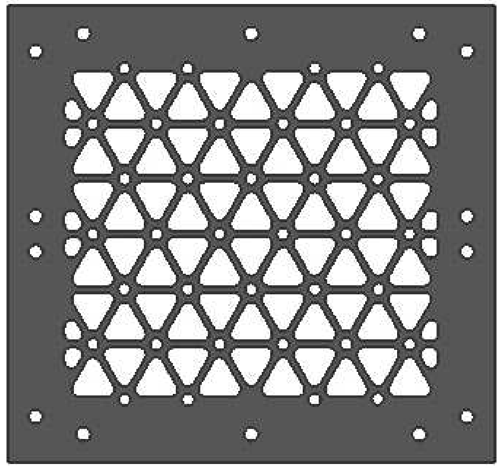


Figure 1.6 MRS SAT Isogrid Panel

The side panels of each satellite required brackets to attach to each other and the top and bottom panels. The use of machined 120 degree brackets allow the side panels to attach to each other while 90 degree brackets allow the sides to be attached to the top and bottom panels. Corner brackets are also placed at every corner of the satellites.

All structural attachments were secured with # 10-24 stainless steel socket head cap screws and lock nuts. The components added to the structure utilize # 8-32 stainless steel socket head cap screws and lock nuts and are attached at the isogrid nodes. All fastener sizes were chosen based on recommendations from AFRL; requirements were given in the User's Guide. Figure 1.7 shows the brackets needed to attach a side panel. The 120 degree brackets were attached on the outside of the satellite to aid in the assembly process.

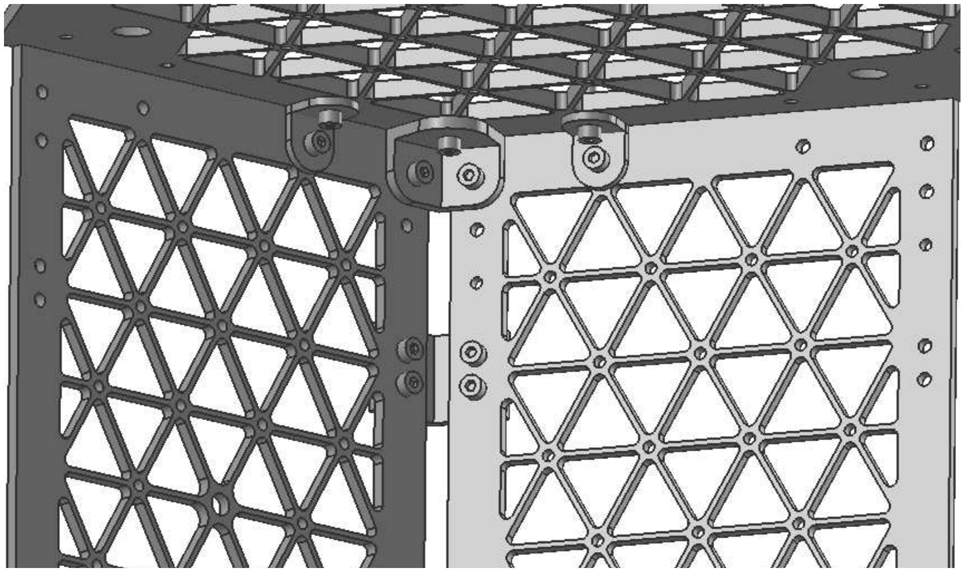


Figure 1.7 Brackets on MR SAT

1.2.2.2. Integration. The UMR SAT subsystems include components that required integration into the structure of the satellites. The Integration subsystem was created in late 2006 when the satellites were nearing assembly due to the end of the University Nanosat Program competition in March, 2007. The Integration subsystem is responsible for organizing and writing the assembly procedures for the integration of the subsystems and their components into the satellites. The Integration lead works very closely with each of the subsystems to ensure that design requirements are being met and that the components can be integrated without major challenges. This includes the layout of components within the satellites and the attachment of each component to the structure, or to the inside of a box. This also includes the placement of connectors for wiring harnesses.

The design of a spacecraft configuration can follow simple steps, with iteration. The following list shows a set of steps, which UMR SAT used, that one can follow when working with spacecraft design and sizing [7].

Step 1: Prepare list of design requirements and constraints

Step 2: Select preliminary spacecraft design approach and overall configuration based on above list

Step 3: Establish budgets for spacecraft propellant, power, and weight

Step 4: Develop preliminary subsystem designs

Step 5: Develop baseline spacecraft configuration

Step 6: Iterate, negotiate and update requirements, constraints and design budgets

Step 1 above was completed by the team chief engineer and program manager, referencing the competition requirements, as well as industry standards. Step 2 was completed at the onset of the project using preliminary trade studies. In Step 3, mass and volume budgets were created and managed throughout the project, and were the task of the Structure and Integration subsystems. Computing, power, and link budgets were also created by the C&DH, Power and Communications subsystem leads, respectively. Step 4 involves subsystem design and was completed at the individual subsystem level. Step 5 was a task for the Integration lead, using subsystem estimates and a 3D Computer Aided Design (CAD) software program, UniGraphics NX 3.0. The Integration lead also focused on making sure that Step 6 was completed in a timely manner. Negotiations between subsystems were held to keep mass and cost down while satisfying as many subsystem requirements as possible. Some iteration was brought on by the Integration lead when updates were required to fit all components within the given mass and volume. Other iterations were initiated by subsystems that needed to change a design component. The Integration lead was charged with keeping track of the budgets and CAD models during the iteration process.

1.3. PURPOSE

This thesis presents the design and implementation of a microsatellite configuration as directed by the UMR SAT Integration subsystem lead. The steps in the spacecraft design and sizing listed above are discussed. Responsibilities and achievements of the Integration lead are presented, including:

- Design of component boxes and their placement within the satellite, along with other components
- Benefits of a prototype satellite used for fit checks, wiring and integration practice as a step in the satellite design process
- Assembly procedures written to aid in the physical manufacture of the flight satellites
- Steps included in the assembly and integration of flight satellites
- Recommendations and lessons learned from these processes

1.4. THESIS ORGANIZATION

This thesis is organized into sections relating to the specific topics introduced above. Section 2 documents relevant literature including university microsatellites, configuration management activities, and assembly integration and test programs. Section 3 discusses the component and subsystem considerations that come into play when configuring a microsatellite, and includes the original and current UMR SAT configurations. Section 4 presents the design details of the aluminum component boxes including their attachment to the structure and components. Section 5 discusses the manufacturing and prototyping activities that are involved with a university microsatellite project, including integration and wiring practice. Section 6 describes the assembly and integration procedures, as well as the equipment and facilities needed. Finally, Section 7 summarizes the various lessons learned during the UMR SAT assembly and integration processes.

2. LITERATURE REVIEW

Before discussing the configuration, manufacture, assembly, and integration of a university-level microsatellite, it is important to understand the advances leading up to this effort. The following summarizes small satellite developments specifically at the university level and relating to design, assembly, and integration.

2.1. SMALL SATELLITES

It was a half century ago when, on October 4, 1957, the Soviet Union successfully launched the world's first artificial satellite, Sputnik 1. This marked the start of the space age and the United States - Union of Soviet Socialist Republics (U.S.S.R.) space race, and the creation of the National Aeronautics and Space Administration (NASA) quickly followed [8]. The first satellites, built in the late 1950s, were small (the first US satellite, Explorer 1, weighed approximately 15 kg) primarily because launch vehicles were limited in the payload mass they could deliver to orbit.

For the next couple of decades after Sputnik 1, launch capability grew along with spacecraft size and mass. Missions became more ambitious as technology evolved. Spacecraft were designed with decade-long development times and price tags exceeding $1 billion [9]. These missions included spacecraft with masses of 1000-10,000 kg. Failures during these missions were devastating to the programs and launch opportunities were few and far between during this stage of the space age. Small satellites with limited capabilities were also being designed throughout, but were not the focus of spaceflight programs.

By the mid 1980s technology had advanced in the field of microelectronics, allowing scientists and engineers to design smaller satellites to perform some of the same jobs as previous large-scale, high-mass missions. These technologies began to facilitate relatively lower mass, lower cost missions. The early 1990s brought about a change in the strategy for access to space. A downturn in satellite mission mass and power was caused by a number of factors including developments in technology and the decreasing NASA budget [10]. Small satellites began to become more practical and popular. Some payload organizations quickly recognized that the ability to fly a simple, small satellite with fast turnaround and lower cost was ideally suited to their needs [7].

Many of these small satellites are designed to perform as groups, or formations, of small satellites. Each small satellite may have limited capability, but as a group may function as well as or better than a single large spacecraft. The current trends in satellite design show that smaller can be better, with lower cost and similar capabilities. Many companies and government agencies are following these trends, seeking less expensive solutions to the satellite design challenge. There is less risk involved with small satellites because if a small satellite in a formation fails, it is much less expensive to replace than if a critical system on a large spacecraft fails.

2.1.1. Small Satellite Benefits and Applications. Potential applications for small satellites are boundless. An array of small satellites in low Earth orbits (LEO) could provide fully connected continuous communications. The small satellites used in these and other clusters consist of large numbers of satellites randomly distributed in their orbit plane without the use of propulsion to maintain their fixed relative positions. A cluster of 400 satellites in LEO could provide 95% coverage of the Earth. The loss of one or even twenty of the satellites only minimally affects the cluster's effectiveness and would be inexpensive to replace [7].

Another application for small satellites is low-cost imaging. Relatively simple guidance systems, along with advanced focal-plane technologies, are used to obtain fine optical resolution. By using clusters of small satellites, frequent image updates can be combined with good ground resolution. These systems can be optimized for applications in agriculture, coastal zone management, or land use and taxation [7].

For the measurement of rapidly varying fields over astronomically significant baselines, one large satellite cannot do the job of many small satellites. By flying tens to hundreds of small satellites in varying orbits, phenomena can be observed. Examples include the charged-particle environments and magnetic field variations of the Earth and Sun. Small satellites are ideally suited for solar observations because high energy orbits are needed, so the low mass of a small satellite is a significant benefit [7].

2.1.2. Small Satellite Classification. Small satellites are currently organized into the four size categories listed below [11]. The categories have not yet been formally defined, and these spacecraft may all be simply referred to as "small satellites." The four classifications are:

- Minisatellite: 100-500 kg
- Microsatellite: 10-100 kg
- Nanosatellite: 1-10 kg
- Picosatellite: 0.1-1 kg

2.2. SMALL SATELLITES AT THE UNIVERSITY LEVEL

The current success of Surrey Satellite Technology Limited (SSTL) is based on almost thirty years of small satellite engineering at the University of Surrey. In 1978, Surrey was offered a piggyback launch with NASA which kicked off the UoSAT-1 mission [12]. UoSAT-1, launched in October 1981, demonstrated that satellite activities could be completed under a university program and that relatively small and inexpensive satellites could be built rapidly to perform sophisticated missions [12].

Based on industry requests for student exposure to a more realistic systems engineering environment, many academic engineering programs have formalized methods to teach detailed system design, fabrication, integration, test, and operation. Weber State University established the Center for Aerospace Technology (CAST) in 1986 to enhance the education of students through the design, development and construction of small satellites. Weber State has flown a number of small satellites and is known internationally for its pioneering work. Students at Weber State University have built and operated earth orbiting satellites and have flown experiments on high altitude rockets. Stanford University announced in 1994 that their Satellite Systems Development Laboratory (SSDL) had commenced full scale development of a new microsatellite initiative [13]. "The SSDL charter is to provide world class education and research in the field of spacecraft design, technology, and operation" [13].

Many other universities have taken similar steps to expose students to satellite design. There have been over twenty universities that have participated in various cycles of the University Nanosat Program competition [1]. The University Nanosat Program was started in 1998 when the Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA) released a request for proposals [14]. The request was for ten universities to participate in a two-year program, the objective of which was to design, assemble, and fly nanosatellites. The ten universities were grouped to form five missions, as follows:

- Emerald
    - Santa Clara University
    - Stanford University
- Ionospheric Observation Nanosatellite Formation (ION-F)
    - Utah State University (USUSat)
    - University of Washington (DawgStar)
    - Virginia Polytechnic Institute & State University (HokieSat)
- Constellation Pathfinder - Boston University
- Solar Blade Heliogyro Nanosatellite - Carnegie Mellon University
- Three Corner Sat Constellation
    - Arizona State University
    - University of Colorado at Boulder
    - New Mexico State University

Various technologies were studied as part of these missions, to include GPS-based positioning, advanced microthrusters, intersatellite communications, satellite coordination and management, satellite crosslinks, gravity gradient tethers, ground operations via the internet, attitude determination precision, and stereo imaging. Reference [14] details more information on these missions.

Another important group of small satellites that has grown rapidly over the past few years is the CubeSat Project. According to their homepage, the CubeSat Project is an international collaboration of over 40 universities, high schools, and private firms developing picosatellites containing scientific, private, and government payloads. A CubeSat is a 10 cm cube with a mass of up to 1 kg. The CubeSat Project was developed by California Polytechnic State University (Cal Poly), San Luis Obispo and Stanford

University's Space Systems Development Lab. The CubeSat program creates launch opportunities for universities previously unable to access space. Developers benefit from the sharing of information within the community. The program benefits the students through hands-on work and benefits private firms and government by providing a low-cost means of flying payloads in space [15].

The CubeSat program strives to provide practical, reliable, and cost-effective launch opportunities for small satellites and their payloads [15]. To do this, they provide the community with:

- A standard physical layout and design guidelines
- A standard, flight proven deployment system, Poly Picosatellite Orbital Deployer
- Coordination of required documentation and export licenses
- Integration and acceptance testing facilities with formalized schedules
- Shipment of flight hardware to the launch site and integration to the LV
- Confirmation of successful deployment and telemetry information

The essence of California Polytechnic State University’s contribution to the CubeSat community is twofold. They provide a standard, reliable, and flight proven deployment system, the Poly Picosatellite Orbital Deployer, or P-POD. The P-POD is a tubular, spring loaded mechanism which takes up very little space. It can be integrated into almost any launch vehicle and protects primary payloads and CubeSats from each other. By participating in a launch coordinated by Cal Poly, developers can focus on design and development rather than on obtaining export licenses and approvals, which is the second contribution to the community [15].

2.3. SMALL SATELLITE DESIGN, ASSEMBLY, AND INTEGRATION

As a case study in the Assembly, Integration, and Test (AIT) phase, the INSAT-2 spacecraft were studied. India's INSAT series of geostationary spacecraft perform the dual missions of communications and meteorology [16]. During the definition phase of the INSAT-2 spacecraft project, systematic studies were completed on several aspects of AIT, including configuration studies, EMI/EMC prediction and analysis, launch vehicle interface definition, mechanical ground support equipment definition, and integrated spacecraft test requirements [17]. The INSAT-2 spacecraft were designed for multiple payload capabilities; these complexities posed many challenges. These studies, however, are similar in scope and definition to many microsatellite programs.

2.3.1. Configuration Studies. The configuration of a spacecraft comes with many tradeoffs. Tradeoff analysis is the essence of system and mission design. The goal of the system designer is to obtain the best compromise among the requirements, desires, and capabilities of the system [18]. Some of the trades to be completed can include propulsion system trades, communications system trades, power system trades, and other technology tradeoffs.

Before the tradeoff analysis, the requirements associated with each component must be understood. Some important factors to consider for each subsystem or component are listed here; the layout design is an iterative process where feedback from the experts in each subsystem is considered [17].

- Functional requirements of each component
- Interfaces (mechanical, electrical, thermal, etc) with the rest of the spacecraft
- Field of view (FOV) requirements of sensors, antennas, etc
- Propulsion system and attitude control requirements
- Thermal constraints
- Electromagnetic compatibility (EMC)
- Physical parameters (center of gravity, moments of inertia)
- Launch vehicle constraints
- Accessibility, ease of assembly

The way in which the components are packaged within the spacecraft volume is another tradeoff. A variety of internal structural design and electronic packaging concepts have evolved in conjunction with configuration designs. Three basic types include dual shear plate, shelf, and skin panel/frame.

The dual shear plate design involves mounting the electronics on flat honeycomb plates or specially designed boxes. The plates are then bolted to inner and outer shear plates which are inserted into the bus structure from the outside; an example is shown in Figure 2.1. The shelf configuration refers to an arrangement where shelves are attached orthogonal to the axis of a cylindrical spacecraft and provide support for electronics and other components. The skin panel/frame configuration uses a basic structural frame or bus. The faces of the structure are closed with plates that may form part of the load-bearing structure; an example is shown in Figure 2.2 [18]. The three types are described in Table 2-1 [18].

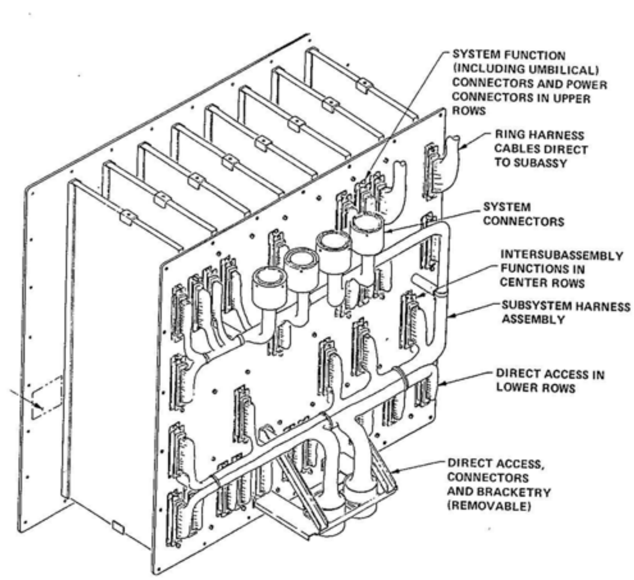


Figure 2.1 Dual Shear Plate Example [18]

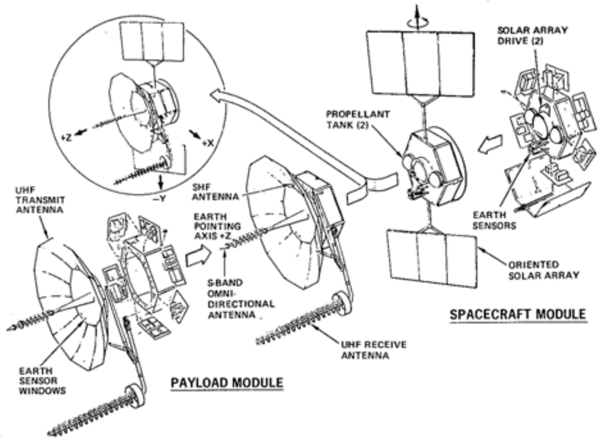


Figure 2.2 Skin Panel Frame Example [18]

Table 2-1 Internal Configuration Options

DESCRIPTION	EXAMPLES	PROS	CONS
Dual Shear Plate			
• Bus Frame • Shear plates close frame inside and out • Custom electronic modules or mounting plates tie to shear plates	• Mariner • Viking • Voyager	• Strong/rigid structure • Good thermal contact • Efficient volumetric packaging	• Requires custom electronics packaging and cabling
Shelf			
• Shelf structure inside spacecraft skin • Electronics packages mount on shelf	• HS 376	• Can use standard "black boxes"	• Less efficient volumetric packaging • More difficult heat transfer path
Skin Panel/Frame			
• Bus Frame • Large skin panels (often hinged) close frame • Electronics mounted on skin	• Flsatcom • Tiros/DMSP	• Can use standard "black boxes" • Good heat transfer contact • Easy access	

The choice of structural configurations is based upon a variety of factors, including overall configuration, mission, payload, and occasionally organizational prejudice.

According to Larson [7], factors known as "configuration drivers" directly affect the configuration for the mission. The payload weight, size, shape and power requirements are drivers, as well as the spacecraft weight, power, solar array area, the launch vehicle adaptor, and the pointing requirements of components. These drivers can be used to estimate the total mass and size of the spacecraft. Once these estimates have been made, it is important to establish budgets, including mass, power, propellant, and reliability budgets. With this, the spacecraft subsystems can be designed [7].

2.3.2. Manufacture, Integration, and Test. There are basic steps in the assembling of a spacecraft [7]. These include:

- Prepare Engineering Data
  - Complete drawings and part specifications
- Manufacture Component
  - Manufacture planning, procurement, assembly, test
- Qualify Component
  - Functional test and environmental exposure
- Integrate and Test Spacecraft
  - Mechanical assembly, functional test, and environmental exposure

The assembly, integration and test operations often cover a major percentage of time in the total project time frame. This process must be planned out well in advance, to include detailed operations lists and steps. A detailed AIT sequence and an AIT operational control plan were developed for the INSAT-2 spacecraft [17]. The actual AIT sequence depends completely on the spacecraft configuration. Identifying separate components or sub-assemblies can help in carrying out parallel work. This can save time in the final assembly and integration if multiple sub-assemblies can be assembled, integrated and tested simultaneously.

Safety plans are also important for the spacecraft and technicians assembling it. Appropriate contamination control of the spacecraft is also imperative to its success. There may be strict requirements for the cleanliness, temperature, and humidity of the environment where assembly and integration take place [17].

2.3.3. Quality Assurance. Quality Assurance (QA) verifies that the manufacture and testing of the spacecraft and its components conform to the engineering data (drawings) [7]. Elements of QA include quality program management, facilities and standards, control of purchases, and manufacturing control. It is important to qualify each piece of manufactured and purchased hardware through QA prior to integration with the spacecraft.

2.3.4. Ground Support Equipment. When planning for the assembly and integration of the spacecraft, an important aspect is the mechanical ground support equipment. A number of assembly fixtures were required for the assembly and integration of INSAT-2. Some of the fixtures were as follows:

- Sub-assembly integration fixtures
- Sub-assembly handling fixtures
- Spacecraft integration fixture
- Appendage integration and special purpose fixture
- Clampbands and special interface adaptors
- Spacecraft handling fixture
- Spacecraft alignment fixture
- Mass property measurement fixtures
- Spacecraft transportation container

These fixtures were fabricated and used extensively during AIT operations [17]. The fixtures incorporated suitable factors of safety to ensure safe handling of the spacecraft.

Microsat Systems, Inc and the Air Force Research Lab worked together in the Roadrunner/Tacsat-2 program to demonstrate the development of a tactically useful small satellite in just 14 months [19]. Along with engineering models of the spacecraft and command and data handling subsystem, the ground support equipment systems were also important. To eliminate system conflicts, three ground support systems were needed, one for payload integration, one for software development, and one for bus hardware integration. If a system has multiple primary payloads, additional systems may be required and should be planned [19].

2.4. THESIS CONTRIBUTIONS

The topics covered in this thesis relate to the configuration, manufacture, assembly, and integration of a university-level microsatellite. The work completed by the author as Integration lead can hopefully assist other university programs in establishing a satellite configuration, manufacturing and assembly procedures, and completing the assembly and integration of a small satellite. The CubeSat, industry, and government small satellite developers may also benefit from the lessons learned throughout the work on the UMR SAT Project.

3. SPACECRAFT CONFIGURATION

Referring to the list of steps involved in spacecraft design and sizing given in Section 1.2.2.2, the initial considerations for selecting a design were evaluated. These steps were followed, keeping component requirements in mind. Preliminary spacecraft configurations were designed in an iterative process. Iterations, negotiations, and updates were tracked by the Integration lead throughout the configuration management process. The end result was a baseline configuration for each satellite.

3.1. INITIAL COMPONENT CONSIDERATIONS

The UMR SAT mission includes nine subsystems with components to be integrated into the satellites. A comprehensive list of components is provided in Table 3-1.

Table 3-1 UMR SAT List of Components by Subsystem

Subsystem	Component
Structure	QwkNut
	Bolt Retractor
	Honeycomb Al
	Al 6061-T6
	Bolts and Nuts
	Zip-Ties
	Helicoils
ADAC	Magnetometers
	Coils
Orbit	GPS receiver
	GPS antenna
	GPS interface board

Table 3-1 UMR SAT List of Components by Subsystem (cont.)

Subsystem	Component
Comm	Transmitter
	Receiver
	Bluetooth Transceivers
	Bluetooth mounting board
	Transmitter antenna
	Receiver antenna
	Bluetooth antennas
	Cables
	Modem
	Communications power board
Power	Solar Cells
	Batteries
C&DH	Viper boards
	Power boards
	Propulsion board
	Magnetic Coils boards
	Magnetometer boards
	1-Wire Interface boards
	Connectors
	Wire
Thermal	Thermal sensors
	Coatings
Propulsion	Tank
	Propellant
	Transducers
	Regulator
	Valves
	Nozzles
	Tubing
	Heaters
	Fill/Drain valve
	Connectors
GSE	Lift tabs

3.1.1. Mass and Volume. The overall mass and volume of the satellites were restricted by the structural requirements previously defined. The mass of the satellite system could not exceed 30 kg, including the provided separation system for the launch vehicle. The satellite system was required to fit into a cylinder with diameter 47.498 cm (18.7 in) and height 47.498 cm (18.7 in).

These requirements flowed down to limit the mass and volume of each individual subsystem and component. Mass and volume budgets were kept up to date to allow for decisions to be made on component purchases, as well as component layout within each satellite. The mass and volume budgets were detailed to the component level. The complete mass budgets for both satellites, at the time of this writing, are included in Appendix A [20, 21].

At the start of the project, each subsystem was allotted a portion of the 30 kg total mass. This was based on perceptions of the types of components that each subsystem would need. As the design matured, the mass and volume budgets became increasingly accurate and the mass allocated to each subsystem was refined. In Figure 3.1 through Figure 3.4, the mass and volume pie charts at the Preliminary Design Review stage are shown for the mass and volume of each satellite. At this stage of the project, there was a mission requirement for a tether between the two satellites, resulting in a Tether subsystem. The mission was scaled back to not include a tether roughly half-way through the competition. The total mass of MR SAT was 22.13 kg and the total mass of MRS SAT was 10.32 kg. This was a total system mass of 32.45 kg, which is over the 30 kg limit. At the early stages the mass estimates were not necessarily accurate, and with most satellite programs the mass estimates seem to increase throughout the program, rather than decrease. This trend was taken into account and contingency plans were organized. At this stage in the design, the propulsion subsystem included a micro-pulsed plasma thruster experiment that was not imperative to the mission, so could be cut from the system at any time, to reduce mass or complexity. A camera was also planned to record the release of MRS SAT from MR SAT during separation mode. Both of these components ended up being cut from the project.

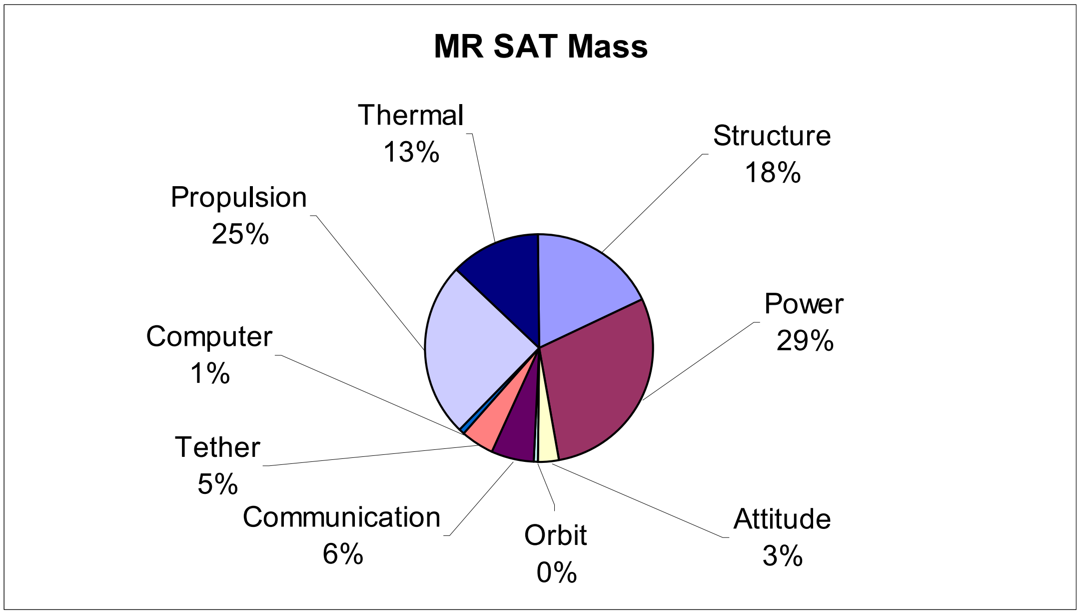


Figure 3.1 MR SAT Mass Distribution by Subsystem at PDR

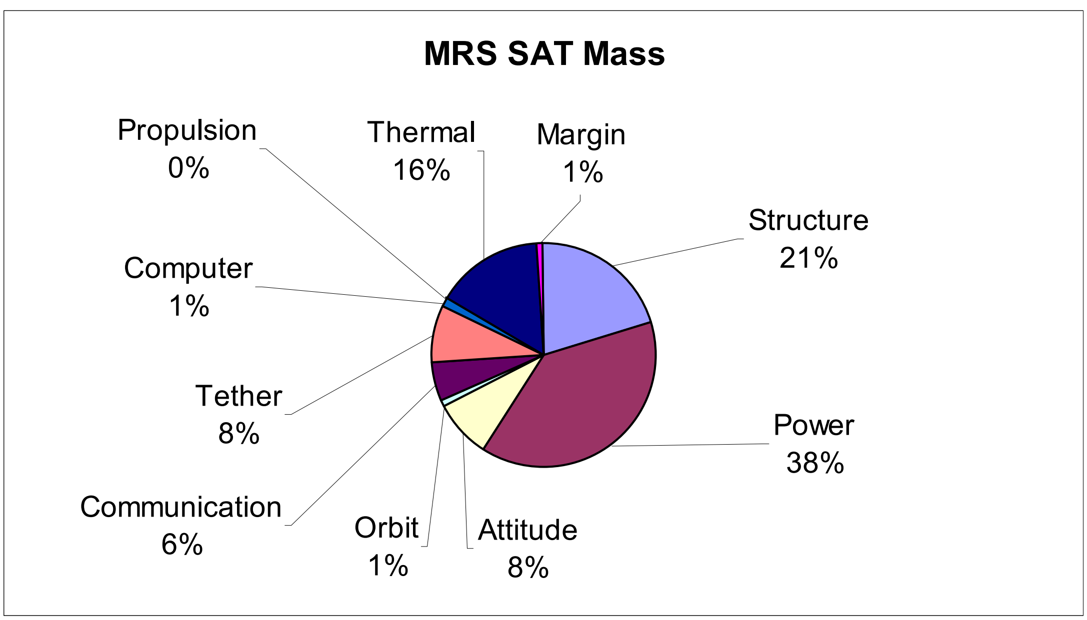


Figure 3.2 MRS SAT Mass Distribution by Subsystem at PDR

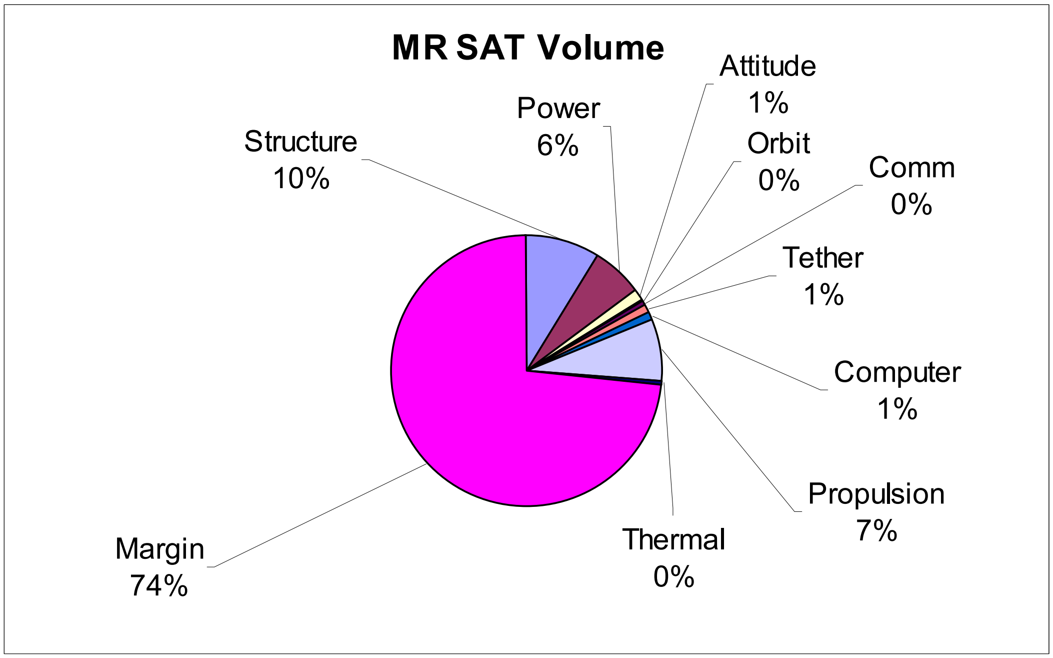


Figure 3.3 MR SAT Volume Distribution by Subsystem at PDR

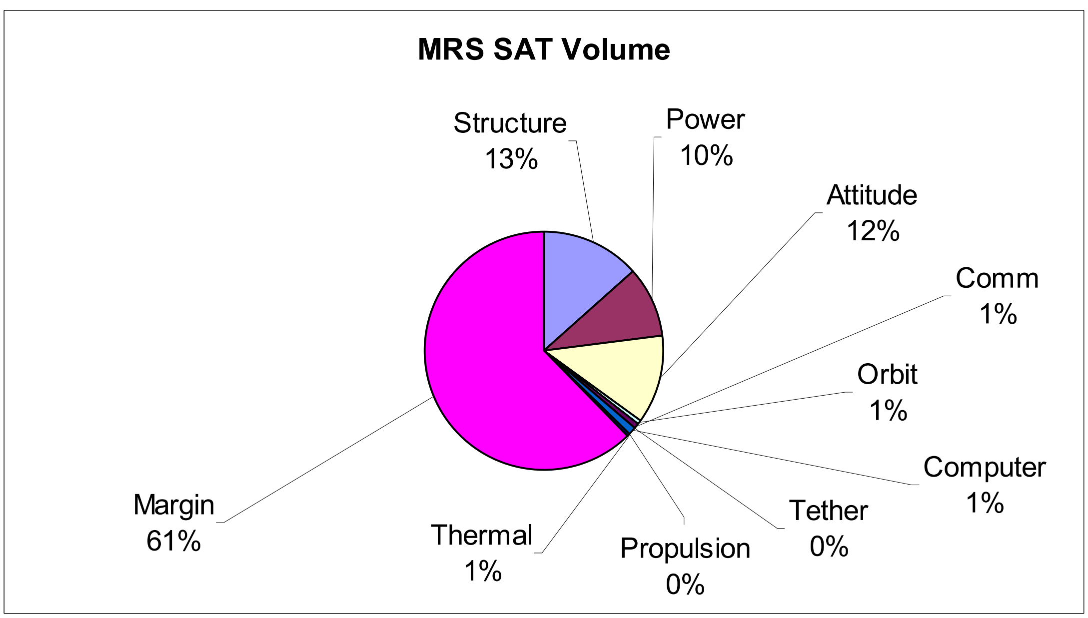


Figure 3.4 MRS SAT Volume Distribution by Subsystem at PDR

In Figure 3.5 and Figure 3.6, the current pie charts are shown for the mass of each satellite. The Structure subsystem includes the component boxes and all attachment hardware, resulting in its relatively high mass. These pie charts reflect the actual mass of components that have been procured and the design mass of those that had not been procured at the time of measurement. The total mass of MR SAT was 23.69 kg and MRS SAT was 8.90 kg. This resulted in a total system mass of 32.60 kg, which is close to the total mass at PDR discussed earlier. The current mass does not include the tether subsystem, micro-pulsed plasma thruster, or camera. It includes actual values for much of the hardware, where the estimates may have been low in comparison.

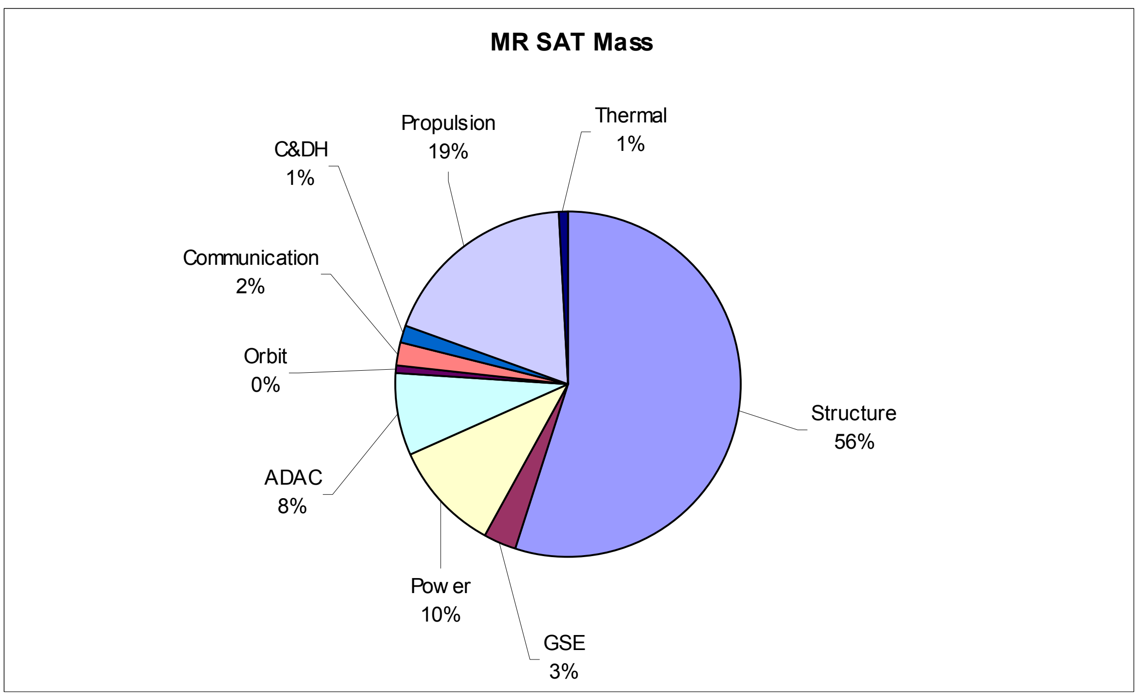


Figure 3.5 MR SAT Current Mass Distribution by Subsystem

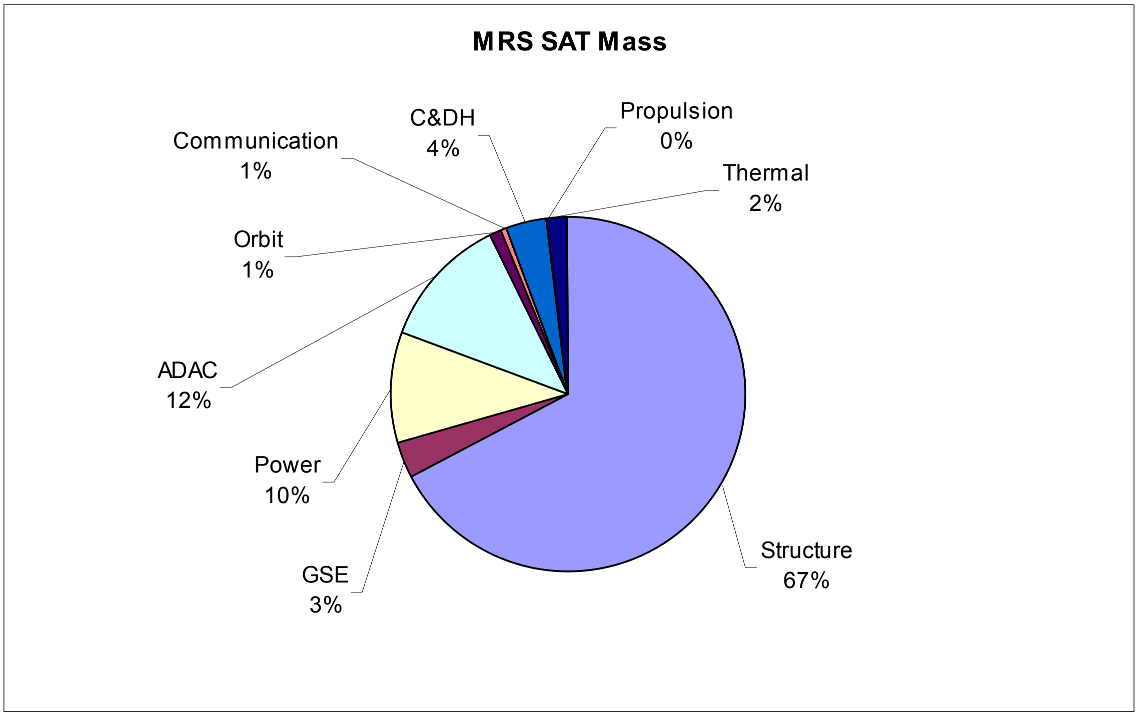


Figure 3.6 MRS SAT Current Mass Distribution by Subsystem

Tracking the volume of each component and subsystem proved not to add any value to the design process. The volume that was being used by the parts was important, but the locations of the components could not be added into the budget, so the volume included in the "Margin" was not necessarily available for other components, due to configuration requirements. The 3-D CAD models were important in designing around these requirements.

Other important values that were calculated and tracked were the center of mass and moments of inertia of the satellites. These quantities were most important for orbit and attitude determination and control, but were also important for the propulsion calculations. The Moments of Inertia (MOI) and Center of Mass (CM) of the satellites have been determined using UniGraphics NX 3.0, the software used to model the satellites. This was done by taking the solid model and applying the proper density to each individual component so that the mass of the component matched the estimate for the component. As stated in the Nanosat 4 User's Guide, the center of mass for the satellite should be less than 0.250 in. (0.635 cm) from the centerline, the z-axis. In addition, the center of mass must lie less than 12.0 in. (30.48 cm) above the X-Y plane [6]. Table 3-2 presents the center of mass and moments of inertia for each satellite as well as the docked pair. At the time of this writing, the satellite system was within the requirements.

Table 3-2 Spacecraft Center of Mass and Moments of Inertia

		Center of Mass (cm from center)			Moment of Inertia (kg.mm3)		
Spacecraft	**Mass (kg)**	**x**	**y**	**z**	**I_{XX}**	**I_{YY}**	**I_{ZZ}**
MR SAT	23.69	0.061	1.251	14.592	504368	478569	503029
MRS SAT	8.90	0.091	0.911	9.426	145872	198079	132012
Docked pair	32.60	0.103	0.539	23.165	1194307	1148918	701358

3.1.2. Satellite Interfaces. The UMR SAT structure will likely be attached to the launch vehicle via a Mechanical Lightband by Planetary Systems Corporation. The winner of the UNP competition is provided this mechanism by AFRL; however they are also available for the university to purchase. The Lightband system is a single impulse system that will eject UMR SAT from the launch vehicle. The Lightband is a circular mechanism which uses 24 ¼”-28 bolts at a 15” diameter. There are strict requirements on the bottom panel of MR SAT that include a stay-out zone for any hardware and a flatness requirement. The Lightband is shown in Figure 3.7. The top half of the Lightband remains with the satellite while the bottom half remains attached to the launch vehicle after separation.

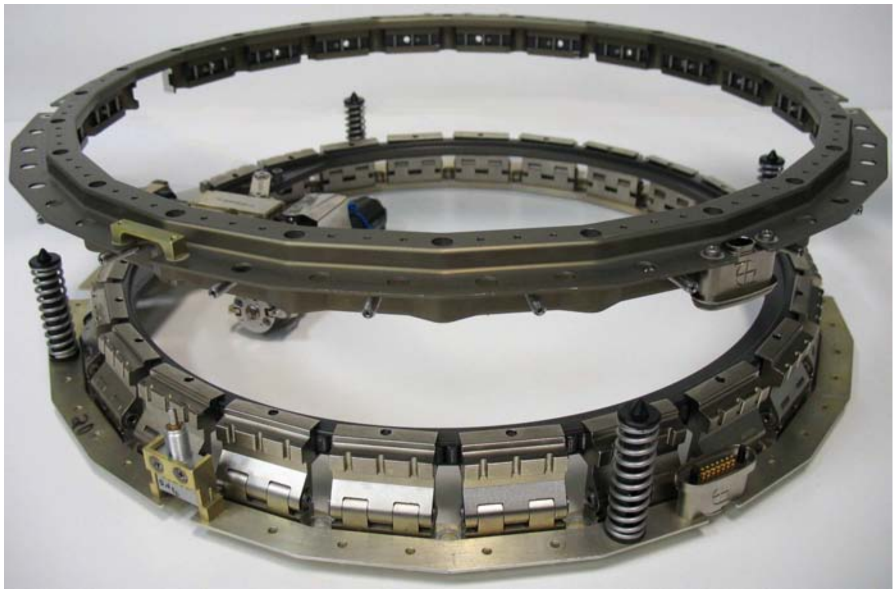


Figure 3.7 Mechanical Lightband (courtesy of Planetary Systems Corporation)

A system-level requirement for the UMR SAT mission involves a separation system between the two satellites. The separation system needs to hold the two satellites securely together until the separation mode of the mission. Many systems exist for this purpose, most of which are high mass and high cost. It was desirable that the system be redundant or at least highly reliable. After completing research into separation devices and conducting a trade study, the QwkNut 3K by Starsys, shown in Figure 3.8, was chosen for the UMR SAT mission. The mission requires the use of one QwkNut 3K. The QwkNut 3K will be attached to the top panel of MR SAT and a Bolt Retractor mechanism, also by Starsys, will be attached to the bottom panel of MRS SAT. The purpose of the bolt retractor is to "catch" the bolt as it is released from the QwkNut device. This will keep the bolt from simply being released into MRS SAT. It also serves to reduce the amount of force imparted on MRS SAT from the bolt retracting into the satellite.

Figure 3.8 QwkNut 3K (Courtesy of Starsys)

These two mechanisms together form the separation system for UMR SAT. The two satellites will be held together with one ¼"-28 bolt at up to 3000 ft-lb of torque. The interface of MR and MRS SAT also requires that the satellites are held stable so as not to twist or compress during launch. The interface will include three points, at 120 degree separation, where the satellites will touch. Allowing the satellites to touch at only these three points removes a flatness requirement for the bottom of MRS SAT and top of MR SAT. These three points will also serve as a cup/cone system that will reduce the likelihood of the satellites twisting with respect to each other. Figure 3.9 presents a basic solid model of the interface.

Both of the satellite interfaces described were very important in configuring the layout of the components within the satellites. The QwkNut and Bolt Retractor must be placed in very specific locations, decreasing the usable volume for other components. The mechanisms must be in line with the center of mass of the satellite system. The QwkNut must be attached under the MR SAT top panel and the Bolt Retractor must be attached on top of the bottom panel of MRS SAT.

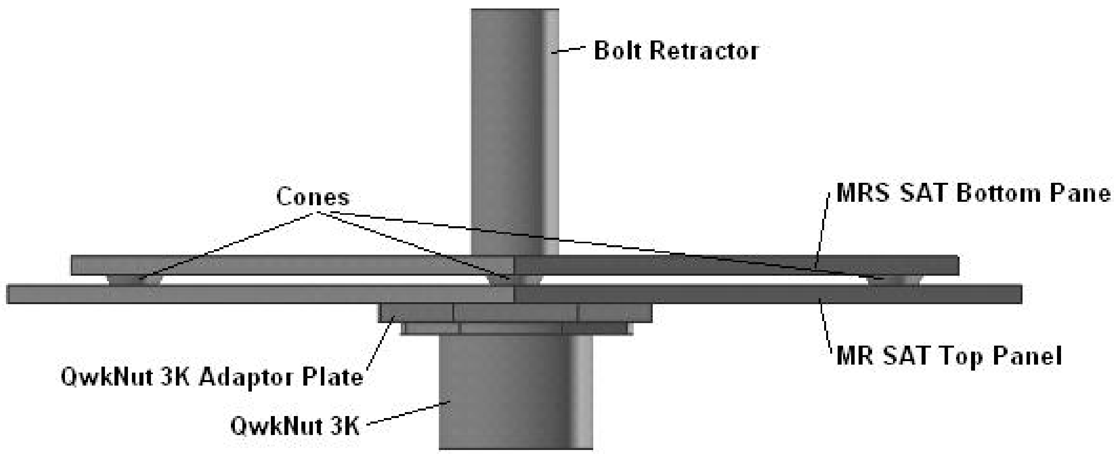


Figure 3.9 MR SAT / MRS SAT Mechanical Interface

3.1.3. Specific Component Considerations. Many of the components in UMR SAT come with positioning requirements. The propulsion tank will expel mass during the mission; therefore the mass of the system will change. To avoid large center of mass shifts during the mission, the propulsion tank should be placed near the center of mass at design. In addition, the positions of the thrusters for the propulsion system are critical to achieving three axis control. Eight thrusters are used on MR SAT, each requiring placement at a specific location.

The Attitude Determination and Control (ADAC) subsystem also includes components that require specific locations or orientations. Each satellite includes three magnetic coils that must be placed orthogonally to each other to achieve three axis control. The coils were also required to be of equal power. There were many options on shape and size, which allowed for more flexibility in placement. Another restriction to be considered was that any components placed physically within the coil must not be overly sensitive to the electromagnetic field the coils would create when powered on; the coils are only powered on while attitude maneuvers are being performed. The original coil design called for three square coils each in three different axes. These coils were large and placing them in the middle of the satellite along three different directions consumed much of the available volume in the spacecraft. With further analysis, the ADAC subsystem engineers were able to determine that the coils need not be orthogonal, but there needed to be a component of force along each of the three axes. This allowed for more flexibility in placement. During the mission, when the magnetic coils are powered on the data from the magnetometers cannot be used because the coils create a magnetic field that interferes with the magnetometer readings.

The Power subsystem had configuration concerns as well. The battery box is a high-mass component on each satellite and as such should be placed as near the center of mass as possible. There are concerns with its loading on the panels as well. The solar arrays should be placed such that the most power is derived from the Sun as possible. MR SAT includes six solar panels, one on each side panel. MRS SAT includes seven solar panels, one on each side panel and one on the top panel. MR SAT does not have sufficient area for a top or bottom solar panel due to the interfaces mentioned earlier.

The Thermal subsystem requires placement of thermal sensors in many locations on the spacecraft. The sensors are small, but require wiring and an attachment method, so their configuration is important. The thermal sensor locations, as decided upon by the Thermal and Integration subsystem leads, are as follows:

- MR SAT
  - Built-in sensors
    - Magnetometer board
    - Thermal board
    - Modem
    - Battery box (two thermistors)
  - Additional sensors
    - Receiver
    - Battery box (outside)
    - Propulsion Tank (three sensors)
- MRS SAT

- Built-in sensors
    - Magnetometer board
    - Thermal board
    - Battery box (two thermistors)
- Additional sensors
    - Large computer box (outside)
    - Bluetooth box (outside)
    - Side panel with magnetic coil
    - Battery box (outside)

Another item to consider when placing components into the satellites were the wiring and connections required. Every component requires some type of connection to at least one other component; some require many connections. To aid in the simplification of the wiring harness, the fewest number of connections were used. The wiring harness diagrams were completed by the Command and Data Handling (C&DH) subsystem. [22, 23].

From the diagrams it becomes apparent that the system is complicated and requires correct placement of components within the structures. Another issue with the wiring harness was the bend radii of the wire and cable being used. This becomes important when routing the wires around other components throughout the satellites. For most wiring, 22 gauge is used and is easily routed. The cable used for the antennas, however, is RG-142 which has an outer diameter of 0.195 inch and a minimum recommended bend radius of 1.00 inch. This had to be accounted for in the harness design. Figure 3.10 and Figure 3.11 show the MR SAT and MRS SAT wiring harness diagrams.

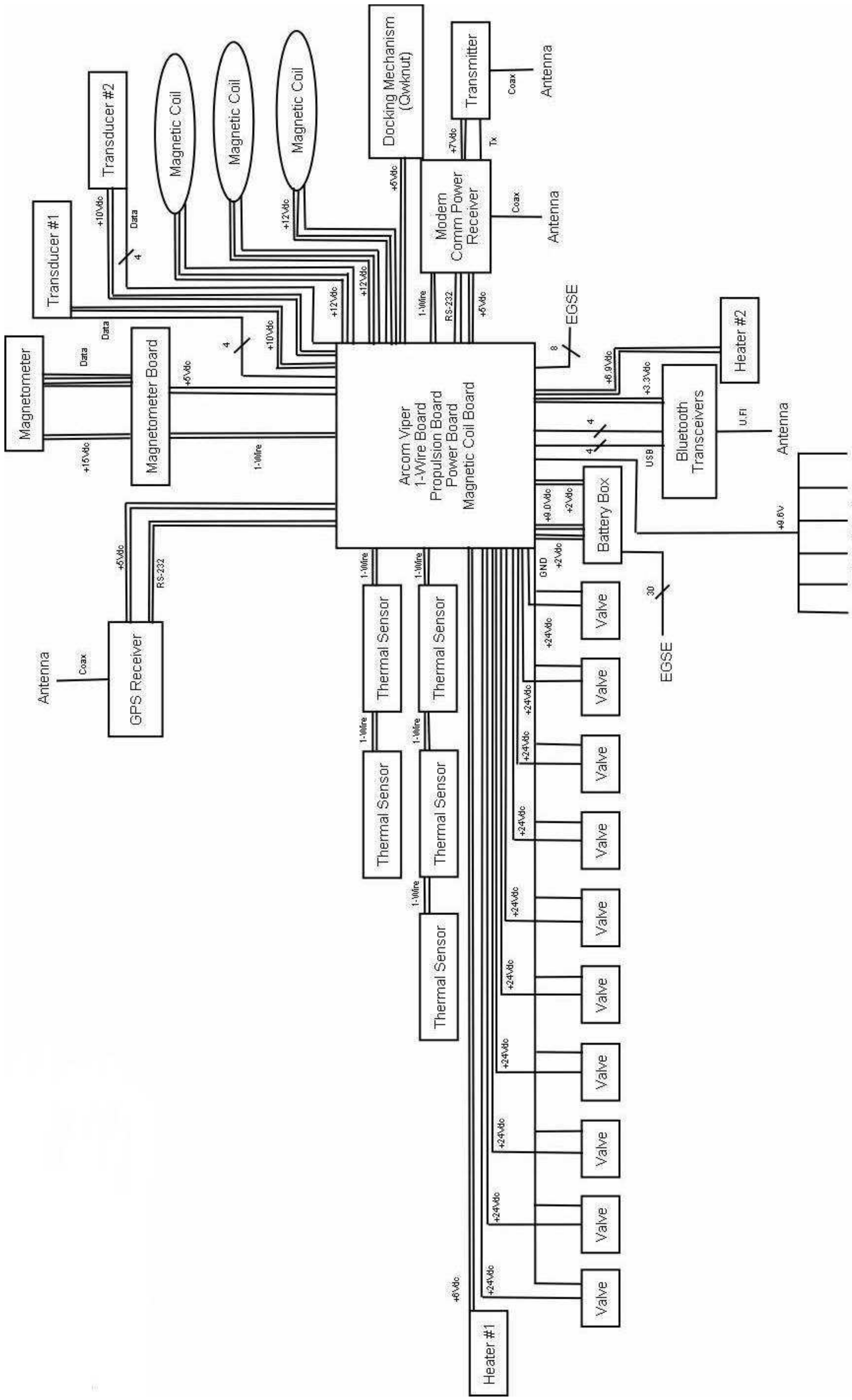


Figure 3.10 Wiring Harness Diagram for MR SAT

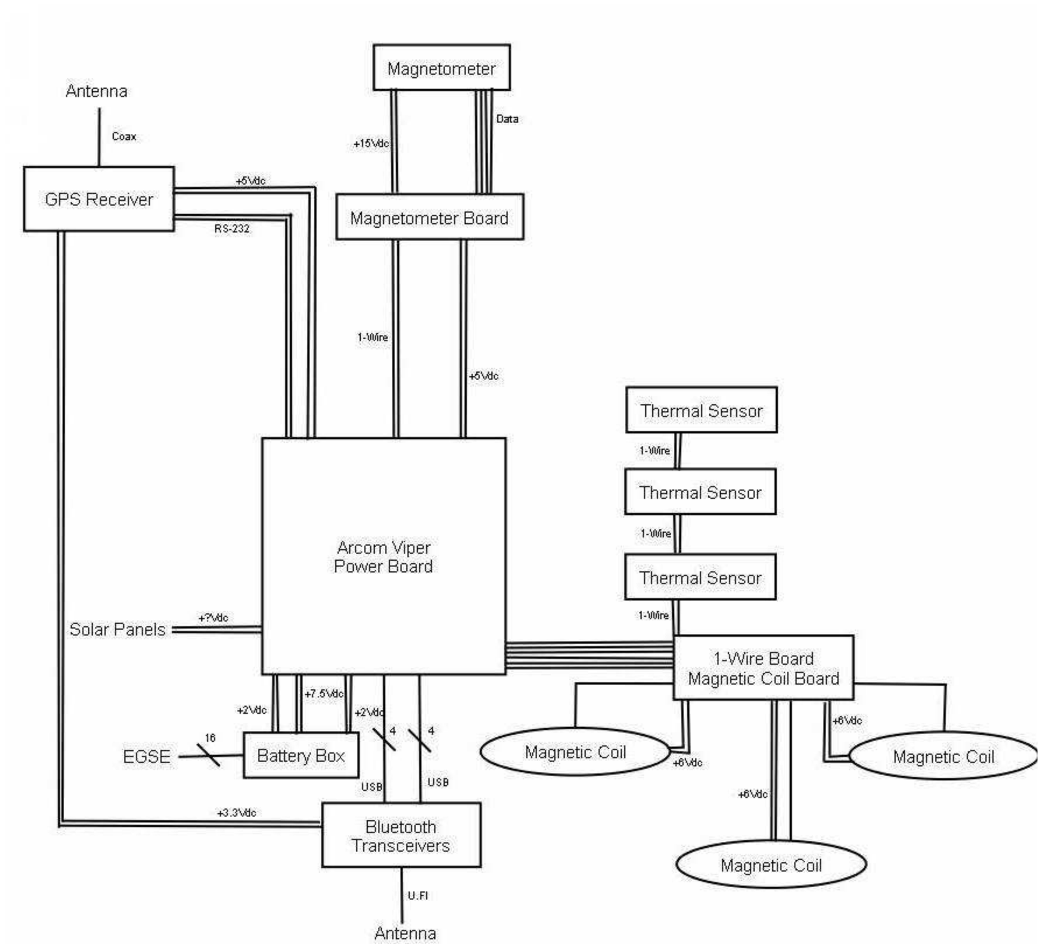


Figure 3.11 Wiring Harness Diagram for MRS SAT

The Ground Support Equipment (GSE) subsystem requires that the satellites be capable of attachment to a table, as well as a crane for lifting, integration, testing and safety purposes. The satellites need tabs on several corners to make this possible. These tabs can serve for ground operations as well as transport, and will need to be located in specific locations on the satellites.

Antenna placement was critical to the mission as well. The GPS antenna must be placed where it is in view of the GPS constellation on orbit. The Communications subsystem also had specific issues with its antennas. The MR SAT receive and transmit antennas need to be in view of the ground while on orbit. The MR SAT and MRS SAT transceiver antennas need to be in view of each other while on orbit, so the Bluetooth units can be utilized.

The pointing concerns for all antennas could only be taken into account once the orientation of the spacecraft on orbit was decided. The panel that will be nadir pointing while on orbit is Panel 1. Panel 1 was chosen because it included the least number of solar cells, so would be the lowest loss of power.

A concise list of the component placement requirements, summarizing the above discussion, is presented in Table 3-3.

Table 3-3 Component Considerations

Subsystem	Component	Requirements
Structure	QwkNut	Bottom of MR SAT top panel and on center of mass line
	Bolt Retractor	Top of MRS SAT bottom panel and on center of mass line
	Honeycomb Al	
	Al 6061-T6	
	Bolts and Nuts	
	Zip-Ties	
	Helicoils	
ADAC	Magnetometers	
	Coils	Orthogonal
Orbit	GPS receiver	
	GPS antenna	On solar panel, facing toward GPS satellites
	GPS interface board	
Comm	Transmitter	
	Receiver	
	Bluetooth Transceivers	
	Bluetooth mounting board	

Table 3-3 Component Considerations (cont.)

Subsystem	Component	Requirements
Comm	Transmitter antenna	In view of ground
	Receiver antenna	In view of ground
	Bluetooth antennas	In view of other satellite
	Cables	
	Modem	
	Communications power board	
Power	Solar Cells	
	Batteries	Close to center of mass if possible
C&DH	Viper boards	
	Power boards	
	Propulsion board	
	Magnetic Coils boards	
	Magnetometer boards	
	1-Wire Interface boards	
	Connectors	
	Wire	
Thermal	Thermal sensors	On specific components
	Coatings	
Propulsion	Tank	Close to center of mass if possible
	Propellant	
	Transducers	
	Regulator	
	Valves	In specific locations for three-axis control
	Nozzles	In specific locations for three-axis control
	Tubing	As little as possible
	Heaters	One on tank, one on lines
	Fill/Drain valve	Connected to tank
	Connectors	
GSE	Lift tabs	On four corners

3.2. SATELLITE CONFIGURATION

With the initial component considerations mentioned in Table 3-3, the configuration of the satellites was managed. The orientation and placement of all components within the satellites was an iterative process. In Figure 3.12 one of the early configuration designs is shown in exploded view. This drawing was completed early in the design process when many of the component masses and volumes were purely estimates. It was apparent from these drawings that there was much work to do in fitting all of the components within the available volume of the satellites.

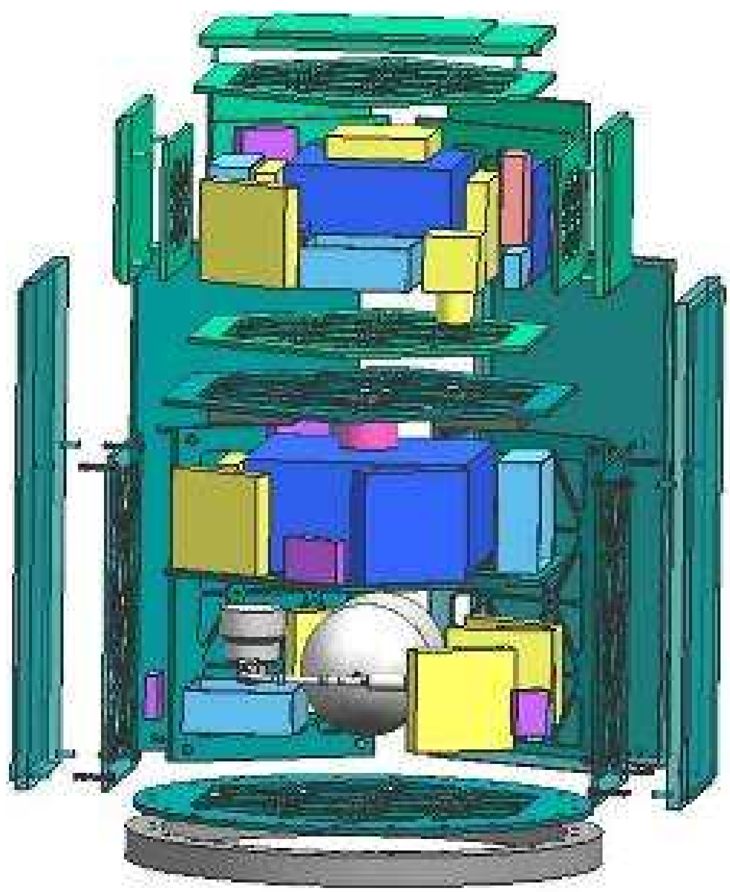


Figure 3.12 MR SAT and MRS SAT Configuration First Iteration

Shortly after these drawings were completed, AFRL made it clear at the Critical Design Review (CDR) that most components would be required to be housed in component boxes, which is discussed in greater detail in Section 4. This changed the layout dramatically as some components would end up sharing a box with other components, and some would need large boxes, taking up more volume than originally planned. The components would also need attachment methods to the structure or the inside of the boxes. Other components, such as the ADAC coils, also changed placement as well. Figure 3.13 through Figure 3.16 show current configurations for MR and MRS SAT, including flowered views to show component placement.

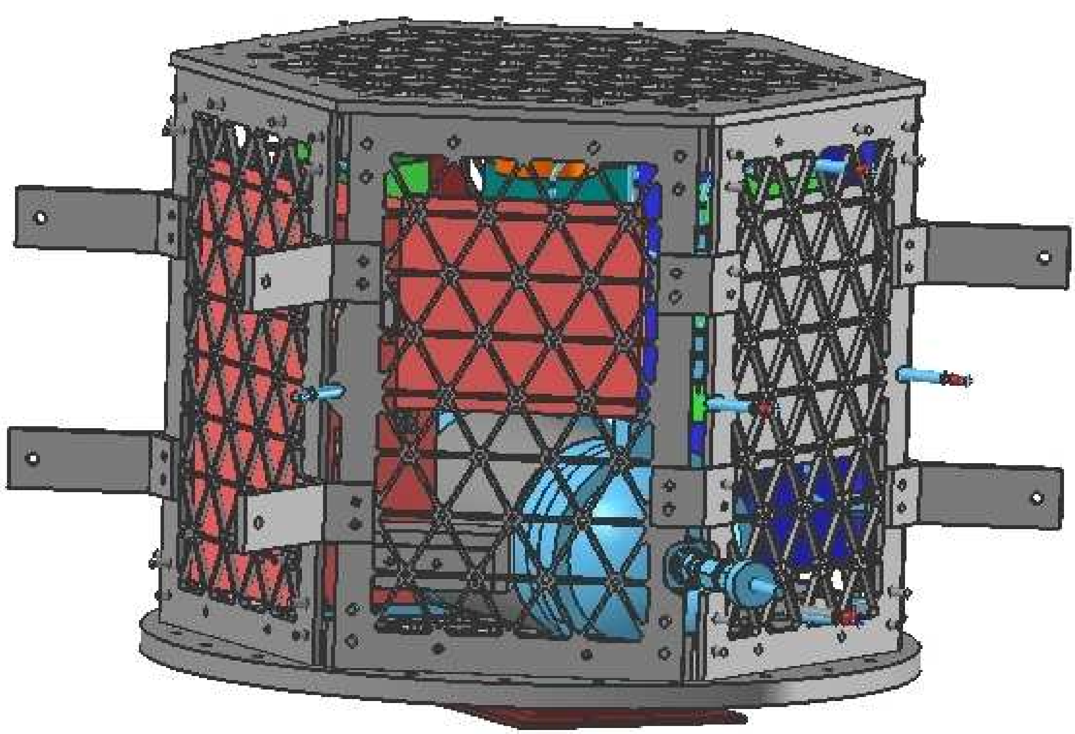


Figure 3.13 MR SAT Current Configuration without Solar Panels

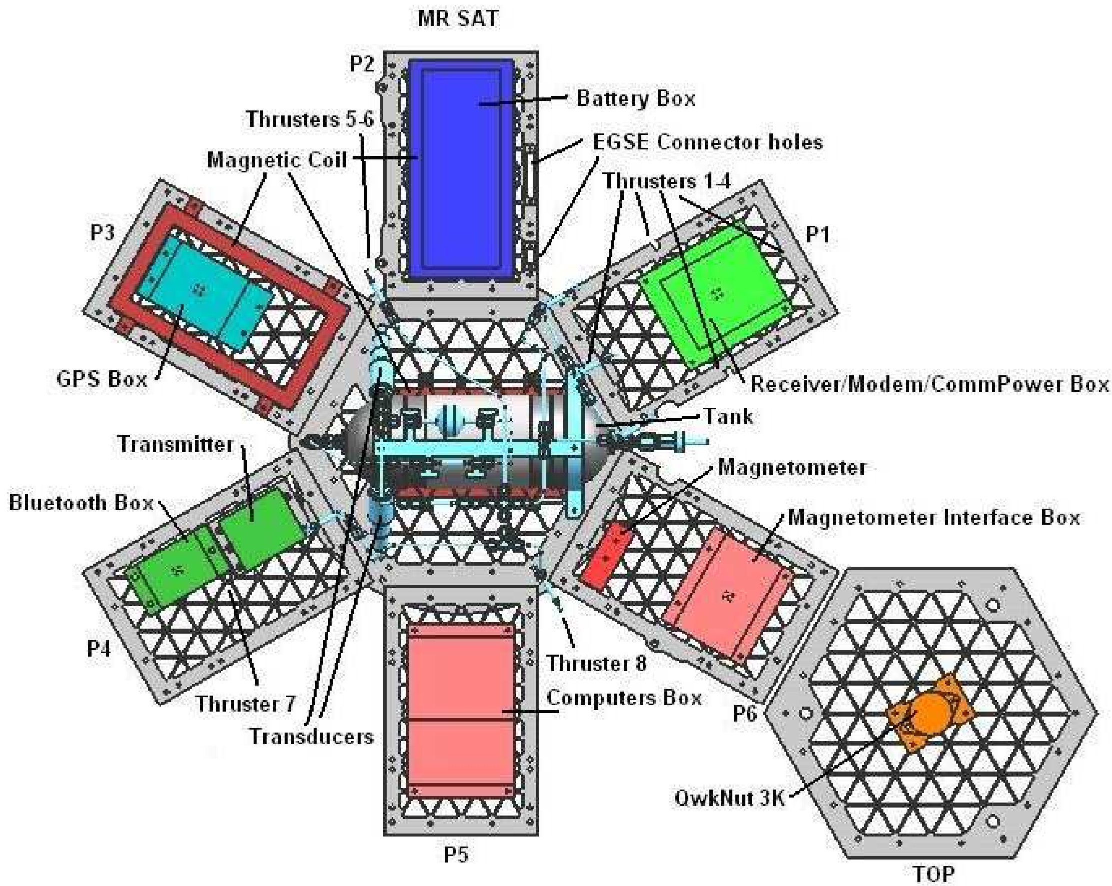


Figure 3.14 MR SAT Flowered View with Component Layout

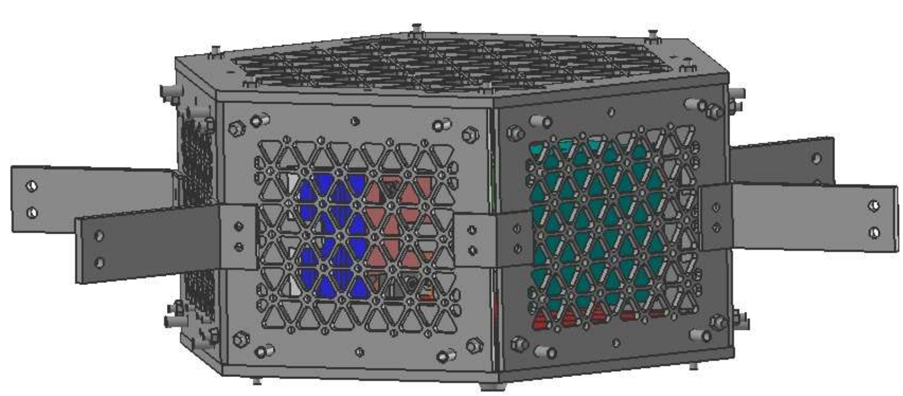


Figure 3.15 MRS SAT Current Configuration without Solar Panels

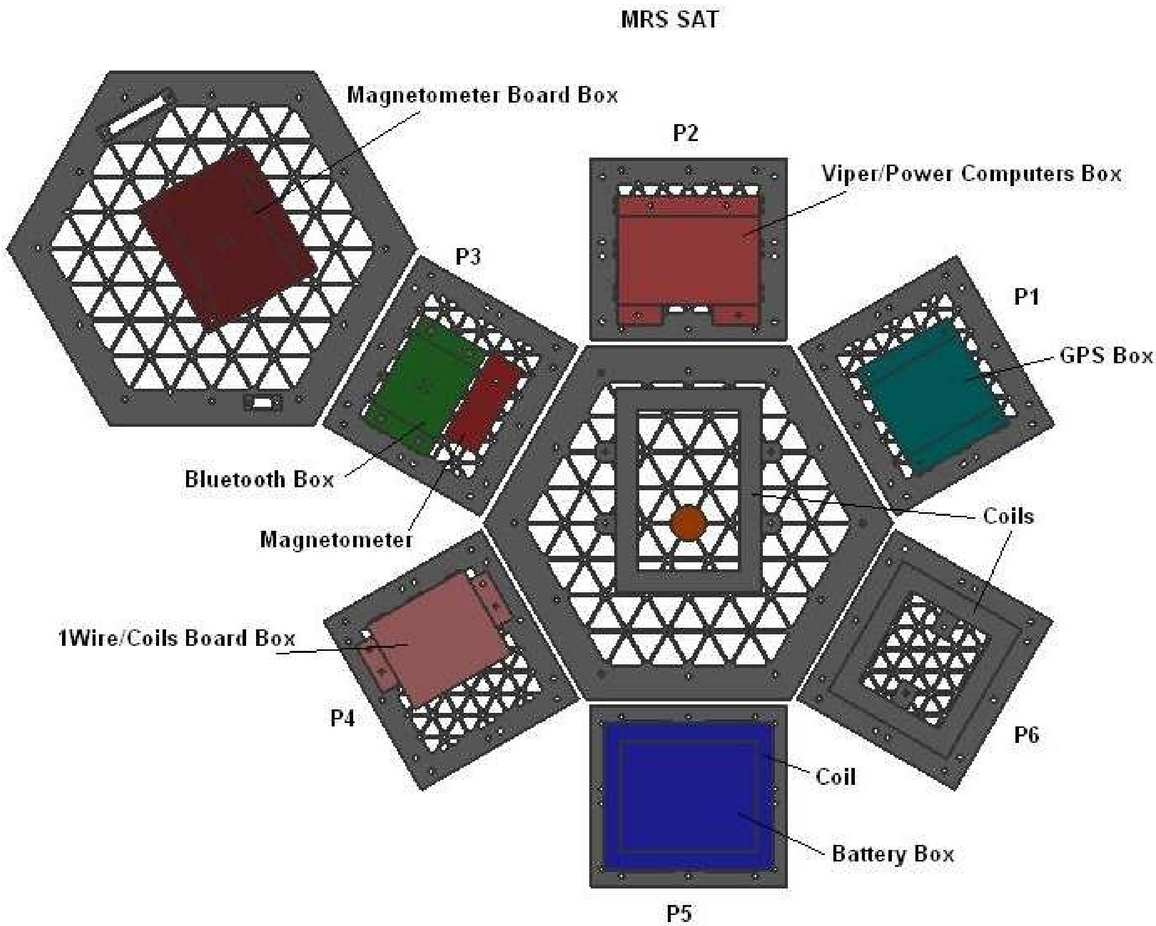


Figure 3.16 MRS SAT Flowered View with Component Layout

The propulsion system is shown in Figure 3.17 as it is routed around component boxes and other components in MR SAT. The transducers and regulator were placed at specific locations along the propulsion tubing.

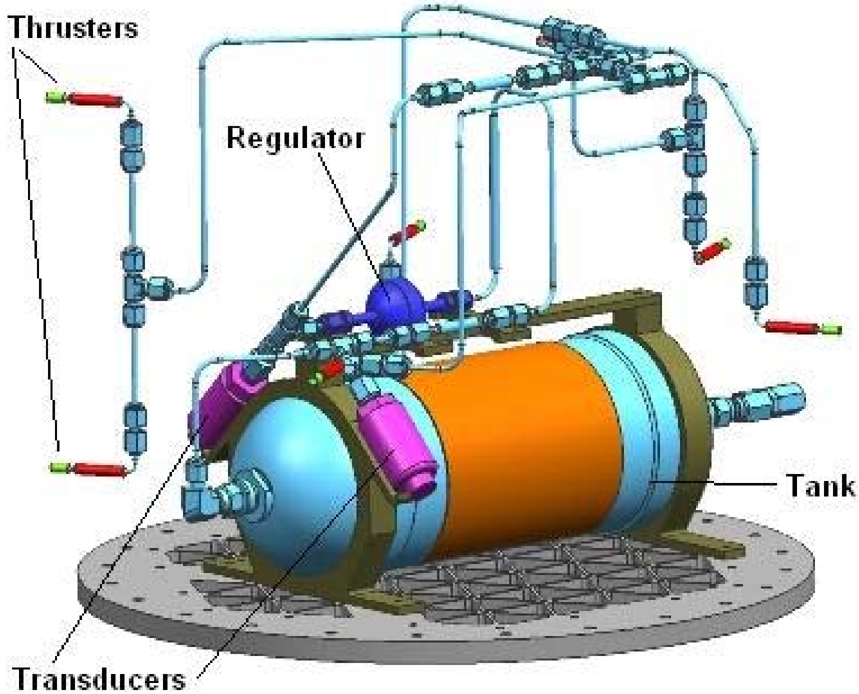


Figure 3.17 Propulsion Subsystem Layout in MR SAT

The propulsion tank was located at the center of the bottom panel of MR SAT. This allows for minimal center of mass changes during the mission. The bottom panel provides sufficient support for the tank and it was not possible to locate the tank at the actual center of mass of MR SAT. The nozzles were placed at the specified locations for three-axis control of MR SAT. This layout is the result of negotiations between the integration, propulsion, and structure subsystems to ensure that the tubing would not interfere with other components. Along with the tubing, the thrusters were also located so as not to interfere with structural components. The thruster locations were decided upon based on performance parameters for the propulsion system then traded with integration aspects including thruster attachment to the structure. Three of the thrusters were designed to be placed at corners of the satellite. Figure 3.18 shows a corner thruster and the modifications made to the side panel to support it. The thruster connectors

(Swageloks) will be zip-tied and epoxied to the structure and the valve will be held in place with epoxy.

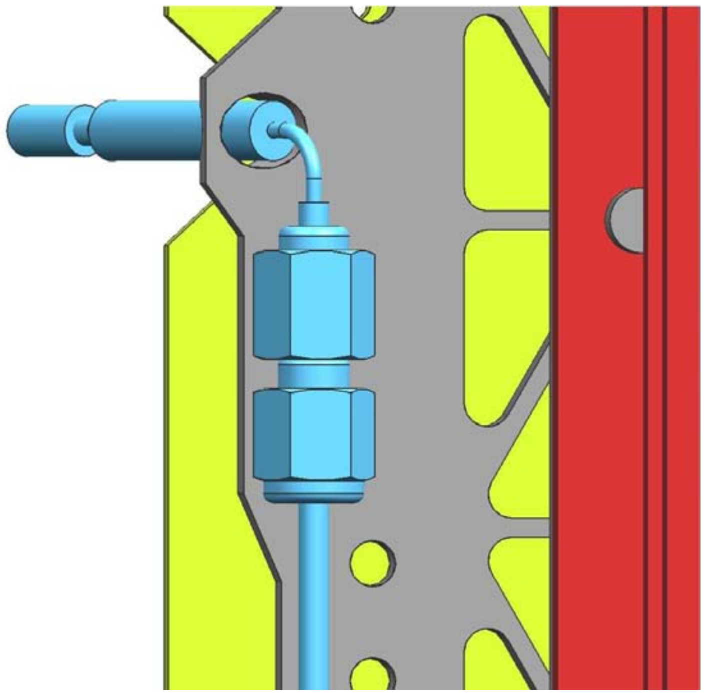


Figure 3.18 Thruster Placement at Corner of Side Panel

The other five thrusters were placed orthogonal to side panels. Panel 1 has four thrusters on it; the bottom and top thrusters are close to brackets for structural attachment. The integration of the thrusters with the structure involved the design of special brackets. Figure 3.19 shows Panel 1 with all propulsion tubing and thrusters that are attached to it. The panel was modified with notches cut out for the two center thrusters. These notches allow the thrusters to be placed as far out from the center of the panel as possible. This is good for performance, while still being supported by the structure and not interfering with other components.

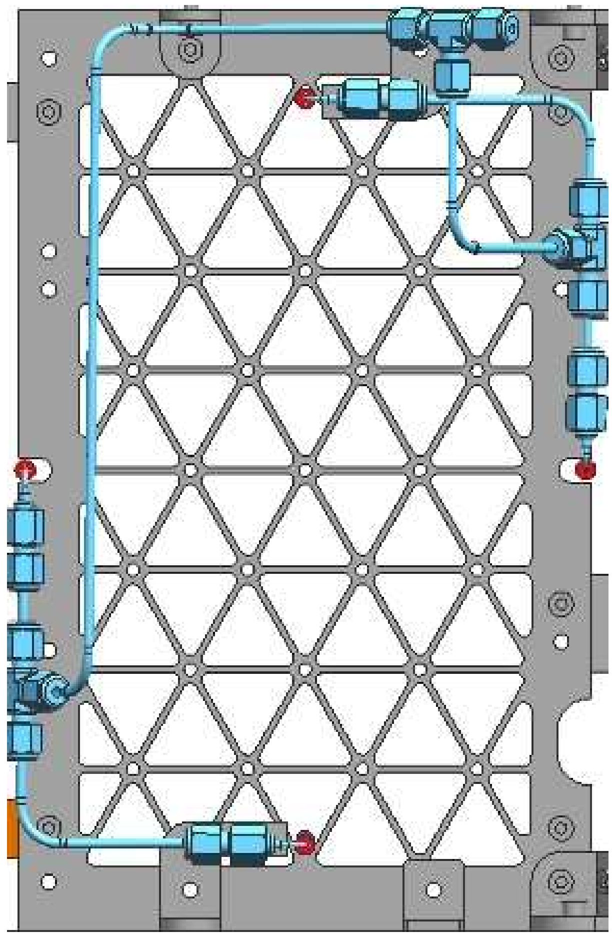


Figure 3.19 MR SAT Panel 1 with Propulsion Components

Figure 3.20 shows a closer view of the special bracket that was designed for the bottom thruster attachment. The Swageloks will be zip-tied and epoxied to the bracket and the valve will be held in place with epoxy.

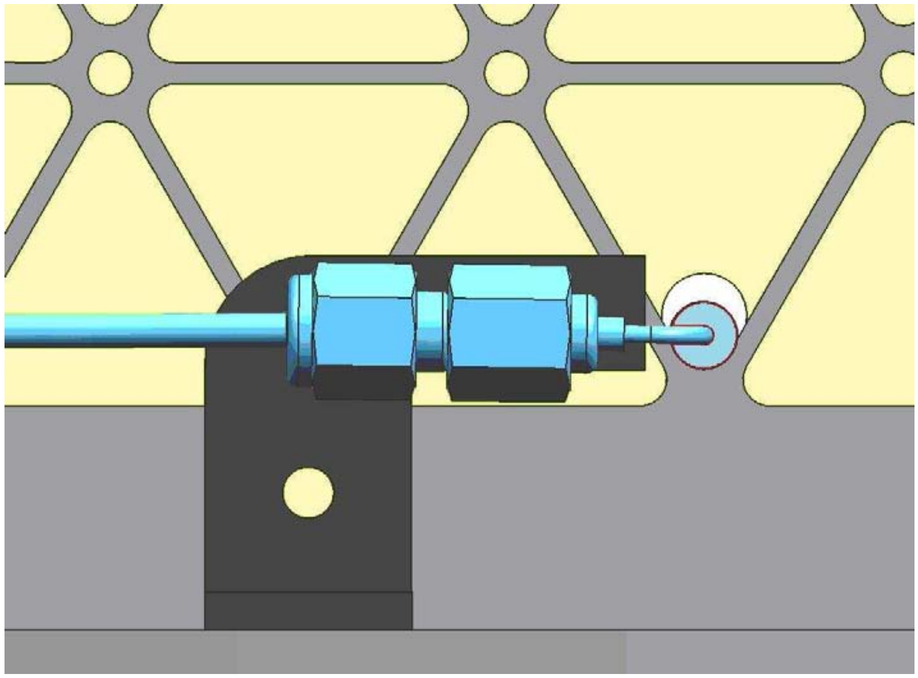


Figure 3.20 Thruster with Special Bracket for Attachment

The ADAC magnetic coils were previously shown in Figure 3.14 and Figure 3.16 in their current configuration. Two of the coils are vertical and one is horizontal, for each satellite. One of the vertical coils is attached directly to a side panel. The other vertical coil is wrapped around the battery box, allowing one machining process for the coil attachment and the box. This is true for both satellites. In MR SAT the third coil is horizontal and attached to the outside of the satellite on the bottom panel. This coil is sized to avoid the Lightband "stay-out zone" as specified by Planetary Systems Corporation. The third coil on MRS SAT is attached inside on the bottom panel, around the Bolt Retractor Mechanism. The ADAC coils meet their requirement for having a component of force in each of the three axes. The coils are shown with their mounting hardware in Figure 3.21.

Figure 3.21 ADAC Coils and Mounting Hardware

The transmitter and magnetometers were purchased from Spacequest and came with aluminum enclosures and attachment points integrated into the component. These attachment points, however, were not aligned with the nodes of the isogrid side panels. In order to attach these components, aluminum adaptor plates were designed. These plates utilized locking helicoils in holes that could not be used with bolts and nuts. The magnetometer's attachment points were through-holes that went through the thickness of the component. The screws needed for this application were 2 inch long # 4, which are not standard fasteners. These adaptor plates with their components are shown in Figure 3.22 and Figure 3.23.

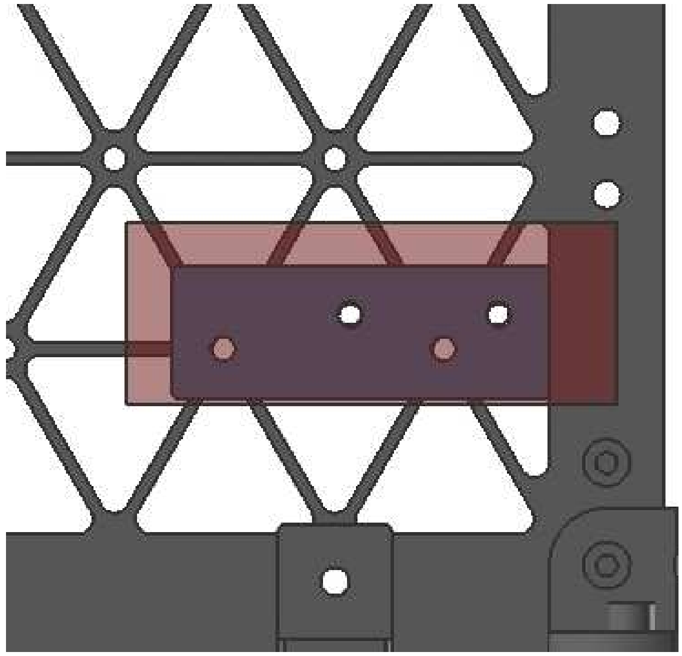


Figure 3.22 Magnetometer and Adaptor Plate on Isogrid Side Panel

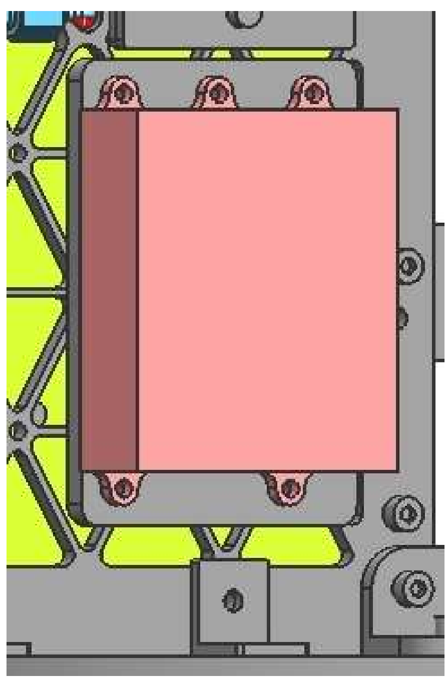


Figure 3.23 Transmitter and Adaptor Plate on Isogrid Side Panel

The QwkNut and Bolt Retractor are located directly on the center line of the satellites. This allows for the deployment of MRS SAT with minimal tip-off. The battery boxes are located on side panels in each satellite. Other component requirements were traded for the location of the battery boxes at the center of the satellites. The boxes were placed opposite other large boxes in the satellites, to reduce center of mass offsets.

The solar cells are attached to the structure with the use of honeycomb aluminum panels and spacers. The honeycomb aluminum is used to support the solar arrays to isolate the solar cells from the structural loading. The attachment of the solar arrays is shown in Figure 3.24 in an exploded assembly view.

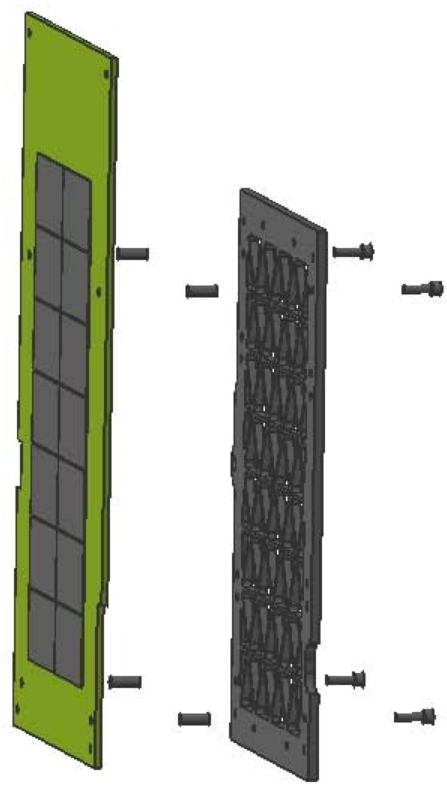


Figure 3.24 MR SAT Honeycomb Aluminum

The GPS antennas are attached on the top solar panel of MRS SAT and on side solar Panel 4 of MR SAT. These are the panels that will be facing away from Earth on orbit, towards the GPS constellation. The receiver and transmitter antennas for MR SAT are both located along the MR SAT side panels and are in view of Earth when on orbit. The Bluetooth antennas for each satellite are on opposite side panels and opposite top and bottom to allow maximum range for the antennas. Figure 3.25 and Figure 3.26 highlight the antenna locations.

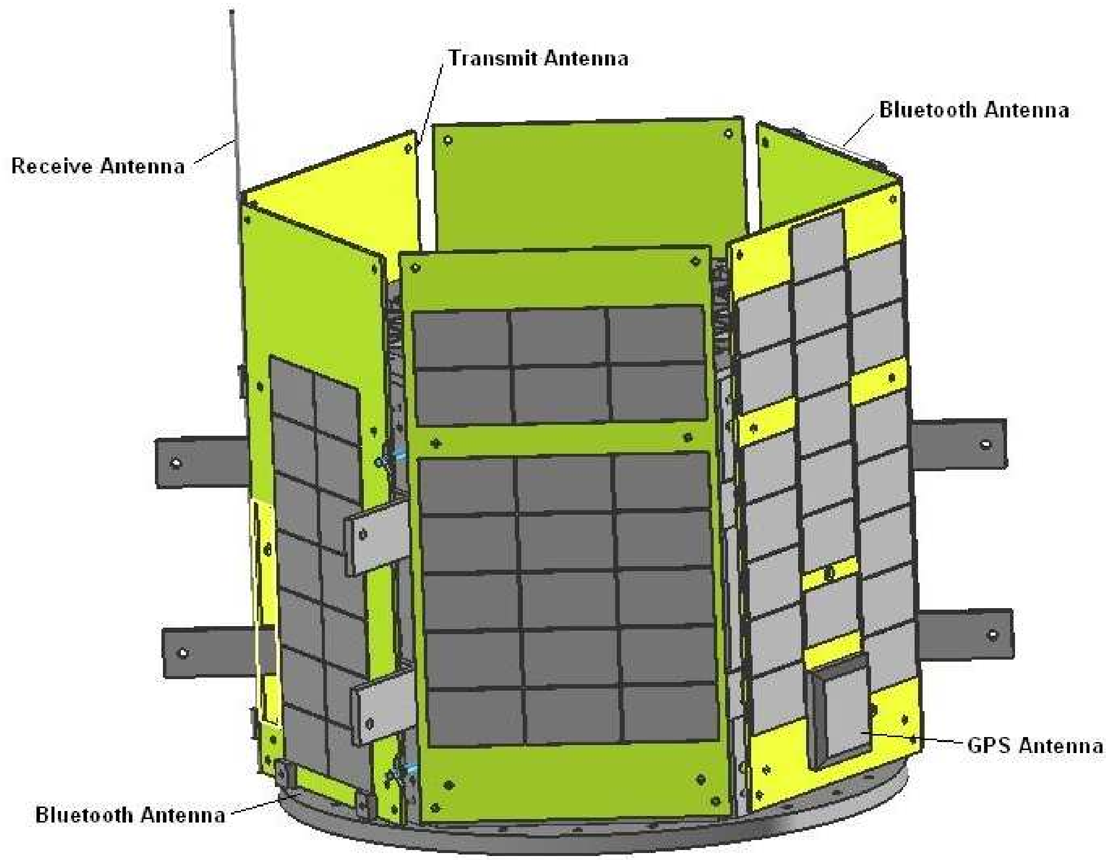


Figure 3.25 MR SAT Antenna Locations

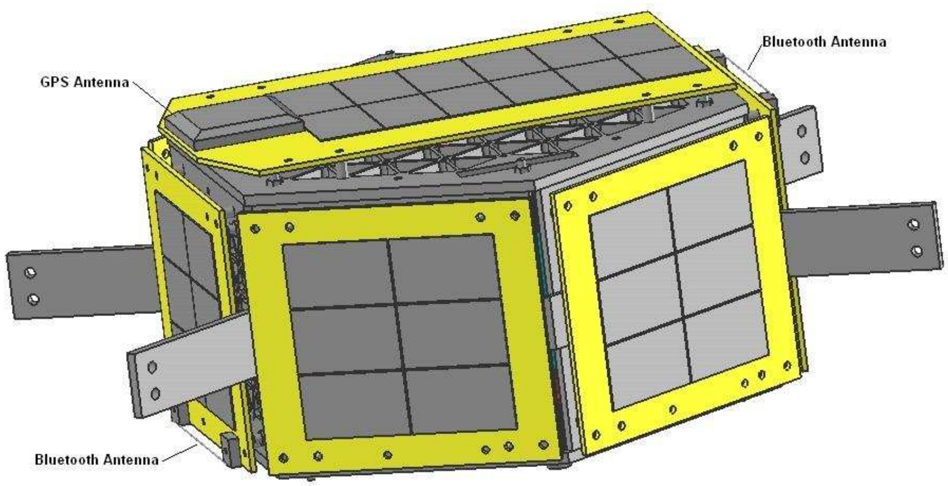


Figure 3.26 MRS SAT Antenna Locations

Components without attachment points, and those sensitive to electromagnetic interference, required aluminum enclosures for containment and attachment. These components were designed and added to the configuration as well. The aluminum enclosures are discussed further in the next section.

4. COMPONENT BOX DESIGN

Several components within the satellites require a Faraday cage to protect them from electromagnetic interference (EMI) and ensure electromagnetic compatibility (EMC). For UMR SAT, this was achieved with the use of aluminum component boxes. Undesirable electromagnetic coupling between the subsystems which are closely packed within the spacecraft envelope is a major concern for an AIT engineer [17]. The individual subsystem engineers were responsible for identifying the components that could cause or be affected by EMI and for ensuring that the Integration lead was aware of the requirements. The aluminum component boxes also serve as a means of attachment of components to the structure. Once all components requiring enclosure or containment had been identified a comprehensive list of requirements was formulated, shown in Table 4-1. Once the requirements were listed, the component boxes and their layout were designed.

Table 4-1 Component Box Budget

Component	Compatibility Notes	Combined in Box with
MR SAT		
GPS receiver	Not compatible with anything electromagnetic	GPS interface board
GPS interface board		GPS receiver
Magnetometer board	Analog signals, so isolate to avoid interference	
Magnetic coils board		Computer boards
Propulsion board		Computer boards
1-wire Interface board		Computer boards
Power board		Computer boards
Arcom Viper board		Computer boards

Table 4-1 Component Box Budget (cont.)

Component	Compatibility Notes	Combined in Box with
MR SAT		
Receiver		Modem, comm power board
Modem		Receiver, comm power board
Comm power board		Modem, receiver
Battery Box	Thermistors and fuse in box	
Bluetooth Transceivers	Analog signals, so isolate to avoid interference	
	Total Boxes	**6**
MRS SAT		
GPS receiver	Not compatible with anything electromagnetic	GPS interface board
GPS interface board		GPS receiver
Magnetometer board	Analog signals, so isolate to avoid interference	
Magnetic coils board		1-wire interface board
1-wire Interface board		Magnetic coils board
Power board		Arcom Viper board
Arcom Viper board		Power board
Battery Box	Thermistors and fuse in box	
Bluetooth Transceivers	Analog signals, so isolate to avoid interference	
	Total Boxes	**6**

4.1. EMI/EMC CONSIDERATIONS

Electromagnetic interference (EMI) is a disturbance in an electrical circuit caused by an external source. Electronics on-board the spacecraft can act as EMI sources. To mitigate the EMI issues, the spacecraft were designed for electromagnetic compatibility

(EMC). The aluminum component boxes designed for the UMR SAT mission were designed to ensure that EMI was not a significant risk to the mission and that the components were compatible when located in the same box.

A number of recommendations made by AFRL regarding box design led to many design requirements. Considerations when designing the component boxes began with requiring each to be made of at least 0.1” (2.54 mm) thick aluminum. The box should be of one piece construction with a lid that included an interference fit at the interface. It also must not contain any holes, except for venting and connectors [24].

4.1.1. One-Piece Construction. One step in ensuring that electromagnetic interference was not going to be an issue was to fabricate the boxes out of one piece of aluminum. Figure 4.1 shows a box bottom CAD drawing. The one piece bottom of the box, along with proper design of the lid and lid interface, ensures that electromagnetic waves can not enter the box and disrupt the components inside.

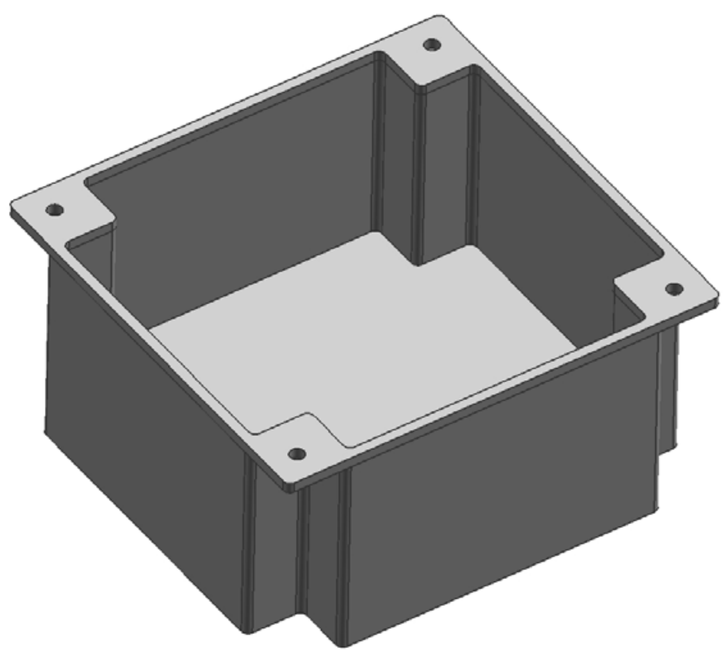


Figure 4.1 One-Piece Box Bottom Design

Other options that would lead to the same benefits as the one piece of aluminum construction were considered. Welding aluminum and bending sheet metal are two possibilities. The University Nanosat Program very strongly suggested that these options were not suitable. Welding of any structural components on the satellites was prohibited and bending of sheet metal was also not encouraged [24]. Another option would be to use several pieces of aluminum and bolt them together. If this option were chosen, each interface would have to be interference fit and include a 90 degree bend. The assembly required with this option versus the one piece option far outweighed the cost of the one-piece manufacturing.

4.1.2. Component Box Lids. The component box lids also had to be designed to ensure EMI was not a concern. The lids were designed with an interference fit and a 90 degree angle between the inside and outside of the box. According to the NASA MEDIC Handbook, seams and joints must maintain a continuous metal-to-metal contact along the seam or joint to ensure shielding integrity [25]. This prevents the electromagnetic waves from entering the box through the gap between the lid and box bottom. In Figure 4.2, the box lid is shown mated and the interference fit is apparent.

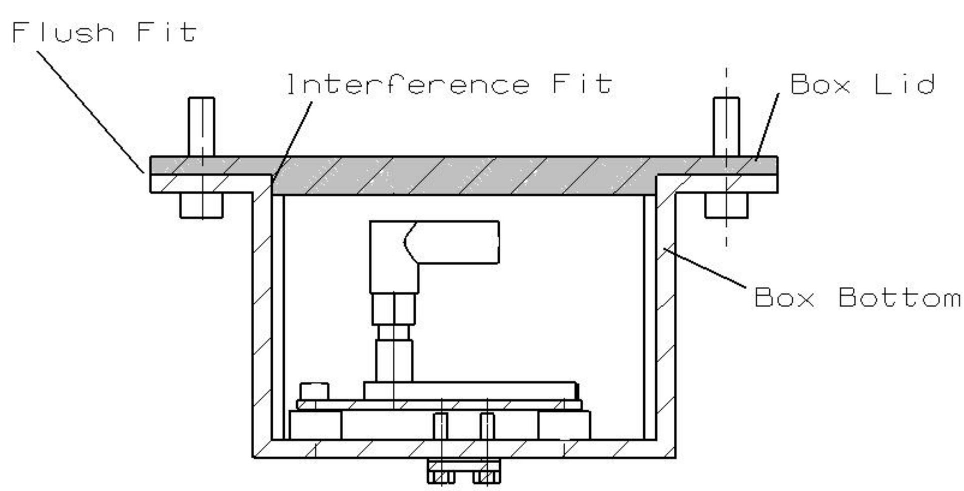


Figure 4.2 Box Lid and Bottom Interface

The lids were designed to be ¼” thick aluminum so the tabs could simply be machined away, leaving an inner thickness of ¼”. The outside tabs had to be machined down to create the 90 degree interface.

4.2. BOX DESIGN

The design of the component boxes was an iterative process. Requirements, size, and shape of many of the components were changing throughout the process, making finalization of box design a long process. The initial table of component requirements was consistently updated and revised to include all new information. In addition to the EMI/EMC considerations discussed above, there were other requirements for the component boxes: They must be able to attach to the structure of the spacecraft, which caused a trade between the size of the isogrid pattern versus the size of the boxes. They must also include attachment points inside to attach the components to them; through-holes were not permitted. The boxes also had to allow for venting during launch depressurization and be designed for ease of manufacture. Once the boxes were designed and the components in each were configured, the components in the boxes had to be wired together. The connector holes were designed on the boxes using the wiring harness diagrams shown in Section 3.

4.2.1. Attachment to Structure. The component boxes were designed to fit to the isogrid pattern on the structure of the satellites. The MR SAT isogrid pattern is different than the MRS SAT isogrid pattern. This, and the fact that each component is a different size, led to the boxes each being unique. It would have been ideal to design the fewest number of different boxes to make machining more streamlined, but the uniqueness of each satellite component did not lend itself to this thought. The satellites had limited usable volume so a one-size-fits-all box could not be designed for use with all components.

The boxes were designed with tabs for the UNP recommended # 8-32 bolts to be inserted for attachment to the structure. The tabs went through several iterations before the final design of each box. It was first thought that the box would include more usable volume if it only had tabs on the corners. Figure 4.3 shows this first box design.

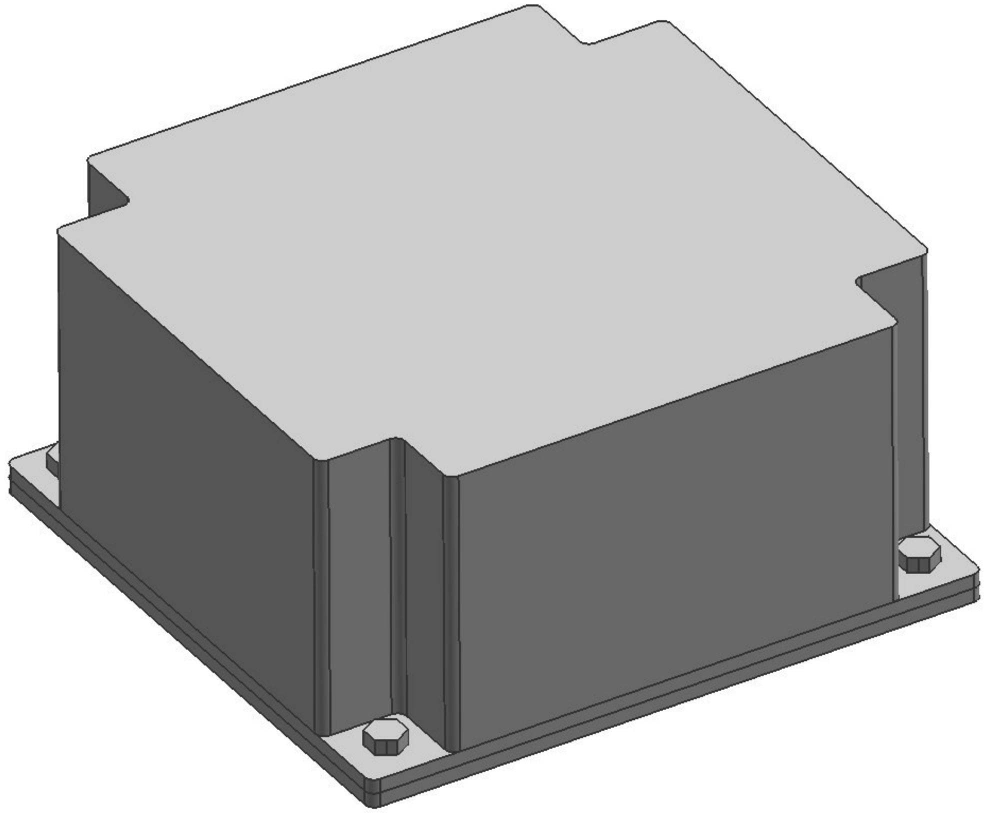


Figure 4.3 Component Box with Four Corner Tabs

The design in Figure 4.3 allowed for maximum volume in the box but it was not necessarily usable volume because the components inside were rectangular in shape. The box design shown in Figure 4.3 would also be difficult to machine out of one piece of aluminum. The tabs were redesigned to be longer and run the length and/or width of the box. Figure 4.4 shows an example of the current box design. The lids were redesigned to fit the box design, making them simpler to machine as well.

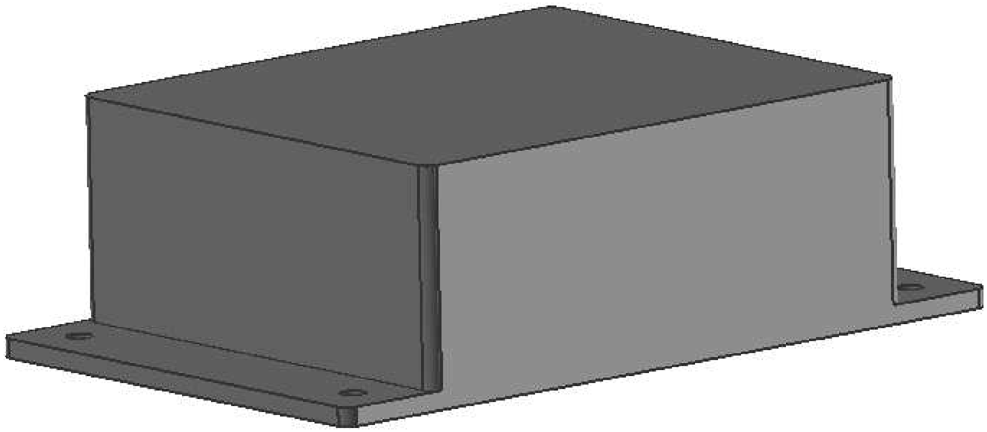


Figure 4.4 Example of Current Box Bottom Design

4.2.2. Attachment of Components in Boxes. The components that required enclosure in the EMI/EMC boxes were mainly printed circuit boards. All of the boards had # 4 holes drilled in them, one on each corner. The onboard computer board, Arcom Viper, came with the holes already drilled in non-uniform locations. The other boards were ordered with the hole placement as designed. The only components that were located in boxes that were not boards were the receiver and the batteries. These were treated differently from the other boxes and are discussed later.

The attachment method used inside the boxes was designed such that no holes would need to be drilled through the boxes. In order to accomplish this, locking helicoils were used to attach the components. The locking mechanism on the helicoils provided the required back-out protection. The helicoil was required to be between one and two diameters in length, so the thickness of the box at the helicoil locations had to be increased.

The first iteration of box internal attachment design included vertical tabs at the top of the boxes where the components would be attached vertically in the box. This design was favored because in boxes with many components, all would be accessible from the top of the box.

The boxes were to be machined using the Computer Numerical Control (CNC) machine on campus. Machine shop personnel helped with the box design process by relaying machine constraints and capabilities. After working with the machine shop personnel, which is discussed further in Section 5, it was discovered that the CNC machine could not cut the holes in the tabs inside the boxes as described above because the holes were drawn from the side of the box and the tool would not fit in the box. It was then decided that the tabs would only work if the components were attached horizontally, so the holes could be drilled from the top. This resulted in islands of material at helicoil locations. Some boxes were not large enough to allow for islands to be used and the helicoils had to be placed closer to the walls. Figure 4.5 and Figure 4.6 show the current box internal attachment methods.

In boxes that included more than one component, the boards were stacked using hexagonal standoffs as spacers between them. This allowed for the same islands to be used for all boards in the box. An example of a box layout with more than one board is shown in Figure 4.7.

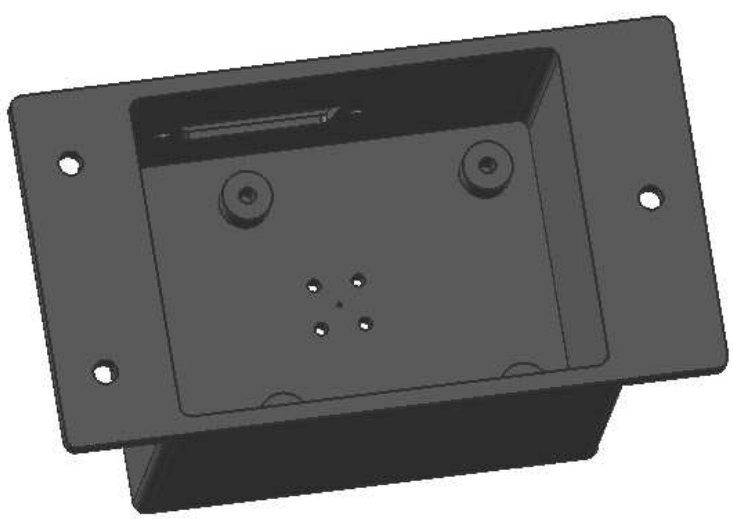


Figure 4.5 Box Bottom with "Island" Attachment Points Inside

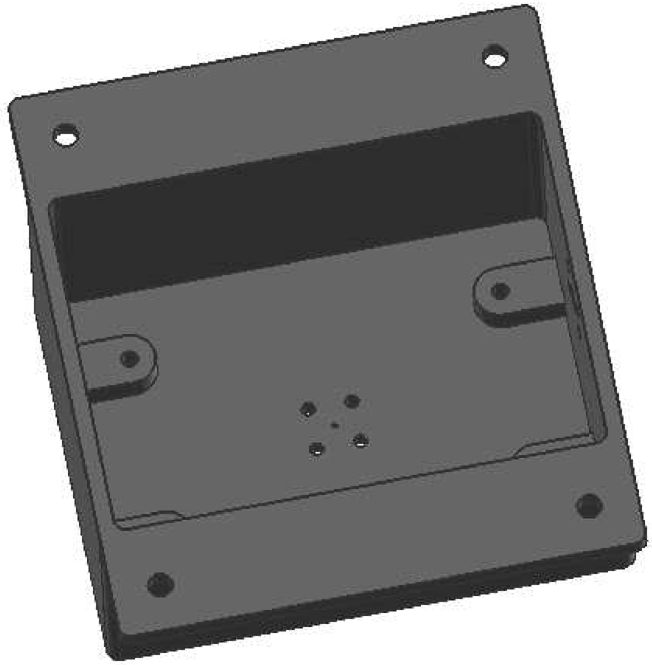


Figure 4.6 Box Bottom with "Peninsula" Attachment Points Inside

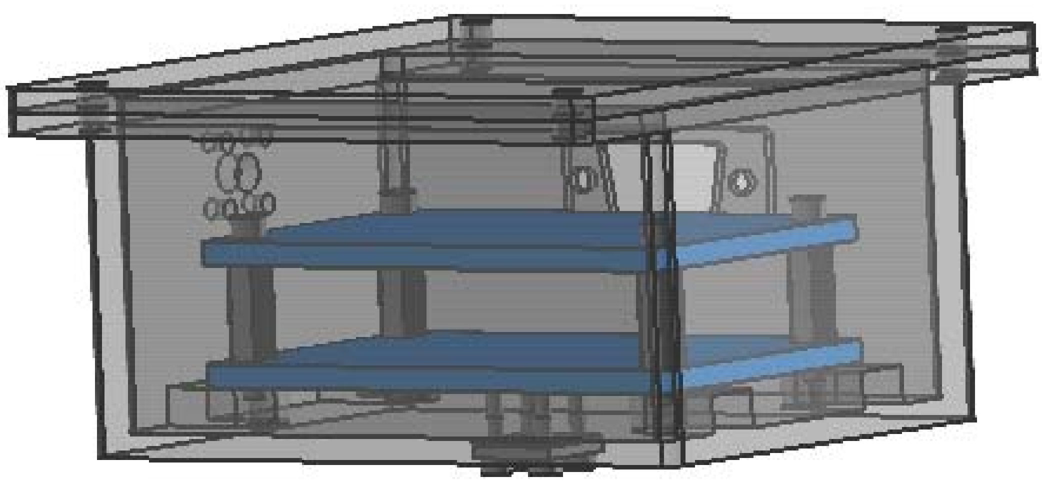


Figure 4.7 Box with Two Boards Mounted Inside

4.2.2.1. MR SAT computer box. The MR SAT computer box was a unique case because it holds five boards, as compared to other boxes which contain one or two. The box houses the Viper board, Power board, Propulsion board, Magnetic Coils board, and the One-Wire Interface board. The Viper board already had its attachment holes drilled in it, which meant that stacking it with another board would require that board to have the same attachment points. All four of the other boards were designed by UMR SAT team members, so their attachment points could be located wherever necessary. The power board was required to be larger than the other three boards based on the components attached to it and was large enough that it could be designed with attachment holes in the same locations as the Viper board. Design challenges involved with this box are discussed in detail in Section 7.

The current design for the inside of the box locates two stacks of boards next to each other. The Viper and power boards are stacked and the other three boards are stacked separately. The two stacks are staggered allowing for connectors to be placed more easily. The final design for the MR SAT computer box, including connector holes, is shown in Figure 4.8.

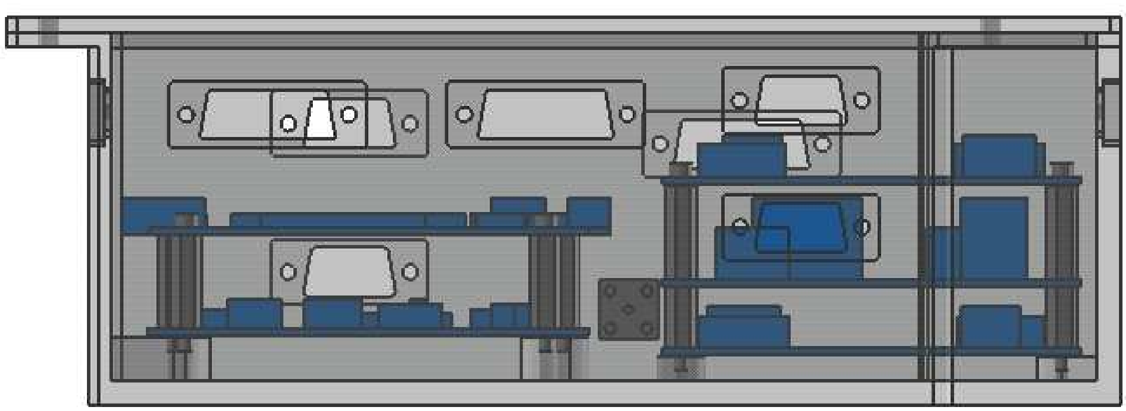


Figure 4.8 MR SAT Computer Box with Current Layout

4.2.2.2. MRS SAT computer boxes. The MRS SAT computer boards were placed into two smaller boxes, each housing two boards; MRS SAT does not have a propulsion board. The boards were stacked horizontally inside each box. The boxes are shown in Figure 4.9 and Figure 4.10.

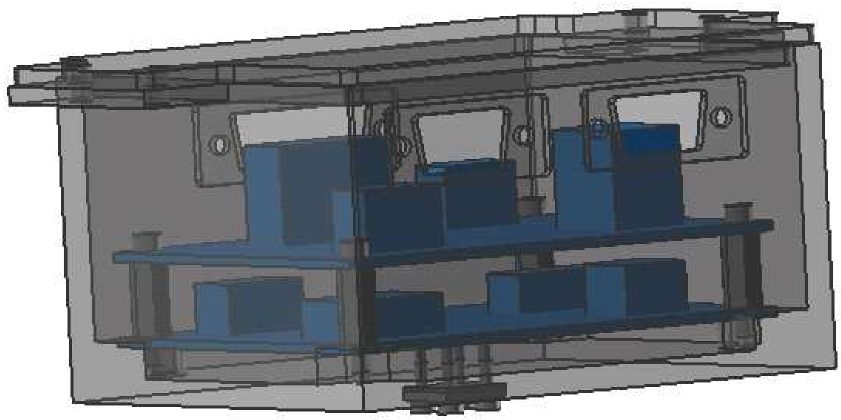


Figure 4.9 MRS SAT Small Computer Box

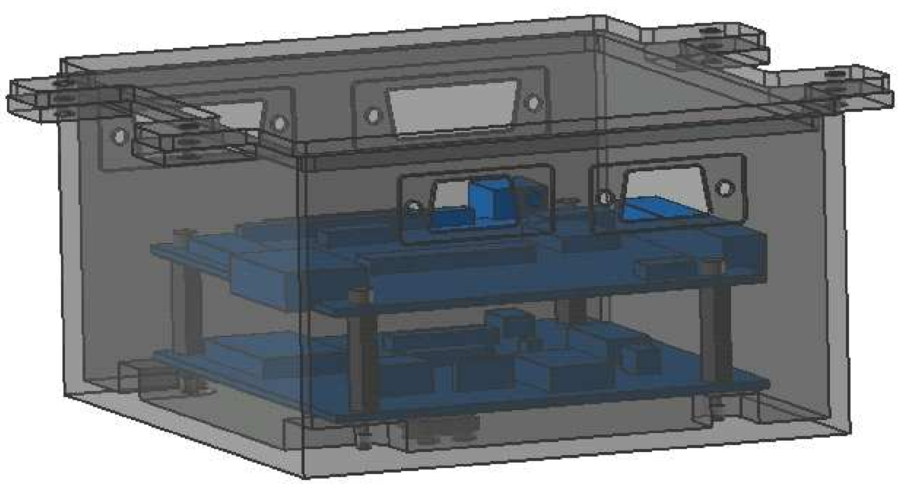


Figure 4.10 MRS SAT Large Computer Box

Both of the MRS SAT computer boxes have modified tabs for attachment to the structure, as seen in the figures, because they are large boxes and interference was encountered with the brackets on MRS SAT.

4.2.2.3. MR and MRS SAT Bluetooth and magnetometer board boxes. The Bluetooth transceiver and magnetometer boards each required their own boxes due to concerns with EMI from the other computer electronics. The magnetometer board converts the analog signal from the magnetometer into a digital signal. The Bluetooth transceivers also required their own box because they send an analog signal to the antenna. Mixing analog and digital signals is not a good design practice because digital signals produce more interference than analog signals and can cause the analog signals to be corrupted. These boards were each attached to the inside of their boxes with locking helicoils. The designs of the Bluetooth boxes are shown in Figure 4.11 and Figure 4.12.

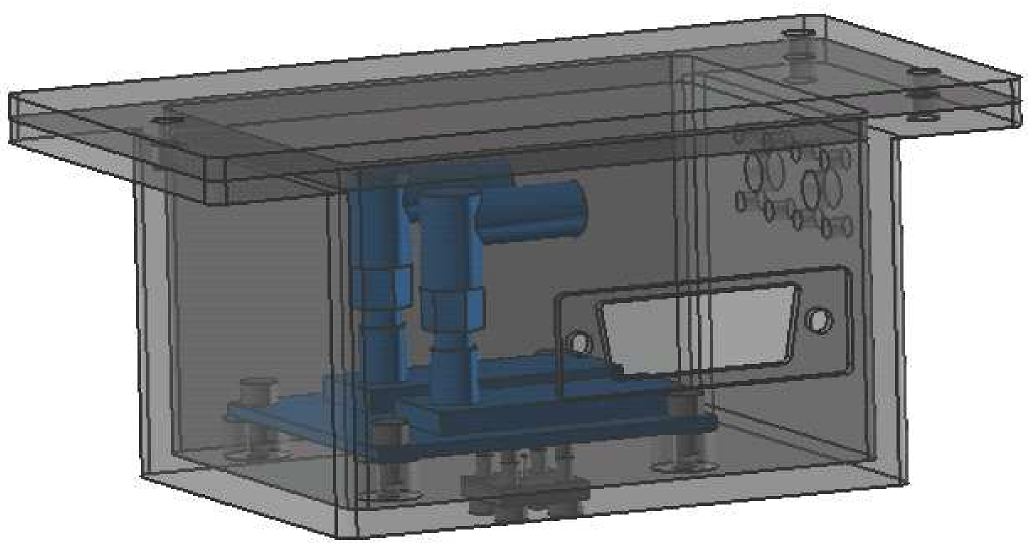


Figure 4.11 MR SAT Bluetooth Box

The main design difference between the MR and MRS SAT Bluetooth boxes are their attachment points to the isogrid for each satellite.

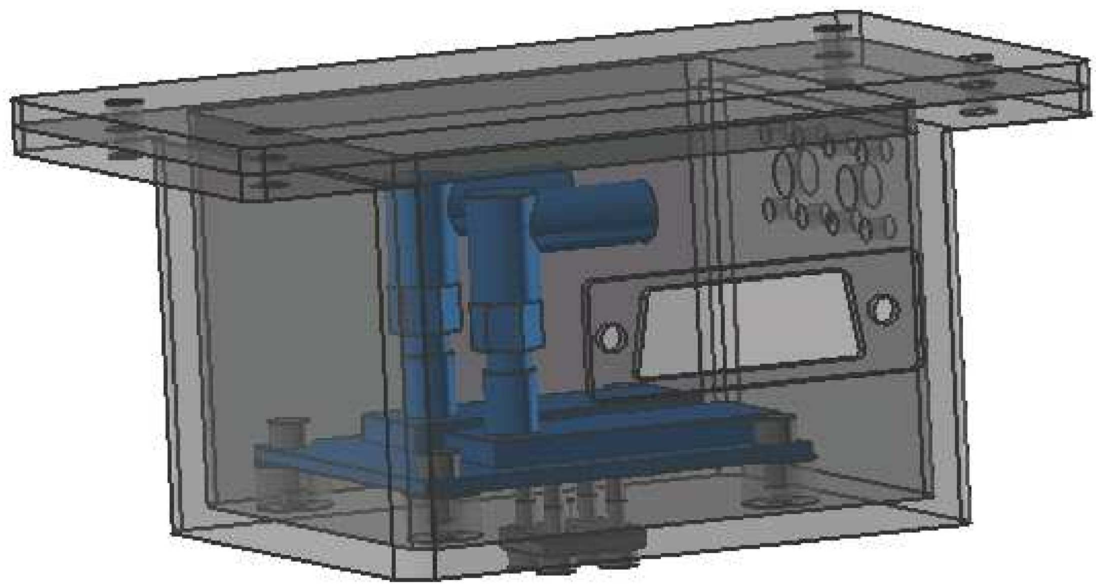


Figure 4.12 MRS SAT Bluetooth Box

The differences between the MR and MRS SAT magnetometer board boxes include the locations of the connector holes and the attachment holes for the isogrid of each satellite. The connector holes were in different locations based on the wiring harness for each satellite. The design of the magnetometer board boxes are shown in Figure 4.13 and Figure 4.14.

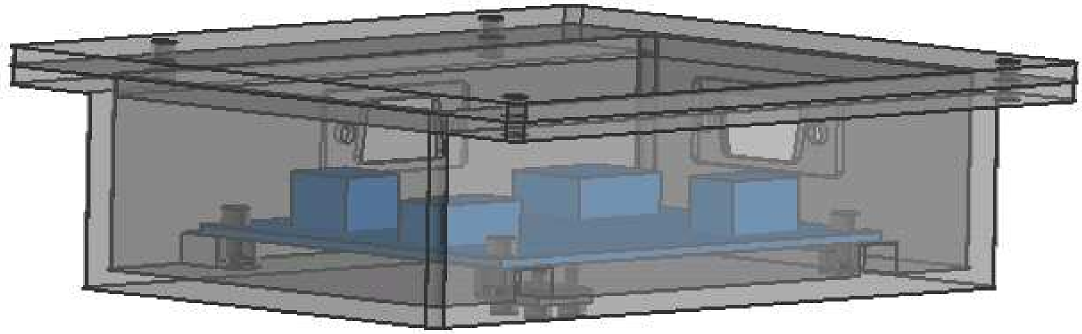


Figure 4.13 MR SAT Magnetometer Board Box

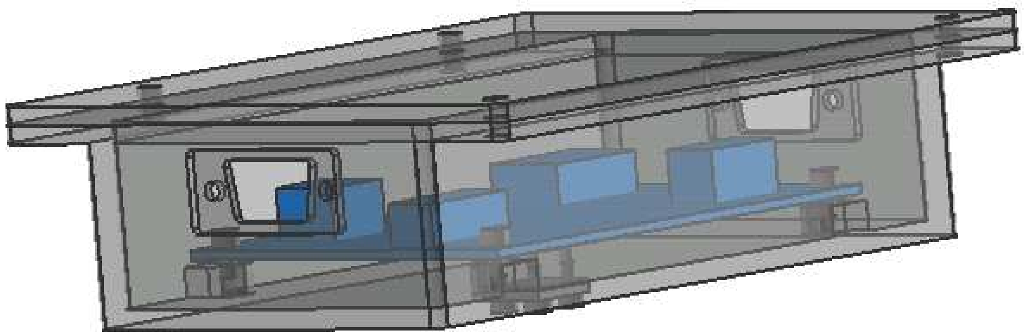


Figure 4.14 MRS SAT Magnetometer Board Box

4.2.2.4. MR and MRS SAT GPS boxes. Each satellite has a GPS receiver and a GPS interface board. These two boards share a box because they are compatible and by sharing a box the wiring between them can be accomplished within the box, thus reducing the number of connectors. They are stacked in the same way as the other boards, using standoffs and locking helicoils. The GPS interface board was designed to be the same size as the GPS receiver which was purchased from Spacequest. By making the boards the same size, the boards could be stacked and mounted easily. The GPS boxes are shown in Figure 4.15 and Figure 4.16.

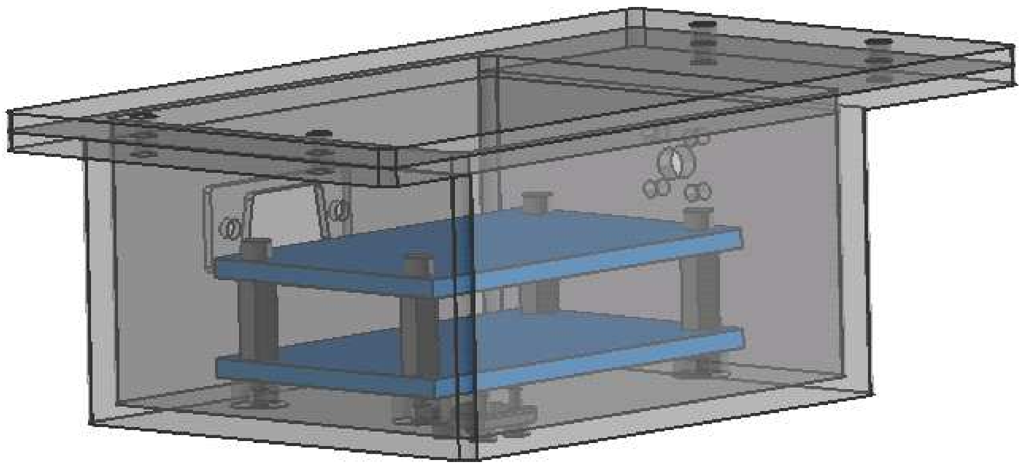


Figure 4.15 MR SAT GPS Box

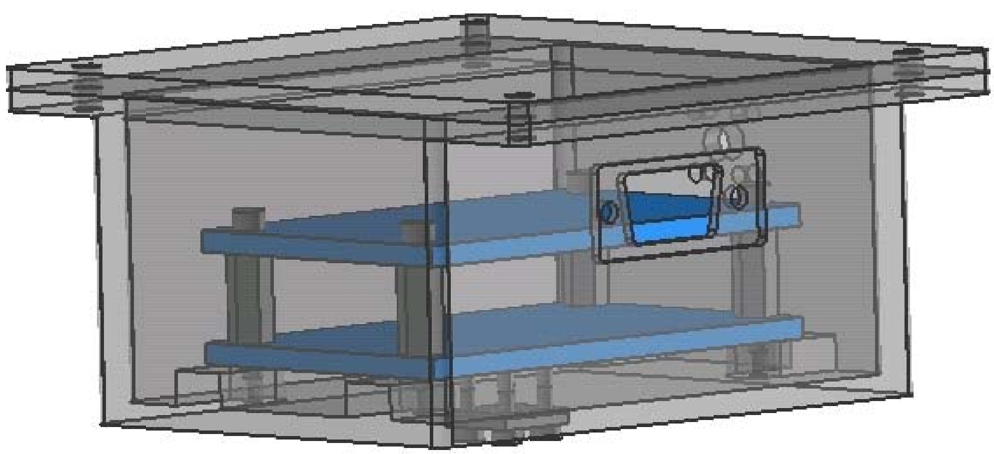


Figure 4.16 MRS SAT GPS Box

4.2.2.5. MR SAT receiver and modem box. The receiver for ground communications, only utilized on MR SAT, was purchased from Spacequest. The receiver is shown in Figure 4.17.

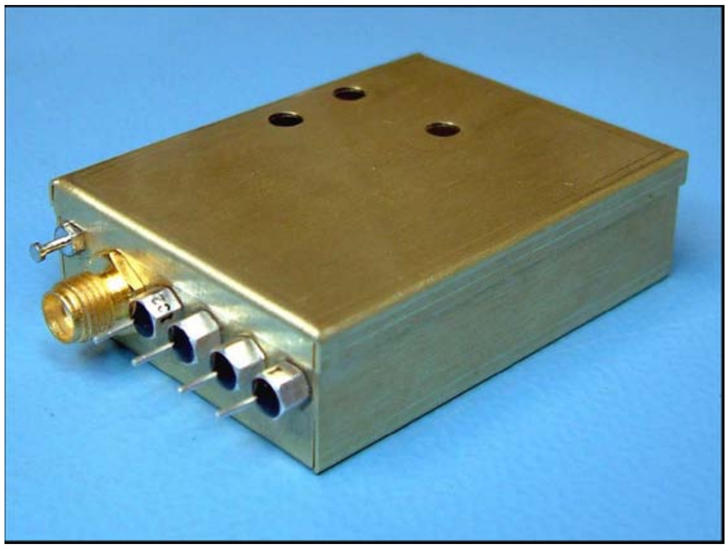


Figure 4.17 MR SAT Receiver

The receiver came with no attachment points for integration with the structure. It came housed in an aluminum case, so did not require a component box. However, since the receiver had no attachment points, it was located in the modem box, which also allowed for simpler wiring with the modem. A slot was designed into the box for the receiver to be attached using structural epoxy. This design, along with the modem and communications power board, is shown in Figure 4.18.

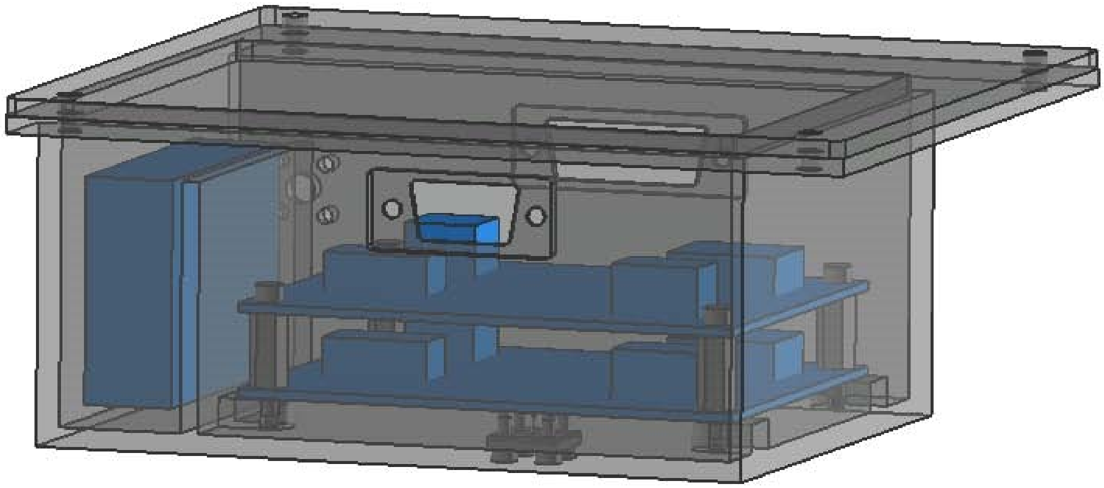
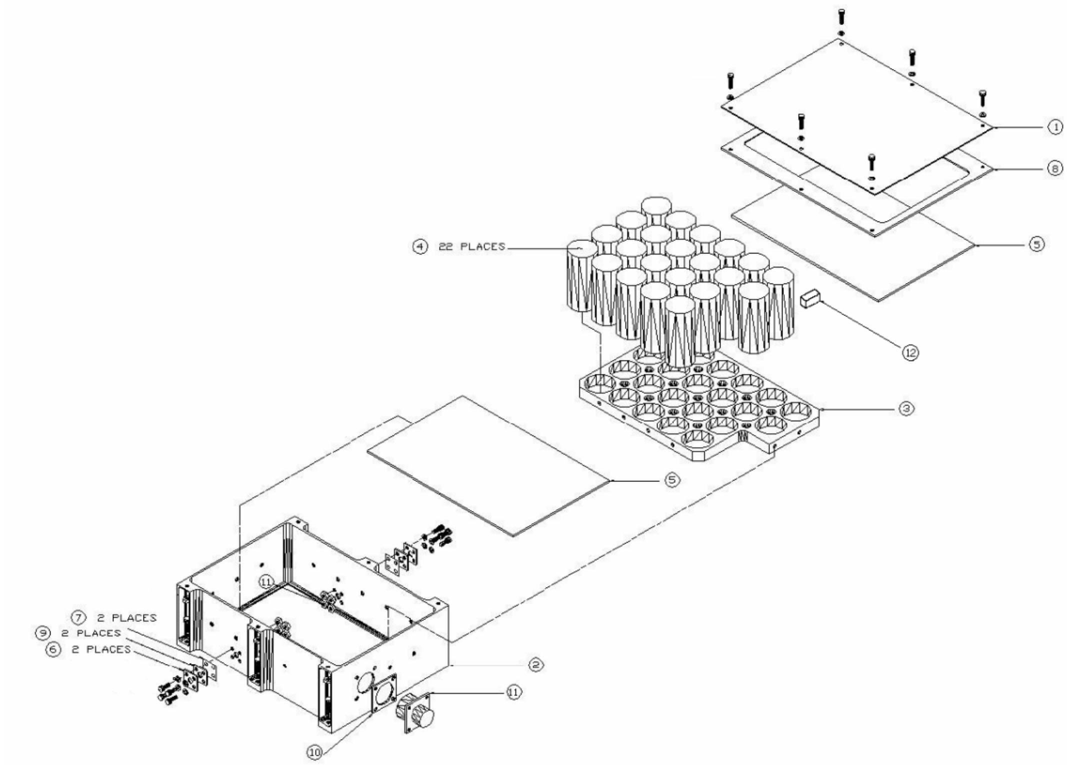


Figure 4.18 MR SAT Receiver and Modem Box

4.2.2.6. MR and MRS SAT battery boxes. The MR and MRS SAT battery box designs were essentially the same. The basic design was given in the Nanosat 4 User's Guide Appendix C, Power System Design Requirements/Guidance. All materials required were given as well as the basic layout.

Figure 4.19 shows the basic design given in the Nanosat 4 User's Guide and the parts list [6]. The design of the UMR SAT battery boxes was completed by the Integration lead and a member of the Power subsystem.

Based on system power budgets, MR SAT required twelve battery cells, while MRS SAT required only five. AFRL recommended that the satellites use Sanyo Nickel-Cadmium (Ni-Cd) N-4000DRL batteries. These batteries are flight proven and safe. The winner of the Nanosat competition received Ni-Cd cells for their satellites.



Item	Description (Representative Material or P/N)	Item	Description
1	Battery Box Lid (Al 6061-T651, etc.), interior coated	7	Vent Hole Mesh (SS 400x400 Mesh, etc.)
2	Battery Box (Al 6061-T651, etc.), interior coated	8	Lid Gasket (Viton MIL-R-83485, etc.)
3	Nonconductive Cell Holder, anodized and/or coated	9	Vent Gasket (Viton MIL-R-83485, etc.)
4	Cells (Sanyo N4000DRL, etc.)	10	Connector Gasket (Viton MIL-R-83485, etc.)
5	Absorbent Material	11	Connector
6	Vent Hole Cover Plate	12	Fuse (axial lead, type ME451-0010, etc., shown in approx. location good for servicing)

Figure 4.19 UNP Battery Box Design and Parts List

An aluminum cell holder was required to isolate the batteries from each other and support them in the box. The cell holder had to be attached in such a way as not to allow electrical conduction between the inside and outside of the box. The holes were fabricated 2 mm wider than the bare cells, to allow room for attachment using thermally conductive epoxy. The cell holders were designed with locking helicoils at several locations to allow them to be attached from outside the box with # 8-32 screws. The thickness was at least four times the diameter of the screws used to hold it in place from the side. The cell holders for MR and MRS SAT are shown in Figure 4.20 and Figure 4.21. There are smaller holes in the cell holders which allow for reduced mass.

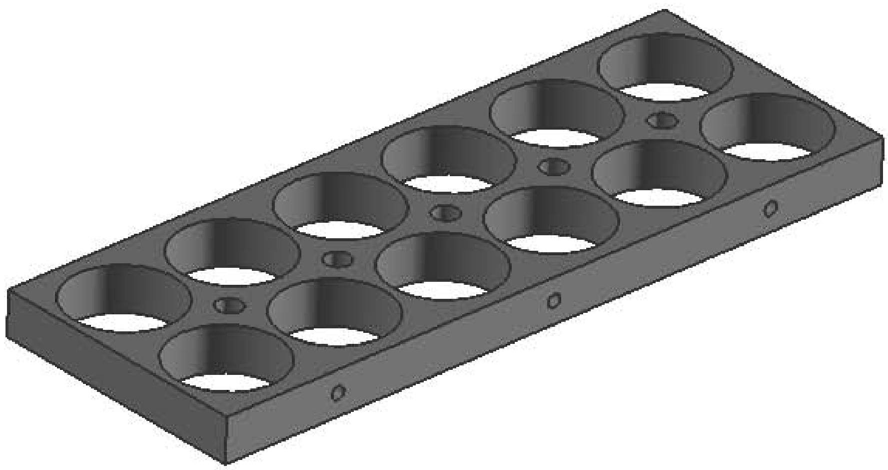


Figure 4.20 MR SAT Battery Cell Holder

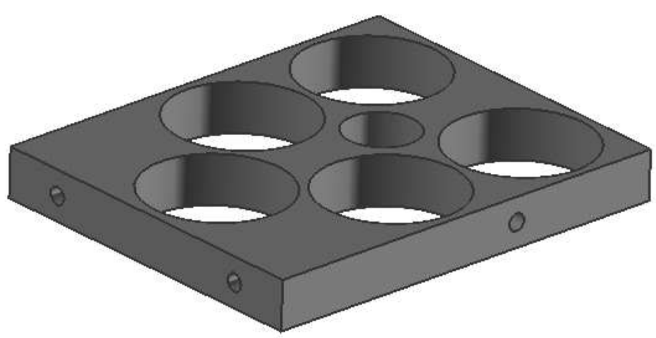


Figure 4.21 MRS SAT Battery Cell Holder

The battery box designs are shown in Figure 4.22 and Figure 4.23. The wiring of the other required components, i.e. the fuse and thermistors with the cells, was designed by the Power and C&DH subsystems. The MR SAT battery box includes eight attachment points to the structure since it is a large, high mass component.

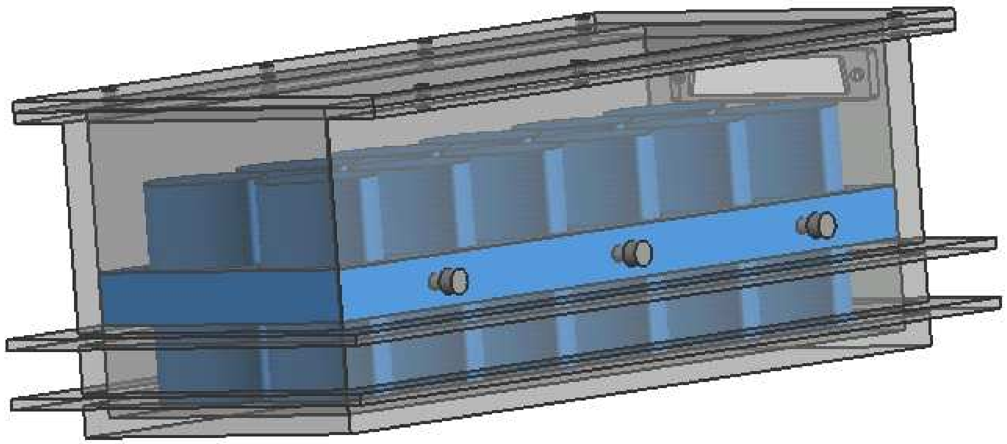


Figure 4.22 MR SAT Battery Box

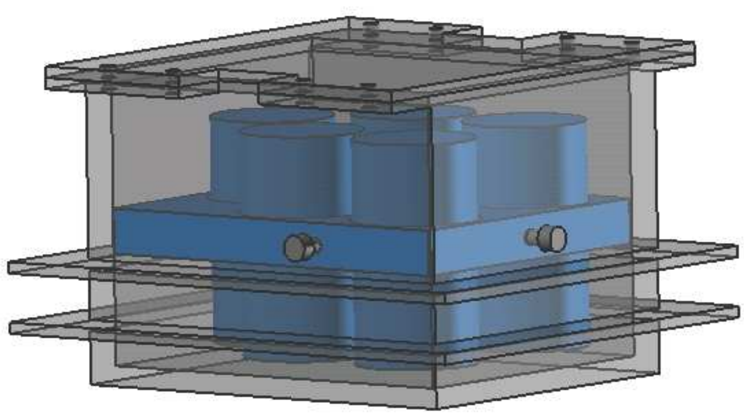


Figure 4.23 MRS SAT Battery Box

4.2.3. Venting. Each of the component boxes was considered a sealed container, so venting requirements were imposed by the University Nanosat Program. Each box required a vent hole large enough to allow for proper depressurization during launch. The vent holes had to be covered with a mesh material, 400 x 400 stainless steel, to maintain the box Faraday cage. The mesh material was held on with an aluminum cover plate and four # 2 bolts. A vent hole is shown in Figure 4.24.

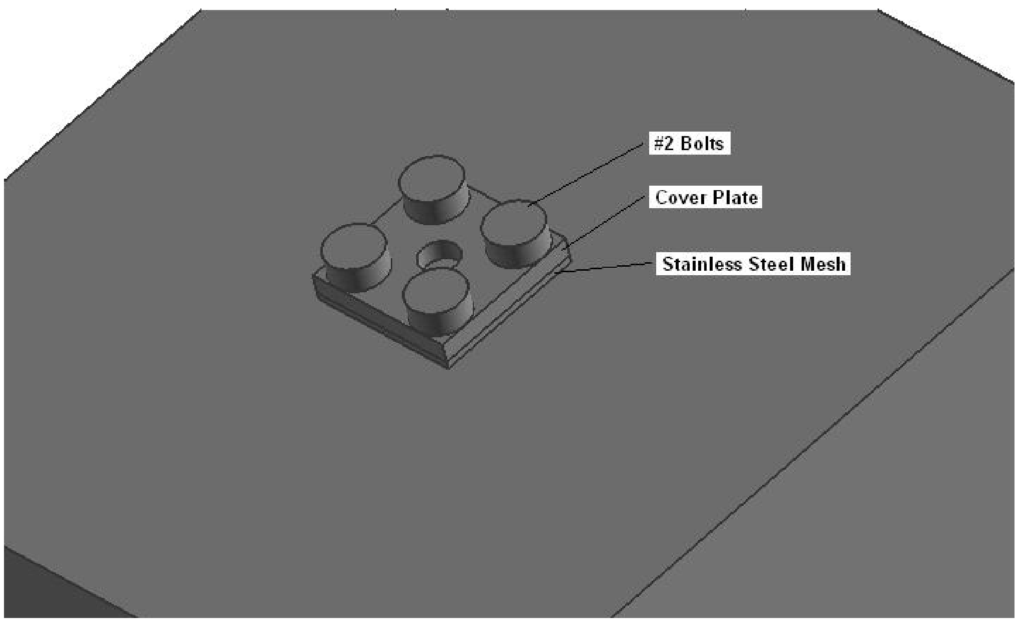


Figure 4.24 Box Vent Hole Components

The size of the vent holes was calculated based on the volume of the box. The model used for this analysis was developed from [26]. The following values were used in the model:

- Depressurization (LV ascent): 0.50 psi/sec, maximum

- Repressurization (Shuttle-specific, descent): 0.30 psi/sec, maximum
- Vent Hole Size: 0.25” (6.35 mm) per 1 ft^3 (2.83×10^7 mm^3)

Using the above model for vent hole sizing, the vent hole sizes in Table 4-2 were calculated for each component box. Due to machinability, a 0.7925 mm hole was used at minimum. The “Vent Hole Diameter Used” column was determined from the actual bit size used in the CNC machining shop. Each recommended hole size was rounded up to the nearest bit size available. Table 4-2 lists the vent hole diameters for all component boxes. The battery boxes required two vent holes each, designed to allow proper venting while preventing electrolyte leakage [6].

Table 4-2 Vent Hole Diameters for Component Boxes

Component Box	Box Volume (mm^3)	Recommended Vent Hole Area (mm^2)	Recommended Vent Hole Diameter (mm)	Vent Hole Diameter Used (mm)
MR SAT Coil Battery Box	1602394.35	1.7921	1.5106	1.5113
MRS SAT Battery Box	709902.00	0.7939	1.0054	1.0160
MR SAT Bluetooth Box	92416.32	0.1034	0.3628	0.7925
MRS SAT Bluetooth Box	82174.40	0.0919	0.3421	0.7925
MR SAT Computer Box	1890189.31	2.1140	1.6406	1.7018
MRS SAT Small Computer Box	230076.00	0.2573	0.5724	0.7925
MRS SAT Viper Computer Box	836242.19	0.9352	1.0912	1.0922
MRS SAT GPS Box	234831.46	0.2626	0.5783	0.7925
MR SAT GPS Box	299656.85	0.3351	0.6532	0.7925
MR SAT Magnetometer Board Box	280770.59	0.3140	0.6323	0.7925
MRS SAT Magnetometer Board Box	243753.75	0.2726	0.5892	0.7925
MR SAT Receiver Modem Box	556903.43	0.6228	0.8905	0.8890

4.2.4. Connector Holes. Once the boxes were designed and the components in each were configured, the boxes, along with all other components, had to be wired together. Using the wiring harness diagrams shown in Section 3, the connector locations were designed on the boxes. The C&DH subsystem determined how many connectors were needed for each box and worked with the Integration lead on where to place each connector on the boxes. The internal wiring inside the boxes, as well as the external wiring required, was considered in the placement of the connectors.

The connector holes were drawn slightly larger than the physical connectors to allow for mating with the box. The box was machined thinner where the connectors were placed to allow room for the screws to secure the connectors. An example of a DB-9 connector hole is shown in Figure 4.25.

Figure 4.25 DB-9 Connector in Box

Additional connectors were required for the antennas. Each antenna used a unique connector. The Bluetooth antennas each required a connector, so two were placed on each box. The receiver also used a circular connector. Figure 4.26 shows the Bluetooth antenna connector holes.

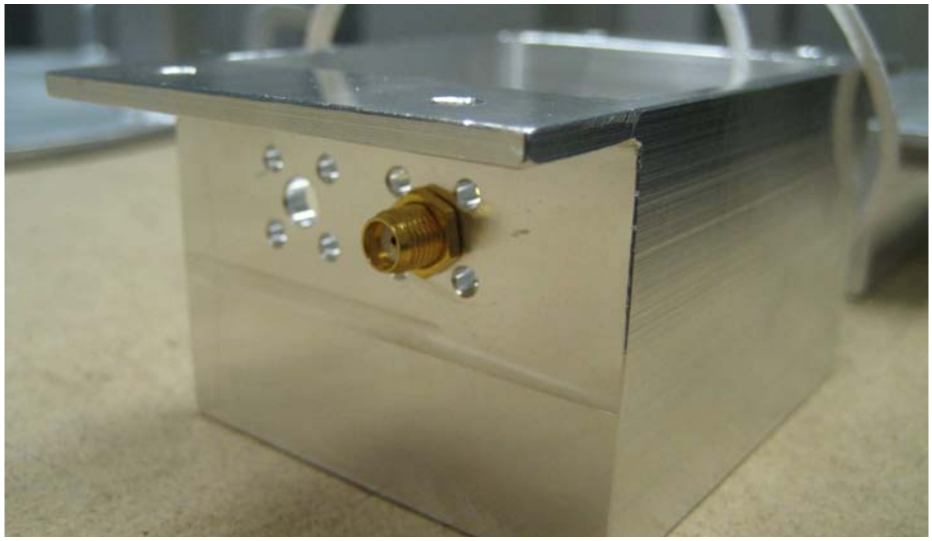


Figure 4.26 Bluetooth Antenna Connector

Some of the challenges encountered while designing the aluminum component boxes included machinability, limitations on manufacturing capabilities, and utilizing available volume. The manufacturing and prototyping of the boxes and other components are discussed in the following section.

5. MANUFACTURING AND PROTOTYPING

The physical manufacture of spacecraft requires proper procedures, facilities, and equipment. The engineering part and assembly drawings must be correct and the parts must be made according to the drawings and specifications. The use of many different machining processes and enabling resources on campus can allow the manufacturing process to run smoothly.

An important step in the manufacture and assembly of a satellite is the prototyping stage. A prototype can divulge a significant amount of important information about the design and can allow for changes to be made early, versus with flight hardware. A prototype also allows for integration of all components to be practiced. This can even include a practice of the wiring harness. The most important pieces of information to be had by building a prototype are fit checks of various components and manufacturing issues.

5.1. MANUFACTURING

The manufacture of a satellite requires detailed engineering drawings, capable machinists, and a quality assurance plan. Manufacturing a satellite takes months of preparation and many more months of labor. There are a few important steps in assuring that each component will be manufactured correctly. The first is to make sure that it is drawn correctly; the next is to make sure that the machinist understands the drawing, and the last is to make sure that the part that was made matches the part that was drawn.

5.1.1. Drawings. Each component of UMR SAT was drawn using the 3D modeling software UniGraphics NX 3.0. Each part that was manufactured, not purchased, was drafted in the built-in drafting software. The details of the drawing were very important. Each drawing included important information about how that part was manufactured. The drawings were all made on a template which was created to serve the purpose of ensuring that all information was included. There were two major types of drawings, part drawings and assembly drawings. Both types will be discussed here.

5.1.1.1. Part drawings. A part drawing was a drawing in which a single item was depicted and detailed information on how to manufacture that part was included. An example of a part drawing is shown in Figure 5.1.

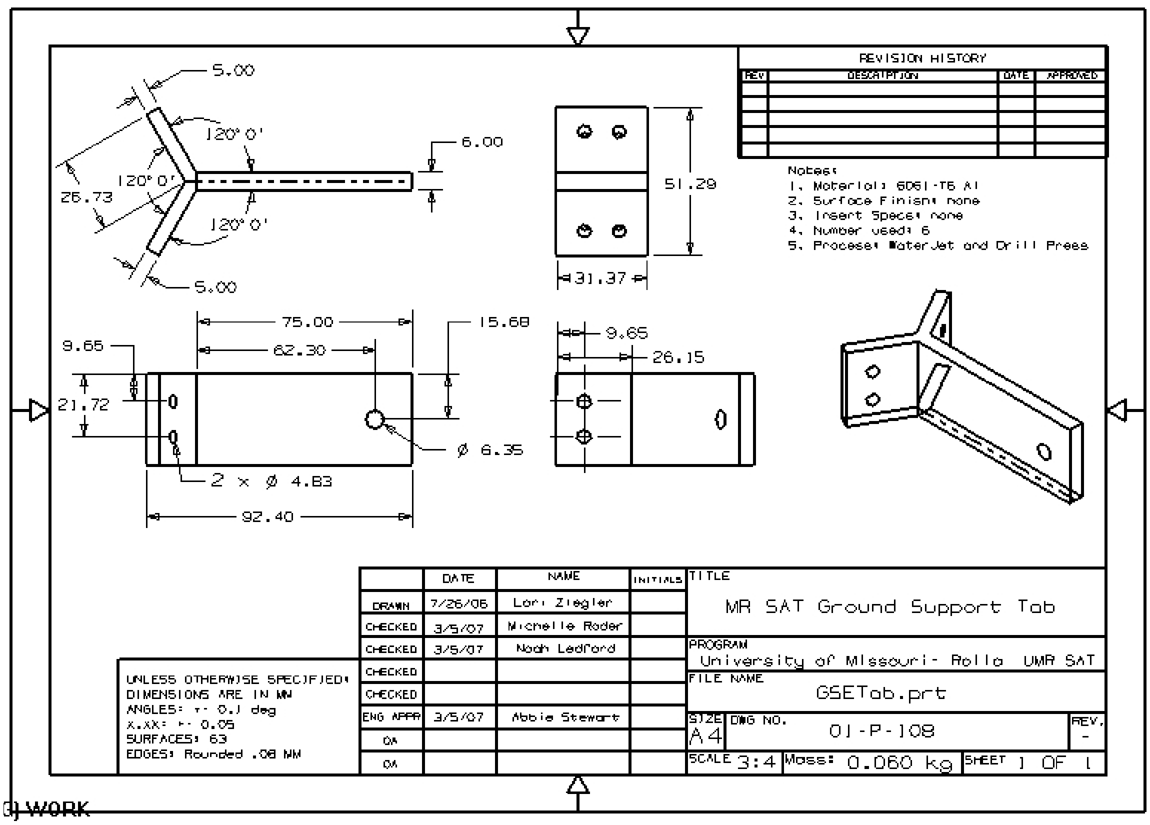


Figure 5.1 Part Drawing of GSE Tab

Some important information that was included on every part drawing was as follows:

- the person who drew it

- the date it was drawn
- any revisions that have been made and the date of revision
- the part number
- part description
- size of paper it was drafted on
- scale
- how many sheets were included
- what units were used
- who reviewed the drawing and the date of review
- engineering approval and the date
- tolerances
- surface finish
- any other manufacturing processes that need to be completed
- insert specifications, if required

5.1.1.2. Assembly drawings. Assembly drawings were drawings in which an assembly of some parts or subsystems was depicted. These drawings did not include detailed information about how the parts were made. The assembly drawings included:

- the person who drew it
- the date it was drawn
- any revisions that have been made and the date of revision
- assembly title and description
- size of paper
- scale
- how many sheets were included
- who reviewed the drawing and the date of review
- engineering approval and the date
- parts list
- any assembly instructions

Each part in the assembly should be listed in the parts list and also pointed out on the drawing. An example of an assembly drawing is shown in Figure 5.2.

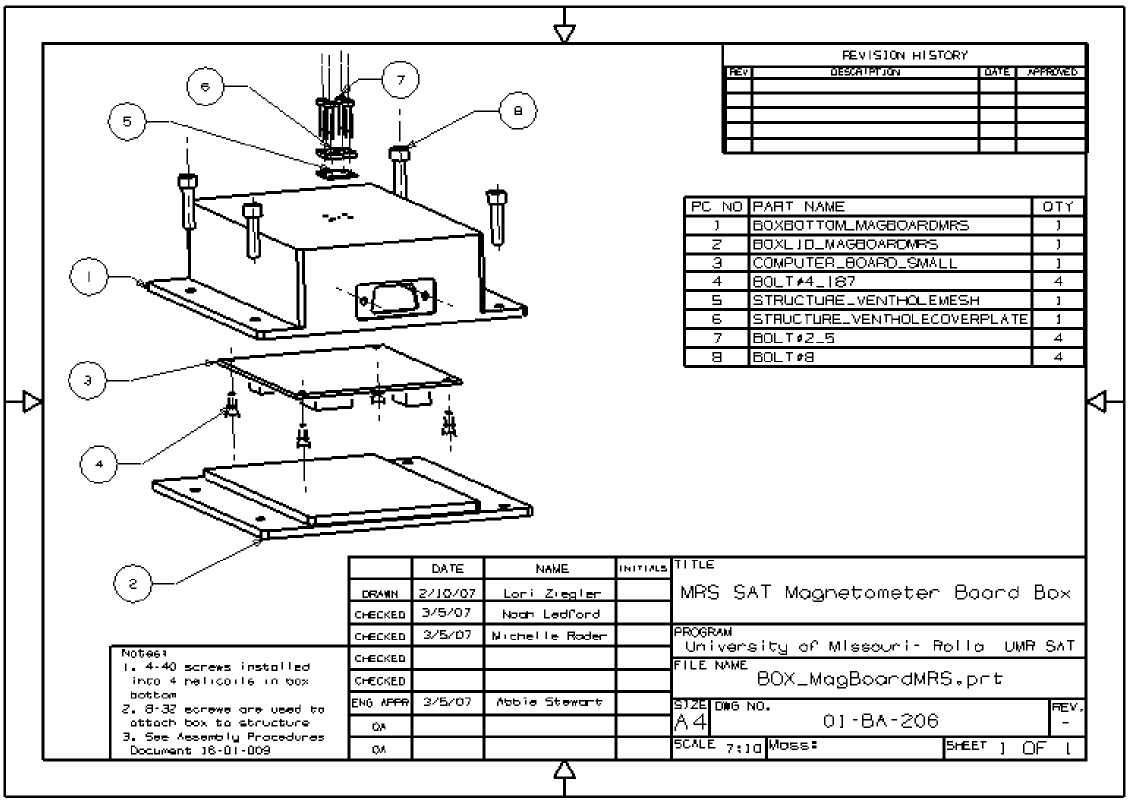


Figure 5.2 Assembly Drawing of the MR SAT Magnetometer Board Box

5.1.2. Machinist Interfacing. Once the parts were drawn and dimensioned appropriately, the next step was to hand the drawings over to a machinist. The UMR Mechanical and Aerospace Engineering Department has a machine shop with three full-time machinists. They were the best resource for drawing specifications as well as the physical machining of the parts. In order to get parts machined in the shop, a work order must be filled out and turned in. The work order must be accompanied by engineering drawings. The best way to proceed with this process was to first go to the machinist with the drawings and ask if there were any problems with them. If a work order was filled out without checking the drawings first, the part may be machined to the wrong specifications. The machinists at UMR were very helpful in making sure that all of the specifications in the engineering drawings were understood. The drawing should stand alone to describe what was to be done in the machine shop. The machinists were also able to attest to the machinability of the part.

On the UMR SAT project, the parts were drawn and detailed to specifications as appropriate. Upon taking the drawings to the shop, a machinist was able to tell by looking at the drawings that the Computer Numerical Control (CNC) machine would not be able to manufacture the part as specified. This step made it possible for the design to be changed before the drawings were submitted for manufacture.

Interfacing with the machine shop saved valuable time throughout the project. The machinists were experts in their field and were able to help make drawings such that there would not be any issues with quality assurance.

5.1.3. Quality Assurance. After each part was manufactured, it was checked for quality assurance (QA). This could be completed by any engineer who was involved with the part. The purpose of QA was to ensure that each part matches exactly to its drawing. The QA process can be streamlined to ensure that every part was checked in a timely manner and for all types of errors. For the UMR SAT project, a document was created to be filled out after each part was manufactured. The document is included in Appendix B for reference. The document required that the engineer checked that all drawing specifications were correct and that the drawing dimensions match the actual measurements.

To streamline the process even more, the QA process could be completed at the same time as the post-processing of the parts. During the FCR build for UMR SAT, the engineers who were assigned to QA for the flight parts were also assigned to the filing and overall post-processing of the parts. All edges were required to be broken so as not to have any sharp edges or corners on any spacecraft part. In order for quicker turn around on the machined parts, the filing of all edges was done by UMR SAT team members.

5.2. PROTOTYPING

Imperative to the success of a spacecraft design was the creation of a prototype, or engineering design unit. The prototype should be identical in form to the flight spacecraft, thus allowing for fit checks to be performed. The prototype did not need to function as the flight satellite would; the creation of a Flat Sat, discussed later, serves this purpose. The UMR SAT prototype was created 9-12 months before the flight competition review.

5.2.1. Structure. The prototype structure was made from aluminum that had been Waterjet cut to create the isogrid pattern. Figure 5.3 shows the Waterjet machine cutting ¼” aluminum for UMR SAT parts.

Figure 5.3 OMAX Waterjet Cutting MR SAT Top Panel

The Waterjet machine is on the UMR campus and was available for use on request, with the aid of a machinist. The flight structure was manufactured in an identical process, making the prototype good practice for the flight build. Waterjet is a procedure that uses water at 40,000-55,000 psi mixed with an abrasive to cut materials [27]. The machine on the UMR campus can cut through over 1.5 inch thick aluminum.

The drawings were first converted so the Waterjet machine software could read them. The machinist, with the help of a UMR SAT team member, created tool paths for the cutter and ensured that all paths were on the outside of the drawing lines. The machine drawings were then reviewed by the UMR SAT engineer and the Waterjet machine was started. The cost of using Waterjet was relatively cheap for intricate patterns that would take a traditional machinist many hours to make. The cost was simply that of the Waterjet machinist's time and of the abrasive used.

The resulting prototype structure is shown in Figure 5.4. All panels were made with the Waterjet procedure.

Figure 5.4 MR SAT and MRS SAT Prototype Structure

5.2.2. Components. Some of the complicated satellite components were fabricated by a Stratasys Prodigy rapid prototype machine on campus. This machine creates prototypes out of ABS plastic using a fused deposition modeling (FDM) process. The drawings must first be converted into stereolithography (STL) format and then the Prodigy software converts the models from STL to a format compatible with the machine, then an authorized user can start the machine. Some of the parts that were made with this machine were the QwkNut, the propulsion tank, and other propulsion components. Figure 5.5 shows the propulsion tank made with the rapid prototype machine. The tank model was too large for the rapid prototype machine so it was made in two pieces and glued together.

Figure 5.5 Rapid Prototype Propulsion Tank

The boxes and other components of the spacecraft were made out of foam board. This was a very inexpensive way to do fit checks of components quickly. The components were all made in a couple days to millimeter accuracy with the foam board.

The components were then taped to the structure in their designed locations. Figure 5.6 shows the components in the satellite structure.

Figure 5.6 Prototype Including Components

5.2.3. Integration Exercises. Beyond doing fit checks of components to verify the 3D CAD models, prototypes also facilitated practice integration. This includes the wiring harnesses. The MR SAT prototype was used to test the wiring harness diagrams that had been drawn. Wiring is a very important, and often overlooked, component of the spacecraft. Wiring also takes up a lot of space that may not have been planned for. The MR SAT structure was laid out in a flower orientation, to simulate the flight integration of the wiring harness. Then each of the wires that would be run in the flight spacecraft was simulated on the prototype with a piece of wire taped from one component (foam board part) to the other. This exercise brought to light just how many wires would need to be run in the satellites and just how little room there was to run them. It also helped to show how many connectors each box would need and where on the box to locate them. Figure 5.7 shows the wiring exercise being performed on the MR SAT prototype.

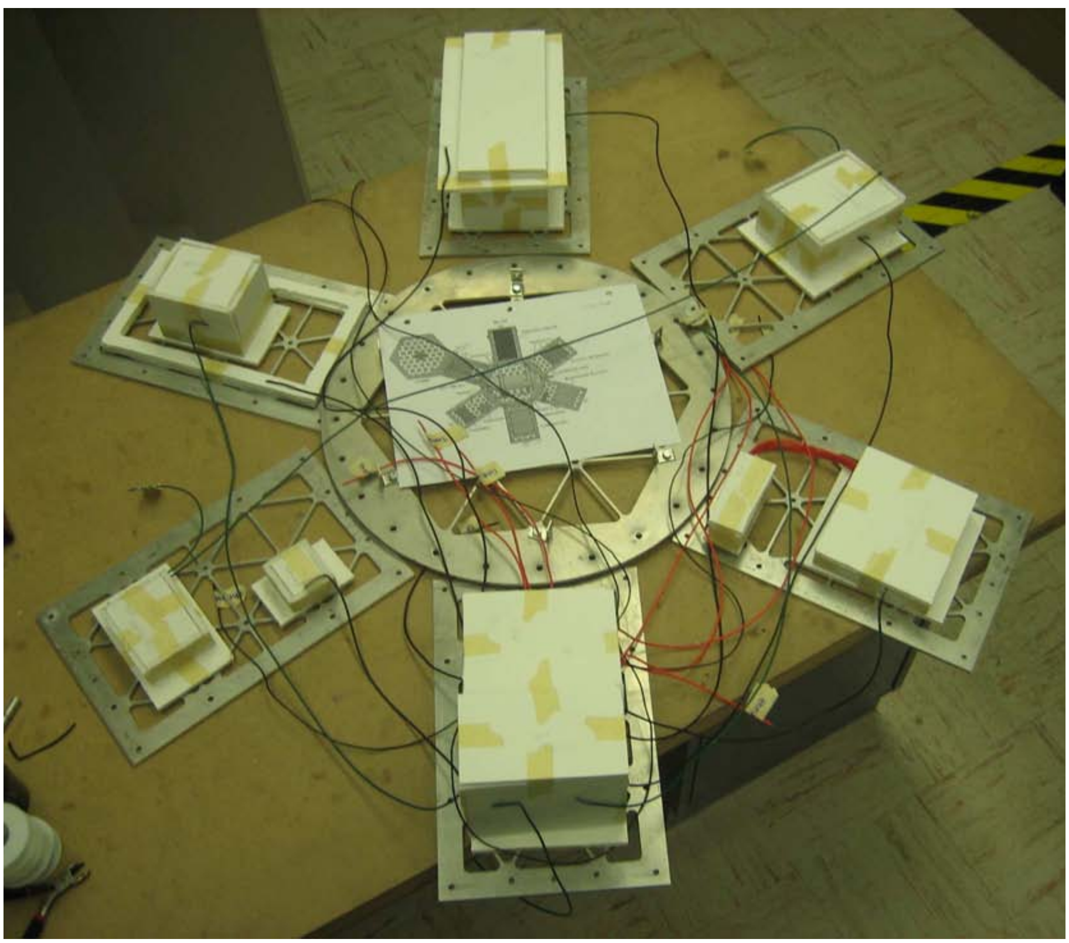


Figure 5.7 MR SAT Prototype Integration Practice with Wiring

The integration exercises also make it possible to see the difficulties that could arise during assembly. An exercise in assembly was performed with the structure with all of its components taped to the side panels. This brought to light some of the clearance issues for the components themselves, as well as for the required tools. All bolts need to be torqued with a torque wrench, so all bolt heads and nuts must be accessible. The isogrid design aids in some cases, but does not allow enough clearance in many others. This was a misconception with the CAD design. It looked as if there would be plenty of room to use tools through the isogrid, but these issues could not be discovered until a physical model was assembled.

5.2.4. Flat Sat. A Flat Sat is a functional prototype of a flight spacecraft, laid out flat on a table to facilitate testing and debugging. A diagram, created by the UMR SAT C&DH Subsystem Lead, of the components involved and connections required can be seen in Figure 5.8.

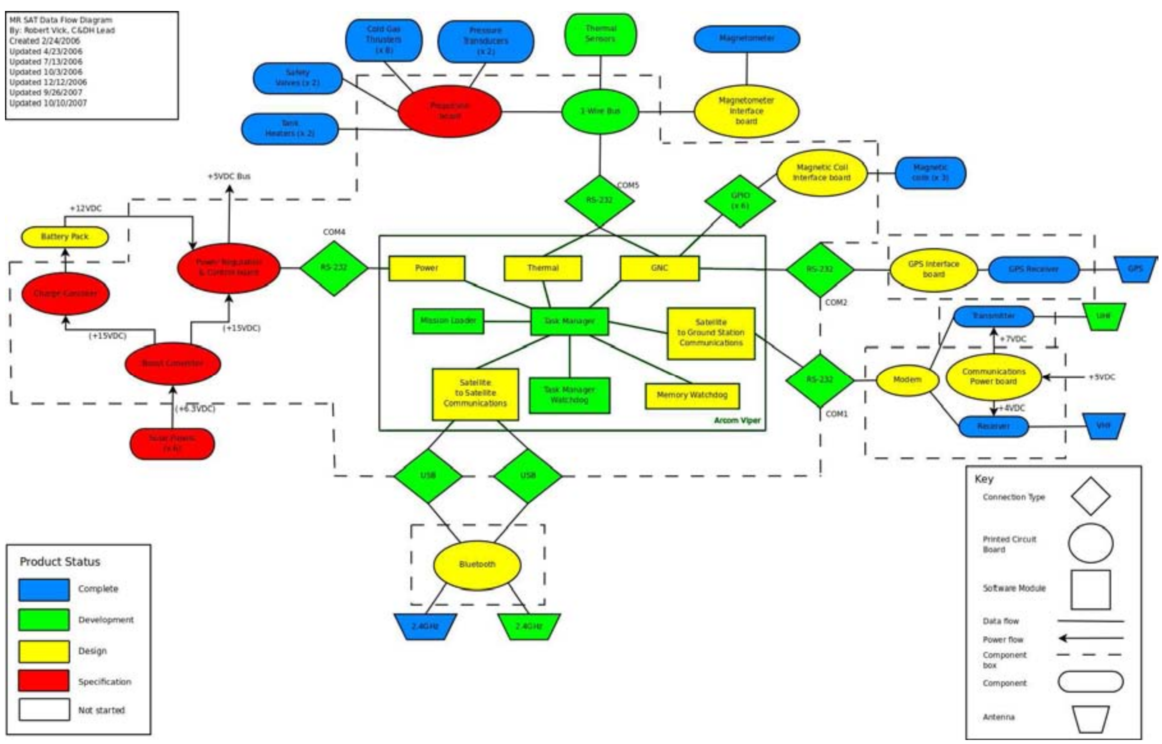


Figure 5.8 UMR SAT Flat Sat Diagram

The Flat Sat does not necessarily include any structural components. The use of a Flat Sat to debug the satellite was a quicker and safer way to find issues with flight hardware. The Flat Sat could be used to test software for functionality without risking flight hardware. The use of functional engineering models early in the program "can eliminate ninety percent of the electrical interface issues that might arise during flight unit integration" [19]. The Flat Sat does not have to stay in a clean room environment, if it does not contain flight hardware, making testing much more accessible. Engineering unit hardware can be used on Flat Sats, as well as flight hardware, making the use of a Flat Sat cheaper than making an extra flight unit for functional testing. The UMR SAT Flat Sat was under development at the time of this writing.

5.2.5. Lessons Learned from the UMR SAT Prototype. The UMR SAT prototype was first manufactured in March, 2006 in preparation for the Critical Design Review (CDR). The main purposes of the prototype were discussed above, but other design issues were discovered as well.

One of the design/manufacturing issues first seen in the prototyping stage was tolerances. Manufacturing tolerances were very important values and had not been designed into the models. The machine shop personnel at UMR had manufactured the parts to the best tolerances they could while making the parts quickly, without being told in advance what the tolerances were. One of the design changes that came out of the prototype was the angled edges on the side panels were replaced with straight edges and the side panels were shortened width wise. Originally, the side panels were designed with edges angled at 60 degrees so they would fit flush against each other. After building the prototype, however, it was decided that the side panels should not touch each other reducing the likelihood of adverse tolerance build up. Tolerance build up was an issue with many parts of the satellite. The tolerances for each part were designed into the drawings for the flight build and the machine shop personnel were able to help with making sure that there would not be an issue with the mating of parts.

Another design lesson that was learned with the prototype was that the isogrid nodes were too far apart to actually attach many parts to the side panels. At the time the prototype was built, the structure was designed based on having larger isogrid triangles to reduce mass; there was not much thought into component attachment. After looking at the prototype and attaching foam board boxes to it, though, it was realized that there were not many locations for components to be bolted to the structure. The isogrid was then redesigned to accommodate more nodes for component attachment with bolts. This would make the isogrid triangular holes even smaller and the above issue of tool clearances an even larger challenge, but would allow ample attachment points.

After practicing assembly and integration with the prototype structure and components, the UMR SAT team was ready to work on the flight satellites. Lessons learned from manufacturing and prototyping the satellites were used in creating appropriate assembly and integration procedures, discussed in detail in the next section.

6. ASSEMBLY AND INTEGRATION

The assembly of the flight satellite can only be completed once all components have been procured and/or built, but should be planned for from the beginning of the project. The assembly and integration of each component or subsystem must be completed before the spacecraft can be assembled. When building a component, subsystem, or satellite system, detailed steps must be followed. The detail and accuracy of the assembly procedures are imperative to the successful build of a spacecraft. The Integration lead was responsible for writing or gathering all assembly procedures and performing the physical assembly and integration of the satellites. The build of the satellites for FCR was completed in the clean tent prior to the review. The satellites were built with the components that had been procured and/or built at the time. Although not all flight hardware was present, the spacecraft were built as flight units. This allowed the team to practice integration of flight hardware and made it possible for some lessons to be learned before the true flight build.

6.1. ASSEMBLY PROCEDURES

A component, subsystem, or system cannot accurately be assembled without detailed assembly procedures. These procedures were standardized by the Integration lead for the UMR SAT project. The format for the procedure can be seen with an example in Appendix C. All procedures were written using this format, which was given in a sample procedure by AFRL and modified for the UMR SAT program. The format and level of detail was specified in a meeting with all subsystem leads and they were expected to complete their subsystem-level procedures. The Integration lead was responsible for the component box procedures, as well as the system-level procedures.

6.1.1. Assembly Procedure Format. The format of the assembly procedures allowed for inclusion of any needed information in the sections preceding the procedures. The information in the assembly procedures includes sections on each of the following:

- Introduction and scope

- Supporting documents
- General considerations
    - Problem failure reports
    - Safety compliance
    - Hazardous operations listing
    - Quality assurance provisions
- Resource requirements
    - Facilities
    - Materials
    - Equipment
    - Personnel
- Assembly set up
- General list of the assembly steps
- Detailed assembly process, to include pictures of each step where available
- Assembly clean-up

All of these sections are important to the assembly procedure and must be detailed to completeness. Each step of the procedure is to be initialed and dated by the assembly technician and a quality assurance engineer. Therefore, two team members are required to be present during any assembly process.

The assembly procedures must include a level of detail to permit a team member to complete the build with no uncertainty on what to do during each step. The steps should be detailed to include information such as what size bolt to use and what level of torque to apply, and should leave space for the assembly technician to include results.

6.1.2. Assembly Procedure Documents. The assembly procedures were given document numbers based on the UMR SAT documentation format. They all reside within the Integration subsystem's documentation, where all documents start with "16-" because that is the subsystem number. The next two numbers reflect the subsystem responsible for actually writing the procedure. The procedures were written at three levels. Some procedures only cover a single component, others cover a box with several components or an entire subsystem, and finally there are system-level procedures.

The component-level procedures include all of the single component procedures. The C&DH boards, communications boards, solar panels and magnetic coils are all included in these procedures. The list of component-level assembly procedures documents is as follows:

- 16-02-001 Magnetic Coils
- 16-05-001 Printed Circuit Board
- 16-05-002 Conformal Coating
- 16-06-001 Solar Arrays
- 16-07-001 Transmit (VHF) Antenna
- 16-07-002 Receive (UHF) Antenna
- 16-07-003 Bluetooth Antenna
- 16-07-004 RG-142 Coaxial Cable
- 16-07-005 RG-178 Coaxial Cable

Assembly of the component boxes required procedures for attaching the components into the boxes, the internal wiring, connectors, and venting components. The component box procedures include the following:

- 16-01-001 MR SAT Battery Box
- 16-01-002 MRS SAT Battery Box
- 16-01-003 MR SAT Computers Box
- 16-01-004 MRS SAT Large Computers Box
- 16-01-005 MRS SAT Small Computers Box
- 16-01-006 MR SAT GPS Box
- 16-01-007 MRS SAT GPS Box
- 16-01-008 MR SAT Magnetometer Interface Box
- 16-01-009 MRS SAT Magnetometer Interface Box

- 16-01-010 MR SAT Receiver/Modem Box
- 16-01-011 MR SAT Transceiver (Bluetooth) Box
- 16-01-012 MRS SAT Transceiver (Bluetooth) Box

The Propulsion subsystem wrote procedures for sub-assemblies of propulsion hardware. These procedures are as follows:

- 16-04-001 Propulsion Tube Manufacturing
- 16-04-002 Propulsion Heater Attachment
- 16-04-003 Propulsion Core Hardware and Tank
- 16-04-004 Propulsion Panel 1 Subassembly
- 16-04-005 Propulsion Panel 2 Subassembly
- 16-04-006 Propulsion Panels 4 & 6 Subassemblies
- 16-04-007 Propulsion Top Panel Subassembly

All of the procedures mentioned above were written to precede the overall MR and MRS SAT assembly procedures. The satellite system-level procedures were written to detail the build process of each satellite in the clean tent with flight hardware. The system level procedures were to be performed only after all above procedures had been performed. The system-level procedures must also take into consideration the small amount of space available in the UMR clean tent.

6.2. FACILITIES AND EQUIPMENT

The flight assembly and integration of MR SAT and MRS SAT takes place in the UMR Space Systems Engineering Lab clean tent, shown in Figure 6.1. The clean tent was rated and tested at Class 100 (100 particles per square foot).

Figure 6.1 UMR Space Systems Engineering Lab Clean Tent

The tent is 6 x 6 ft and includes a changing area, shelves, and an Electrostatic Discharge (ESD) safe table. The changing room allows access to complete clean tent attire. The shelves house the components, fasteners, and any tools needed. The table is just large enough to permit both satellites being assembled simultaneously. This takes proper planning, however. The table also includes a vise that was screwed onto the table for stability. The other important components in the clean tent were the mechanical ground support equipment.

6.2.1. Mechanical Ground Support Equipment (MGSE). The MGSE was designed by the Ground Support Equipment (GSE) subsystem of the UMR SAT team. The requirements for the MGSE included providing support for the spacecraft during integration, allowing for the spacecraft to be transported while at UMR and handled at any other location. The MGSE includes panel stands for use on the clean tent table, a crane for transport, and tabs on the satellites for attachment to other ground support equipment.

6.2.1.1. Crane. The crane was designed and built at UMR for lifting MR and/or MRS SAT. The crane has been proof tested to 400 lbs, which gives the required factor of safety of five for the combined satellites. The crane was just tall enough that it could fit in the clean tent, permitting the crane to lift the satellites after flight integration. The crane was intended to be used for any lifting of the satellites while at UMR. It could also be transported with the satellites to another testing facility. The crane is shown in Figure 6.2.

Figure 6.2 UMR SAT GSE Crane

The crane also included a “cable tree” which allowed the steel cables that hung from the crane to line up with the tabs on the satellites, making lifting safer and easier. The cable tree is visible in Figure 6.3, hanging from the crane. The cables and tabs that will attach to the satellites are shown in the figure as well.

Figure 6.3 Cable Tree

6.2.1.2. Integration stands. During assembly and integration it is required that the side and bottom panels be supported by MGSE. The integration stands were designed and built at UMR by students and machine shop personnel. Stands were created for each bottom panel of the satellites to allow the assembly technician to reach under the satellite if needed. The stands also supported the satellites while they were attached to the clean tent table. Figure 6.4 and Figure 6.5 show the bottom panel stands for MR SAT and MRS SAT.

Figure 6.4 MR SAT Bottom Panel Integration Stand

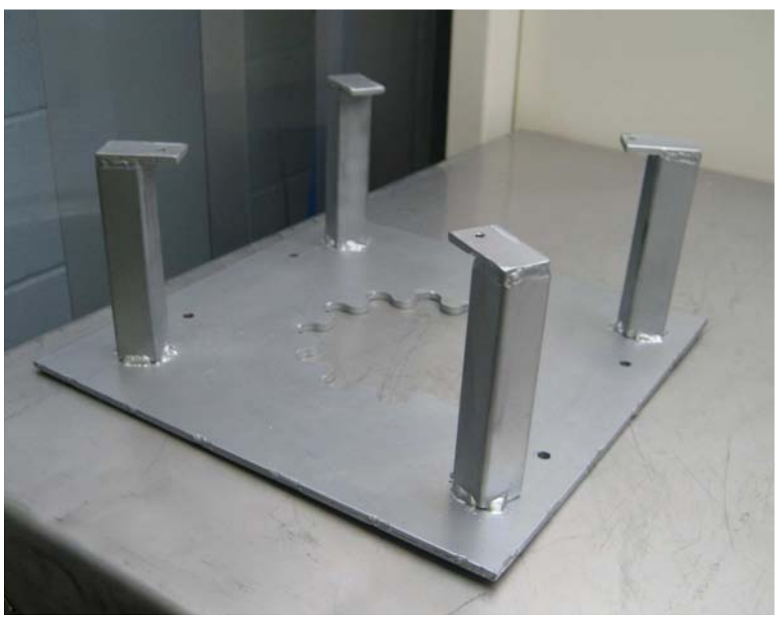


Figure 6.5 MRS SAT Bottom Panel Integration Stand

Stands were also designed to support the MR SAT side panels during integration. The side panel stands were designed to hold the panels vertically surrounding the bottom panel. This was to aid in the wiring process and allow shorter wires to be used than if the panels were lying flat on the table during wiring. This also required less space on the clean tent table than if the panels were all lying flat. Another important benefit of the panel stands was that since several of the side panels included propulsion valves, supporting them vertically was safer for the nozzles that extend through the side panels. The side panel stands were designed to lock into place with the bottom panel stand, fixing all stands to the table. This allowed for full support of the satellite during integration. Figure 6.6 shows a MR SAT side panel stand.

Figure 6.6 MR SAT Side Panel Stand

MRS SAT side panels were smaller than the MR SAT side panels and did not require accommodations for propulsion hardware. Therefore, the side panels could simply be placed around the bottom panel, lying flat on the table; there was not a need for a side panel stand for MRS SAT. The vise that was attached to the clean room table was used to hold the side panels while components were being attached.

6.2.1.3. Satellite support tabs. Ground support tabs were added to each satellite to be used when the satellites were being lifted with a crane or supported on a table. The tabs were designed to serve dual purposes: as brackets to hold the side panels together and to be used for GSE. There are eight GSE tabs on MR SAT and four on MRS SAT. The tabs on MR SAT are located on four of the six corners with two sets: one closer to the bottom of the satellite and one closer to the top. Figure 6.7 shows the MR SAT GSE tab design. Figure 6.8 shows the MRS SAT GSE tab design and Figure 6.9 shows the MR SAT and MRS SAT GSE tab layout.

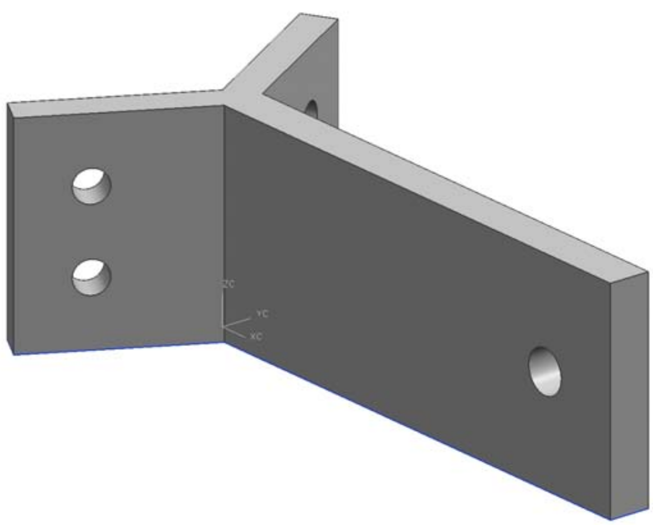


Figure 6.7 MR SAT GSE Tab Design

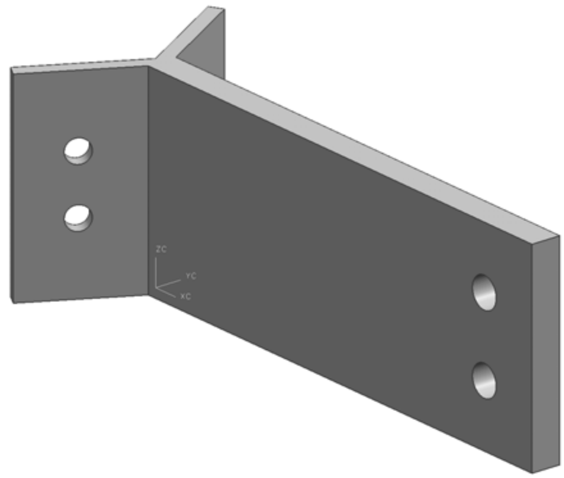


Figure 6.8 MRS SAT GSE Tab Design

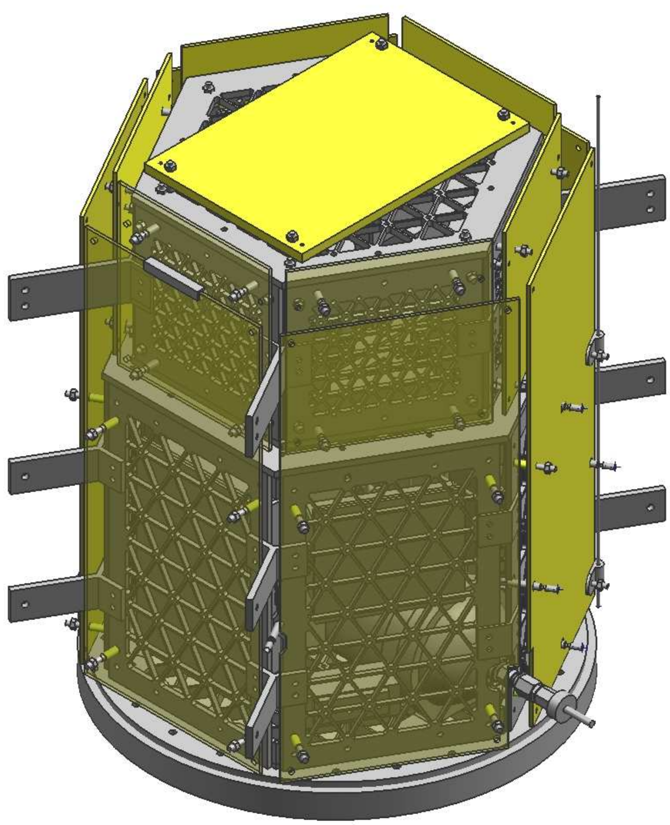


Figure 6.9 MR SAT and MRS SAT GSE Tab Layout

The higher set is primarily for use with the crane and the lower set is primarily for use on a table. Two bottom tabs can be used in conjunction with two top tabs to support the satellite in a horizontal configuration, which could be useful for testing and/or launch vehicle mating. The tabs cannot be used unless the satellites are fully assembled. The tabs on MRS SAT are also located on four of the six corners and have two holes so they can be used for the crane and/or the table mount and be switched easily by first attaching both pieces of equipment and then removing the one not needed.

6.2.2. Clean Tent Layout During Assembly. A procedure was written to address the limited available space in the clean tent. Scaled drawings were completed to show that both satellites could in fact be assembled at the same time. The use of the shelves in conjunction with the table was very important in the assembly process. Required fasteners were housed in a set of labeled drawers, which took up less space and made finding the size needed very simple. Figure 6.10 shows the fastener container.

Figure 6.10 Fastener Container

The fastener container could be moved to the shelves or tabletop based on need. A drawing of the clean tent layout is shown in Figure 6.11. The figure shows the location of the changing room, shelves, and ESD assembly table.

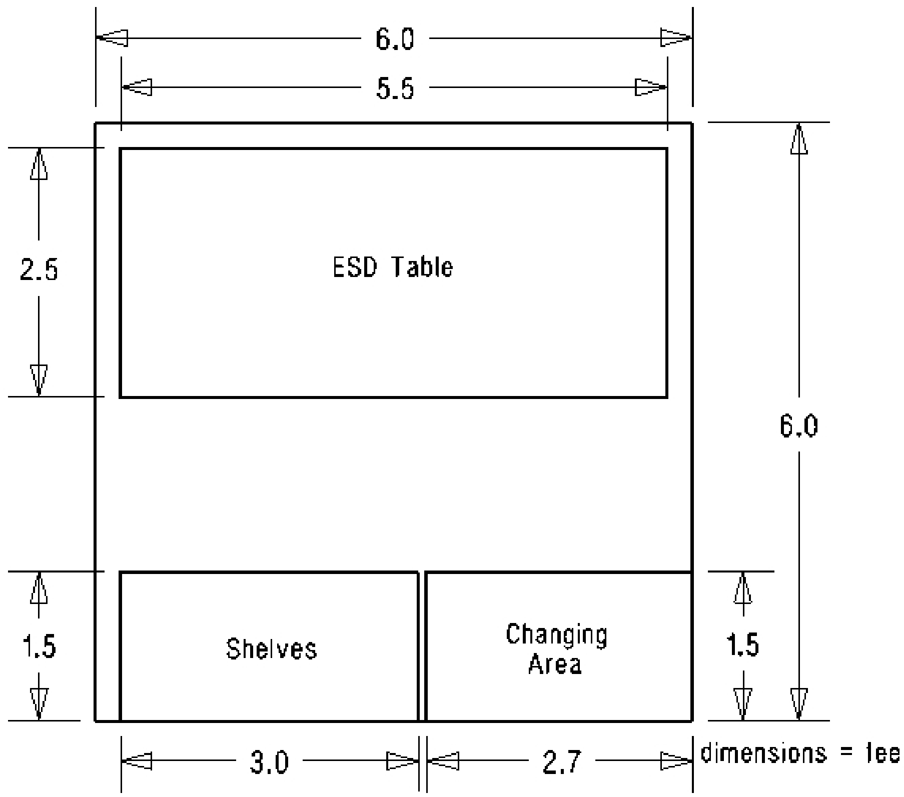


Figure 6.11 UMR Space Systems Engineering Lab Clean Tent Layout

6.3. SYSTEM-LEVEL ASSEMBLY LAYOUT AND PROCESS

The assembly of satellites can be very complicated and include many detailed steps. To assist in this process, for the UMR SAT project, CAD models were used to manage the flow of components during the assembly and integration process. The scale models were very helpful in ensuring that there would be enough space available in the clean tent for the physical assembly of the satellites. This was an important step because it led to decisions on which panels should be assembled first. The basic assembly steps for the UMR SAT project follow.

The first step in the system-level procedures was to prepare the top panel of each satellite. The top panels were not immediately used in the assembly process for either satellite, but they required too much space on the clean tent table to be assembled later once the bottom panels were fixed to the table. Both satellites required component attachment on the top panels. The components were attached to the top panels and then they were placed securely on the shelves for later attachment to the rest of the satellite.

The MR SAT side panel stands were then placed on the clean tent table. All six stands were used and all fit easily on the table. The MRS SAT side panels could also be placed on the clean tent table at the same time. The components and boxes were attached to each side panel one at a time. Figure 6.12 shows a MR SAT side panel on a panel stand during assembly.

The MRS SAT side panels and the MR SAT side panels on their stands were then arranged on the table to allow space for the bottom panel stands. With the side panels out of the way, the bottom panel stands were attached to the table, one at a time. The MR SAT bottom panel stand was attached first.

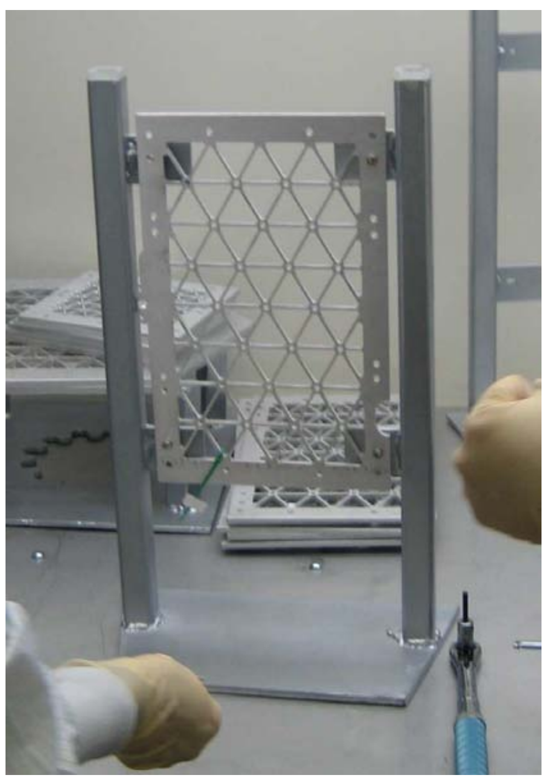


Figure 6.12 MR SAT Side Panel on Panel Stand

Once the MR SAT bottom panel was securely attached to the stand, the propulsion core hardware subassembly could be attached to the MR SAT bottom panel. The propulsion subassemblies had been completed and checked by quality assurance personnel before system-level assembly began. The bottom panel of MR SAT with the propulsion core hardware is shown in Figure 6.13. The bottom panel is supported by the bottom panel stand.

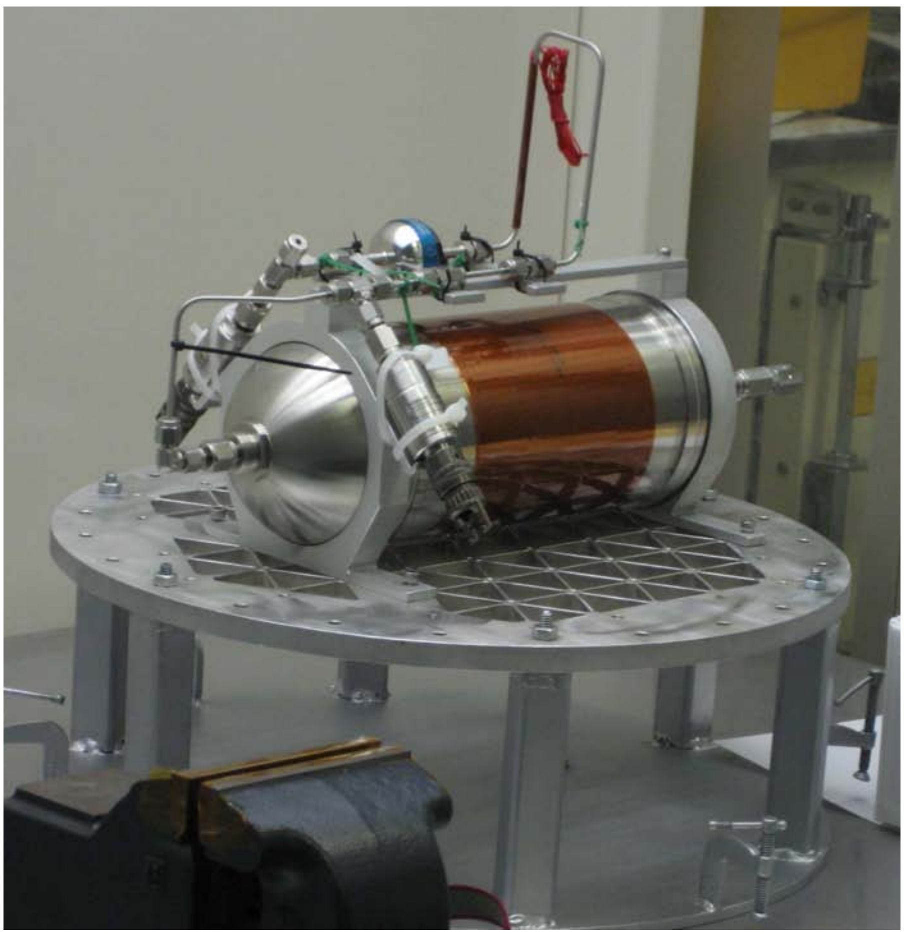


Figure 6.13 MR SAT Bottom Panel on Stand with Propulsion Core Hardware

Once the MR SAT bottom panel subassembly was attached, the MR SAT side panels were arranged around the bottom panel, as shown in Figure 6.14. This created room on the other half of the table for the MRS SAT bottom panel stand and panel to be attached to the table.

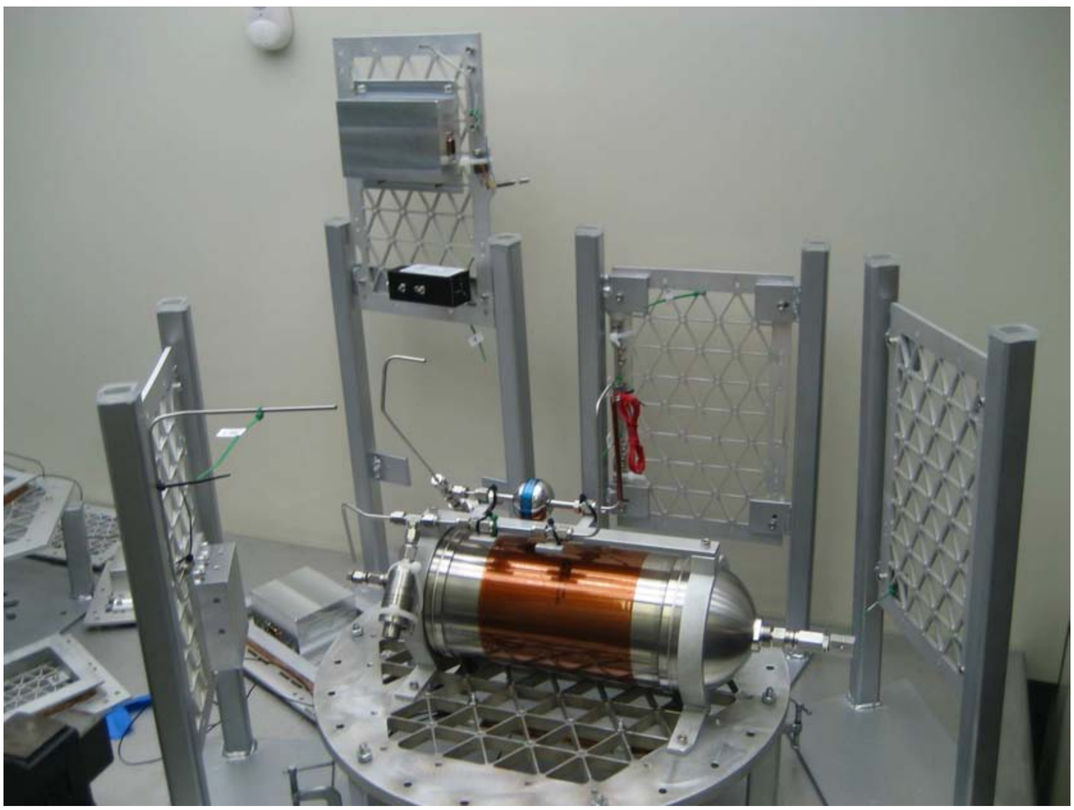


Figure 6.14 MR SAT Side Panels around Bottom Panel

The final step in the clean tent table layout plan was to arrange the MRS SAT side panels around the MRS SAT bottom panel. This layout is presented in Figure 6.15.

Figure 6.15 MRS SAT Flowered Panels during Assembly

Once all side panels were arranged, wiring commenced. The C&DH subsystem created wiring harness diagrams, shown in Section 3, which were used to design the physical wiring harnesses within the satellites. Creation of these documents allowed for planning of wire counts, lengths, and paths within the satellites.

The C&DH subsystem also created wiring harness documents which detail the wiring harness diagrams as well as the connectors for each box and the pin-outs for each connector [22, 23]. The Integration lead worked closely with the C&DH subsystem in locating the connectors on each box, which is discussed in more detail in Section 4. This level of detail was essential for the assembly process.

After the wiring harness integration, the structure could begin to be assembled. The sequence of assembly for MRS SAT was simple; each side panel was attached to the bottom panel in order 1-6. As each panel was added, it was bolted to the bottom panel and any adjoining side panels. MRS SAT is shown in Figure 6.16 partially assembled. Since most flight hardware was not present in the component boxes, the wiring harness was not completed for the FCR build.

Figure 6.16 MRS SAT during Assembly

Once all side panels were attached and all wiring was secured, the top panel was attached, completing the satellite. Figure 6.17 shows MRS SAT complete for FCR. The honeycomb panel with the solar array was attached last, and the plexi-glass sheet covering it was attached to protect the solar cells. The Power subsystem fabricated one solar panel for each satellite for the FCR build.

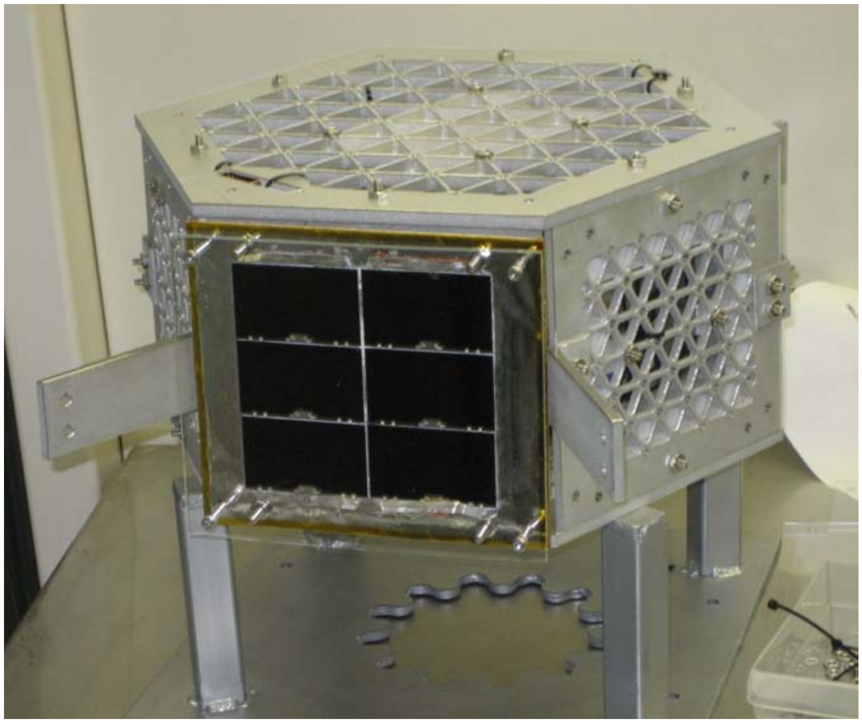


Figure 6.17 MRS SAT Assembled for FCR

The MR SAT sequence of assembly was more complicated, mainly due to the propulsion system. The order in which each side panel was added to the bottom was decided based on practice integration with the prototype satellite. After trying many options for the sequence of assembly, the following was chosen:

1. Side panel 1
2. Side panel 2
3. Side panel 4
4. Side panel 6
5. Top panel
6. Side panel 3
7. Side panel 5

This sequence allowed for all propulsion components to be attached first, including the ones attached to the top panel. There was room within the satellite, with the last two side panels not attached, to secure the tubing and other propulsion components. Figure 6.18 shows MR SAT during assembly before the top and last two side panels were attached.

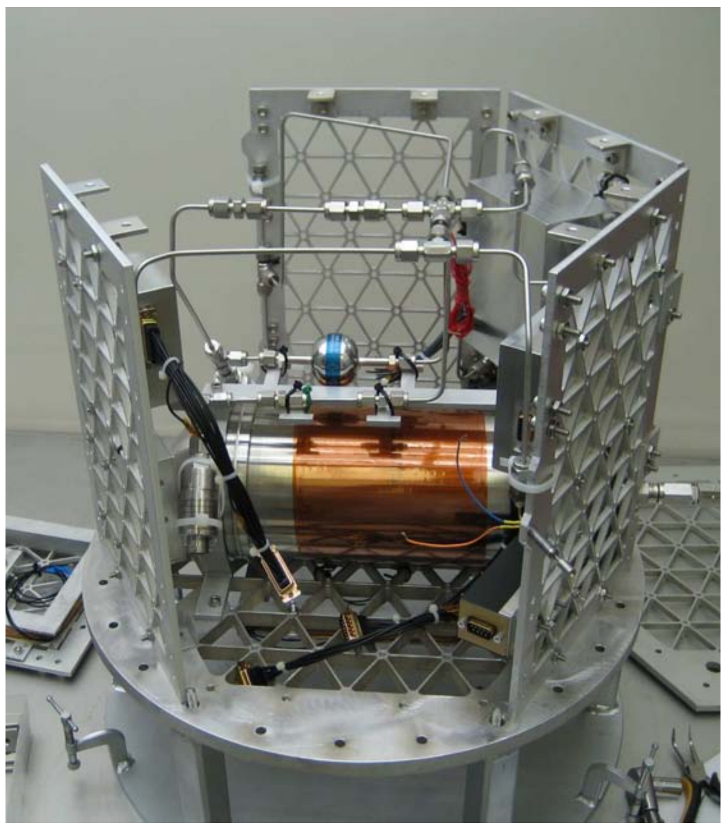


Figure 6.18 MR SAT Before Top and Panels 3 & 5 Attached

The propulsion tubing is visible throughout the satellite. Figure 6.19 shows MR SAT during assembly before the last panel was attached.

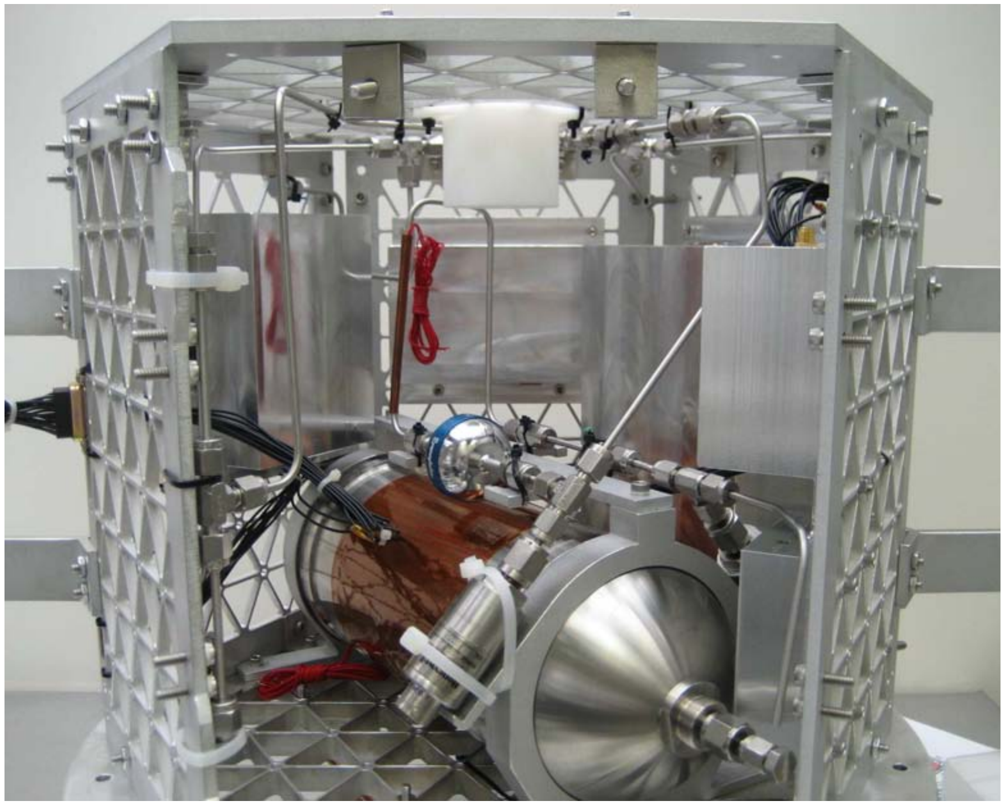


Figure 6.19 MR SAT Before Last Side Panel Attached

The honeycomb panel supporting the solar array was attached last, and the plexi-glass sheet covering it was attached to protect the solar cells. Figure 6.20 shows MR SAT in its complete configuration for the FCR build. This figure shows MR SAT being secured to the bottom panel of its shipping/display box. A shipping/display box was also fabricated for MRS SAT. These boxes were designed to keep the satellites clean while on display at the competition and other events. The boxes were designed and fabricated by the UMR SAT GSE subsystem and were manufactured from steel tubing and plexi-glass.

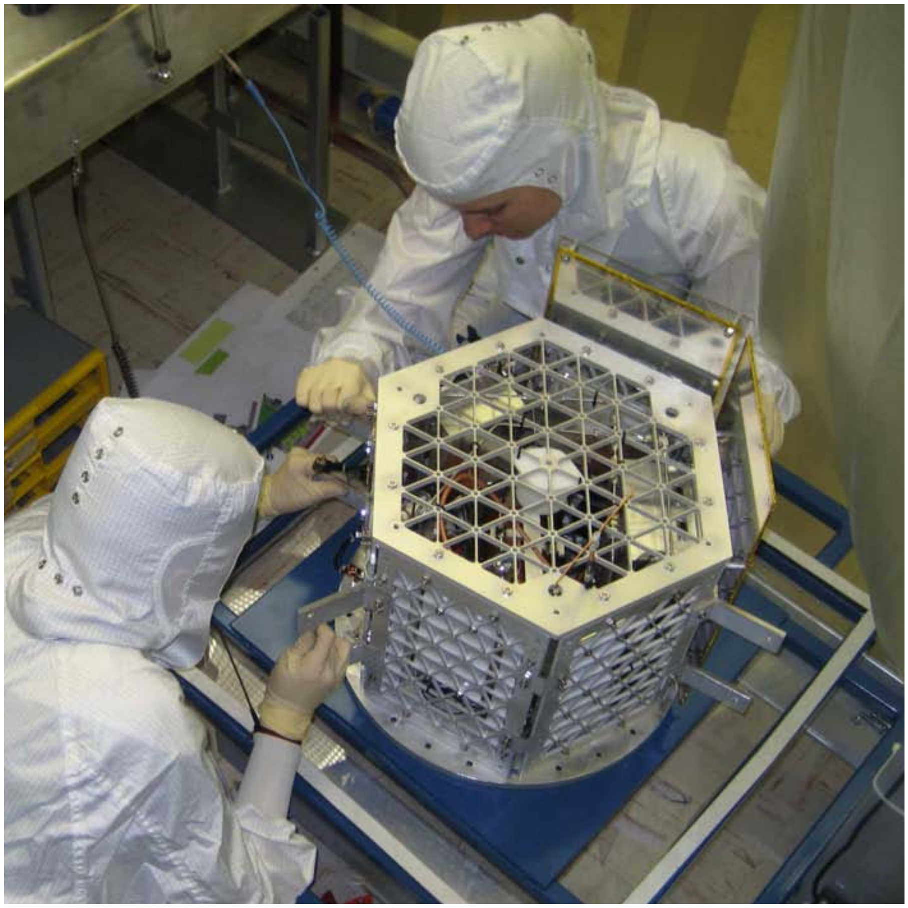


Figure 6.20 Assembled MR SAT

6.4. IMPORTANT DOCUMENTATION

During the assembly process, there are documents that must be kept up to date. First, the assembly procedures must be initialed by the assembly technician and the quality assurance personnel. Along with keeping up with quality assurance, it is also required that the assembly technicians track the cycles of each piece of flight hardware. For example, the QwkNut 3K can only be cycled a limited number of times before it is no longer suitable for flight. A document was created for this purpose; in Excel table form, shown in Table 6-1. Each piece of flight hardware that is cycle critical has its own Excel file for this purpose. Table 6-1 also includes examples.

Table 6-1 Cycle Tracking Document

Cycle Tracking					
Cycle #	**Date**	**Time**	**Reason for Cycle**	**Initials/Date**	**QA Initials/Date**
Examples:					
5	2/5/2006	2:45pm	Functional Testing	JS 2/5/06	SM 2/5/06
13	5/24/2006	10:15am	Video demonstration for AFRL	LZ 5/24/06	NL 5/24/06
1					
2					
3					
4					

Another document that may need to be filled out is a problem/failure report (PFR). There is a section in the assembly procedures and testing documentation for PFR's to be listed when they are outstanding on any flight hardware. A problem/failure report is to be filled out when any problem or failure in an assembly step takes place and requires corrective action to be fixed. If the problem was fixed on the spot, before the QA had been checked, then it would not require a problem/failure report. An example of a case when a problem/failure report would be required was if a solar cell cracks while assembling the solar panel onto the structure. The solar cell would not be replaced on the spot, so would require future corrective action and would need to be listed as a PFR. The list of PFRs outstanding against an assembly procedure would be similar to the one shown in Table 6-2.

Table 6-2 PFR List

Document Number	Summary of Discrepancy

The assembly and integration of MR SAT and MRS SAT required planning, preparation, and came with many challenges. Challenges and recommendations are presented through lessons learned in the next section.

7. LESSONS LEARNED FROM INTEGRATION OF UMR SAT

In preparation for the University Nanosat Program Flight Competition Review (FCR), the UMR SAT satellites were assembled in March, 2007. Even with detailed and thorough assembly procedures and an organized clean tent, the assembly and integration process was not without challenges. It was learned that proper design and planning could eliminate many challenges during the integration process.

The protoflight assembly was completed in the clean tent at the University of Missouri - Rolla Space Systems Engineering Laboratory. Before entering the clean tent, materials and equipment were gathered and stocked. The assembly procedures for all subsystems and systems were compiled into a binder and placed in the clean tent, along with many CAD drawings of the completed satellites for reference. Other materials that were collected were fasteners, Ground Support Equipment (GSE), and tools including a torque wrench.

The UMR SAT team encountered challenges during the integration process, however most were overcome and protoflight satellites were completed in time for the flight competition review. Many of these challenges are discussed further in this section, along with the lessons learned while overcoming them.

7.1. DESIGN FOR MANUFACTURE

The first set of challenges in the design and assembly process came about during manufacture. The biggest lesson learned was to work with the machine shop personnel well before the design was finalized. The machine shop personnel in the UMR Mechanical & Aerospace Engineering Department were able to give guidance on the manufacturability of the design. Many of the manufacturing challenges were presented in Section 5; however they are discussed further here.

An important lesson learned stemmed from the fact that all machining was done in English units. This required all drawings to be converted from the designed metric units to English so that the machine shop was able to process them. This also required the 3D models to be converted into English units from metric, which required some research into how to convert units in UniGraphics NX 3.0. This added a step in the process that cost time and left room for errors. There were already other steps in the process of getting the drawings ready for manufacture, depending on the machining process it would undergo. The WaterJet machine used an integrated CAD/CAM (computer aided manufacturing) package with the OMAX machine, so the structural drawings were converted into .dxf files that could be read by this package one part at a time. This also left room for error because the UMR SAT team was not familiar with the program and had trouble checking the drawings. The CNC machine used software called Surfcam. The drawings of the boxes and other parts made with CNC were converted first into English units, then into a .dwg file so they could be opened with Surfcam, and then converted into machine code and tool paths. The lesson learned here was to draw all parts in English units to save time and confusion with the machine shop. The University Nanosat Program also used English units, so this would make conversion into their system simpler as well.

7.1.1. Component Boxes. When designing a box out of a block of aluminum, there were many challenges in designing for manufacture. The boxes were to be machined using the CNC machine on campus. This machine had limitations on the diameter and length of drill bits that could be used. This proved to be important in that some boxes were designed too deep and tools had to be ordered which slowed the machining process.

In a couple cases, the boxes had to be redesigned to allow for machining. The original design for the interior of the MR SAT computer box was to orient all five boards vertically, with the box being designed with a stepped depth, as shown in Figure 7.1. At the time of this design, there were only going to be four boards located in this box, so only four are pictured in Figure 7.1. Internal attachments involved inserts affixed to the inside of the box, to which each board would be fastened. The inserts solved the machinability issue for vertically aligned boards with tabs that could not be created. Because of the complexity of using inserts and machinability issues with drill bits of insufficient length to machine a box this deep, the internal layout of the box had to be redesigned.

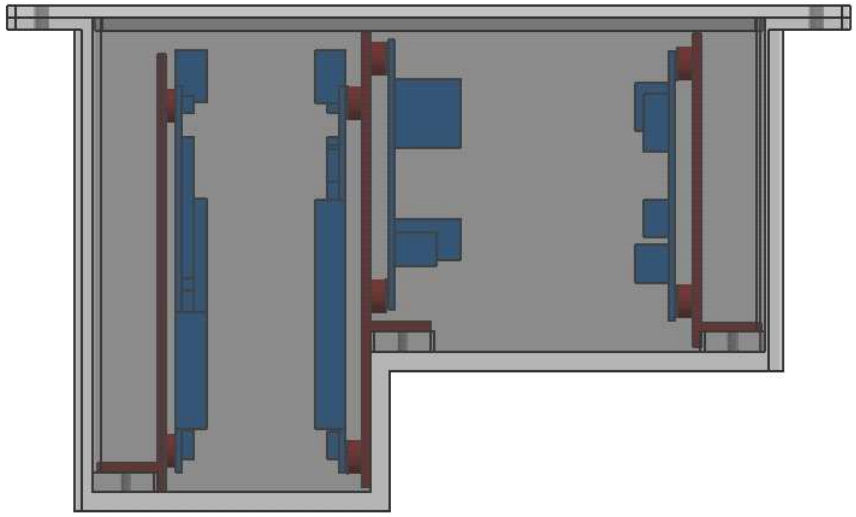


Figure 7.1 MR SAT Computers Box with Inserts Design

The redesign included making the box longer on one side, keeping the same attachment points to the structure, while allowing for the boards to fit horizontally. This redesign made the attachment inside the box simpler than designing some way to attach the boards vertically. The redesigned and final layout of the MR SAT computers box is shown in Figure 4.8 in Section 4.

Another challenge in designing the component boxes was that the walls were thin. They were designed at 0.10" thick, based on advice from AFRL. Some of the boxes were designed as deep as 3". This produced a very thin wall over that depth. The CNC machine drill bits that would need to be used to drill 3" deep were not suitable for precise wall thicknesses due to the fact that the bits would be vibrating at those depths. The machine shop personnel recommended thicker walls for boxes over 2.5" deep. This was a lesson that could have been learned early by discussing CNC capabilities with the shop personnel.

7.1.2. Box Lids. The component box lids were designed with an interference fit. The outside tabs were to be machined down to create the 90 degree interface. The

Waterjet machine was able to cut the ¼” aluminum to size and a mill was used to machine down the tabs. The rounded corners needed to mate the lid with the box were challenging to machine. The lids were machined by either running them through the mill at a 45 degree angle or by simply using the mill to remove a notch to mate the box with the lid. Figure 7.2 and Figure 7.3 show these two methods.

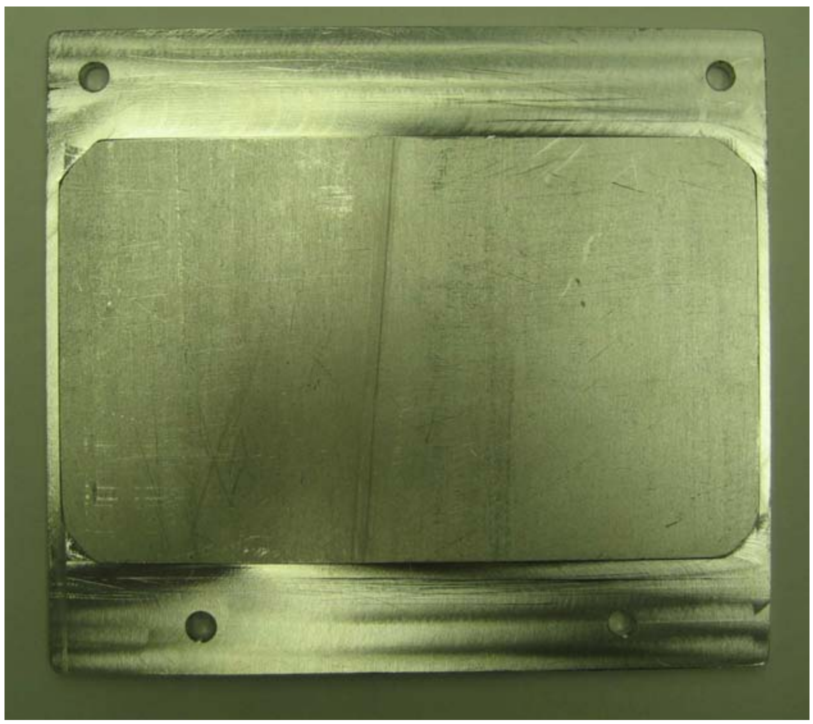


Figure 7.2 Box Lid with 45 Degree Angle Tab Corners

The lesson learned here was to design the lids with an interference fit that could be machined. It was not proven if the lids in their current state would satisfy EMI concerns.

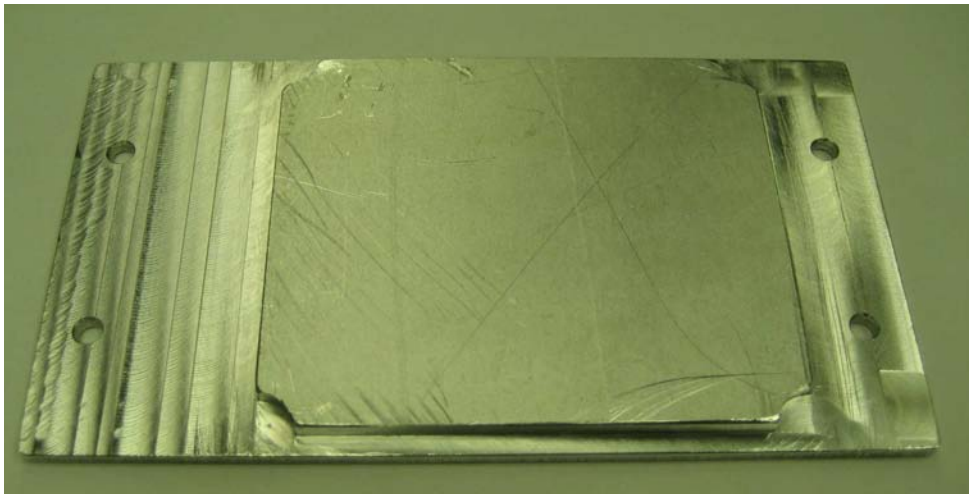


Figure 7.3 Box Lid with Notched Tab Corners

7.1.3. Holes. During the critical manufacture and build of the spacecraft, time could have been saved if simple machine shop rules of thumb were understood. Holes in the side panels, brackets, and boxes were not drawn to specification; they were drawn to the size of the bolt diameter. Through-holes needed to be drilled to a certain size bigger than the bolt and holes that are going to be tapped needed to be drilled to a certain size smaller. Holes that require helicoils to be inserted needed to be drilled to yet another diameter. These sizes were available in charts in the machine shop area and were based on drill bit sizes and tolerance concerns.

Some attachment holes in the bottom of boxes were not designed in ideal manufacturing locations. To minimize the size of the box, the box was designed just large enough to house the computer board or component inside. The holes in the computer boards are pre-drilled very close to the edges. This resulted in some attachment holes being designed at the bottom of boxes and very close to edges and/or corners. The boxes were designed deep enough that the drill bit that was needed to drill the designed hole was too wide to fit into the box and still make the hole as close to the wall as desired. This challenge was only overcome by re-designing some boxes to make the attachment hole locations far enough away from the walls. In some cases, there was not enough room between the holes and the walls for an “island” of material to be created for the helicoil attachment hole. In those cases, “peninsulas” that were connected to the walls were required, as shown in Section 4.

The lesson learned here was to research the drill bit diameters and lengths so that the boxes could be designed to manufacture without lost time in redesign. Another design parameter that comes out of this lesson regards the radius of the inside corners of the boxes. A deep box required a large diameter drill bit to reach down inside; this meant that the radius of the inside corners would be large. The original design drawings of the boxes were drawn as sharp corners, which was not possible to machine. The only boxes where this became an issue were the battery boxes, the other components still fit in their boxes even with the rounded corners.

7.2. PREPARING FOR ASSEMBLY

Preparation for assembly within the clean tent was required. The materials and equipment needed for assembly should all be checked and verified before the assembly process begins. This lesson was learned early when the torque wrench needed to tighten all bolts on the satellites was not working. The torque wrench never “clicked” to indicate that it had reached the desired torque. To overcome this, the wrench was used until resistance was felt on the bolts, which was not ideal. The torque wrench should have been tested well before it needed to be used for the flight build. The wrench was purchased at Fastenal and they replaced the malfunctioning torque wrench in just a few days, but after the flight build had already taken place. Another lesson learned here was that spare tools should always be kept on hand. There was only one tool of each type in the clean tent. In some cases, a tool was needed for some type of work outside the clean tent during the time it was needed inside. Time would have been saved if the tools did not need to be passed back and forth, requiring cleaning each time before reentering the clean tent. There were also times when the same tool was needed in two places in the clean tent and both assembly technicians could have been using one.

Another lesson with the torque wrench was that the assembly technicians should have learned how to use it ahead of time and practice. This would have saved time in the clean tent. This lesson also applies for any other equipment that was used for flight assembly. Everyone should be familiar with the tools before entering the clean tent. Another lesson to be learned from this was to order the tools and other materials, such as fasteners, well in advance so that there is time to check them and practice.

The fasteners were ordered from Fastenal with about three months until flight build. This seemed like plenty of time to receive, clean, do quality assurance, and prepare them for the flight build. By the time the fasteners arrived there was not much time to do QA and clean them; this process was done within a few hours. Ordering the fasteners earlier would have saved time during the rush at the flight build. One positive lesson that was learned was to keep the fasteners organized and easy to access while in the clean tent. To this end, the UMR SAT team purchased a set of drawers and labeled them for each fastener size. There were also enough drawers for the brackets and spacers. This saved time during assembly because the drawers were placed on the clean tent table within easy reach.

In preparing the clean tent for assembly, a set of shelves was installed in the corner. These shelves housed the parts that were not currently on the table, materials, and equipment needed for assembly. The shelves were within easy reach of the assembly technicians which saved time during assembly. A bin was placed on the top shelf to hold the tools needed, which kept them organized. The shelves in the clean tent were very useful during assembly, especially when panels, boxes, or other components had been assembled but were not ready for the system level build.

A lesson that was learned during assembly was that in preparation for the assembly and integration process, some sort of intercom system should have been installed in the clean tent. There were many times during the assembly process when the technicians inside needed something and had to open the curtain and request for someone in the lab to help them. There should always be at least one person in the lab while there are people in the clean tent. This saves the assembly technicians from having to leave the clean tent, which requires removing the layers of clean tent attire. With someone in the lab, then the intercom would help get the assembly technicians what they need in a timely manner.

Another important aspect of preparing for assembly is practice integration. This is discussed in Section 5 but is also important here. The lesson learned was to perform fit checks of the wiring into the component boxes before final integration. Time was short during the UMR SAT assembly, so the wiring was not ready for assembly in time to perform a fit check. This would have helped in many cases where the connector hole location and the length of wire within the box did not match up. If there had been a fit check, then the wiring could have been designed to fit exactly within the box. A good example of this was the Bluetooth Transceiver boxes. The boxes were very small but required wiring to the electrical connectors, as well as cabling to the antennas. The wiring setup for the Bluetooth boxes is presented in Figure 7.4. This is the wiring for only one of the two Bluetooth units that were housed in each Bluetooth box.

Figure 7.4 Bluetooth Box with Wiring

Another lesson to be learned in preparation for assembly was to check that all connectors fit in their designed connector holes. This lesson was learned when trying to assemble the Bluetooth boxes. The antenna connector holes were circular and were designed based on the actual connectors. There was not enough clearance for the connectors to fit through the box, which wasn't discovered until integration. The boxes had to be re-drilled on the spot, cleaned, and passed back into the clean tent so that integration could continue. The connectors could have easily been checked ahead of time.

7.3. GROUND SUPPORT EQUIPMENT

The mechanical GSE was designed without any prior experience with assembly and integration of spacecraft. During the assembly and integration process, many lessons were learned on how to improve the GSE. The purpose of the MGSE was to support the structure of the satellites during integration and allow for ease of assembly. The components of the GSE were the crane, stands, and tabs, as discussed in Section 6.

There were several issues that arose with the ground support equipment in general. The stands were all designed out of steel, which made them sturdy and durable, but also heavy and not easily maneuvered in the clean tent. Since they were made of steel there was issue with possible rust, so the stands were all coated with several layers of rust-preventing enamel spray paint. This became an issue when attaching panels to the stands when spray paint began to chip off. This created paint chips and dust inside the clean tent, reducing the cleanliness. The lesson learned here was to make the GSE stands out of a material that would be easy to maneuver and not require spray paint, i.e. aluminum.

The side panel stands were designed to support the MR SAT side panels during attachment of components to them. Challenges arose when attaching certain components that would not fit on the panel stands. The tabs on the GSE stands were designed large enough that many components could not be attached to the panels. The tabs could have been machined down to a smaller size, had the problem been discovered earlier. The tab interference issue is shown in Figure 7.5. The solution came with holding the side panels with the vise that was in the clean tent while attaching components to them. The vise that was attached to the clean tent table was useful in many steps in the assembly process, so a positive lesson was learned here.

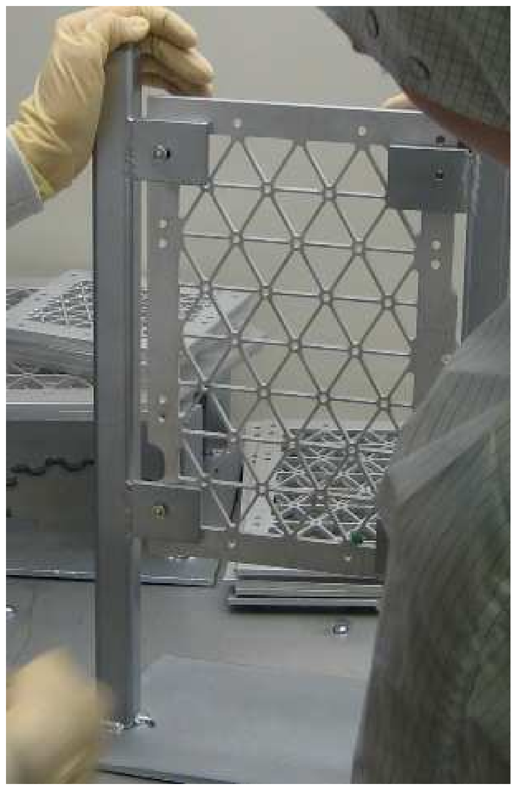


Figure 7.5 MR SAT Side Panel on Stand with Tabs

Another issue with the side panel stands dealt with the thrusters that were placed at the edges of the panels at an angle. The stand columns interfered with the thrusters. The panel was positioned higher on the stand to forgo this issue, shown in Figure 7.6.

The lesson learned here was to perform a practice assembly with the GSE stands before the flight assembly so that interference issues could be worked out.

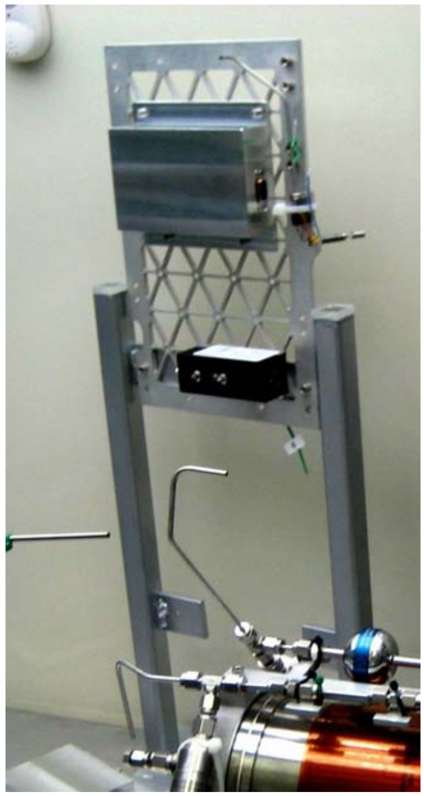


Figure 7.6 MR SAT Side Panel on Stand with Thruster

The bottom panel stands were attached to the table with bolts through holes that were custom drilled. This allowed for security and also easy removal of the satellite when built. The bolts were simply removed and the satellite was placed directly into its clean shipping box. There were challenges with this system however. The MR SAT bottom panel was held onto the stand with threaded rods going up into six of the

Lightband bolt hole locations. This design worked to hold the satellite; nuts were used to keep the bottom panel in place. However, when the side panels were attached to the bottom panels they were so close to the threaded rods that the nuts could not be removed, so the panels had to be taken off so that the nuts could be removed. This meant that the satellite was not locked down to the table, it was only held in place. The rods were long enough that this was not a severe problem, but for the flight build, the satellites will need to be more secure. Figure 7.7 shows the bottom panel stand and the rod interference. The lesson learned here was to attach the bottom panel to the stand in places that would not interfere with the assembly of the satellites.

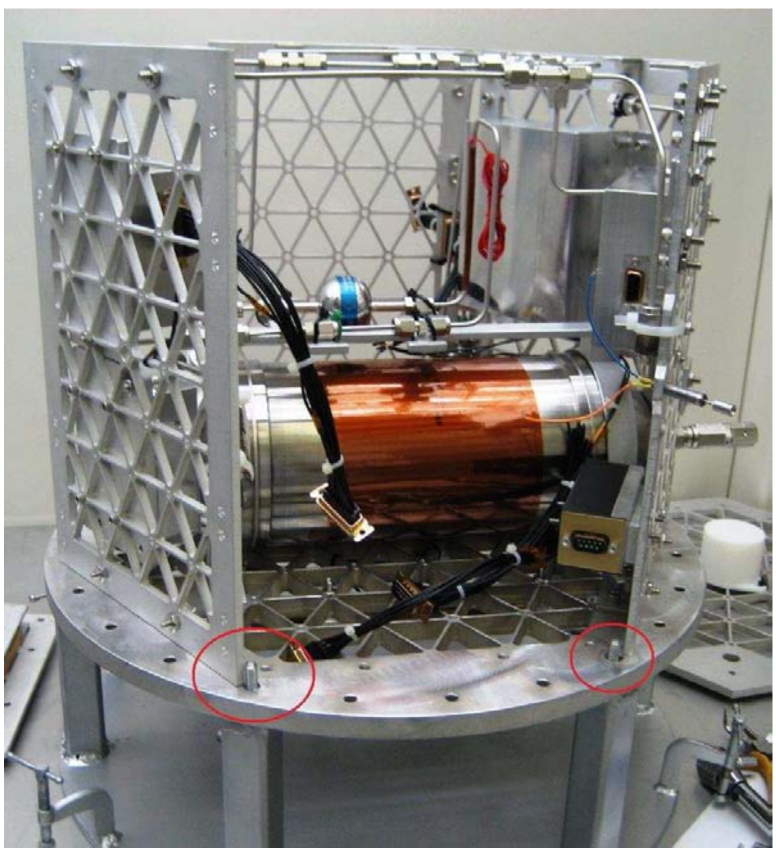


Figure 7.7 MR SAT Bottom Panel on Stand without Nuts to Secure It

Another issue with the MR SAT bottom panel stand was that there was not easy access to all sides of the satellite. When attaching side panels in the back of the satellite, it was required to reach all the way around the satellite. This was not ideal and could prove harmful to other components, including thrusters that extended out of other side panels. This challenge was overcome in the FCR build by picking up the satellite and rotating it so the rods fell into different Lightband holes each time. This allowed for easy access to each side panel, but was not a safe way to handle flight hardware. The lesson learned here was to design a GSE bottom panel stand that allows for rotation of the bottom panel for easy access to all sides. The stand would still require stability and attachment to the table.

7.4. DURING ASSEMBLY

Aside from the GSE challenges, many other lessons were learned during the assembly process. One of the issues that was encountered several times during assembly was with ground wires. Each person working on the clean tent table had to be grounded to keep the table ESD safe. This was done with wristbands that were attached to the table with alligator clips; the table was grounded to the facility ground. The alligator clips were not attached securely enough to the table and often came loose during assembly. This could potentially damage electronics on the satellites. The lesson learned here was to find a more stable way of clipping the wrist bands to the table to ensure proper grounding at all times.

Another lesson that was learned during integration was to label everything. The propulsion subassemblies were all labeled with zipties and a label maker. This helped with integration because the assembly technicians were not necessarily propulsion subsystem members and would not know which assembly was for which panel. This labeling system could have been used with other components as well. Labeling all parts would save time in locating the parts needed for each step of assembly. This would also help with MRS SAT since all side panels appear the same but have small differences. The side panel that was designed for the MRS SAT computer box has extra holes outside the isogrid since the box is large. It was discovered during integration that this side panel had already been used to attach another box and been placed aside. When it was time to attach the computer box, it was revealed that the side panel had been used. The box that had been attached had to be removed. Had the side panel been labeled, time would not have been wasted removing the box.

This leads to another lesson that was learned during the assembly process. This lesson was to check and double check each part before completing a step of the assembly process. The magnetometers on both satellites had been originally attached to the side panels backwards. This was discovered later when the magnetometers interfered with the other side panels and brackets within the satellites. Figure 7.8 shows the magnetometer on the side panel. They had to be removed and reattached in the correct orientation. Again, this wasted time.

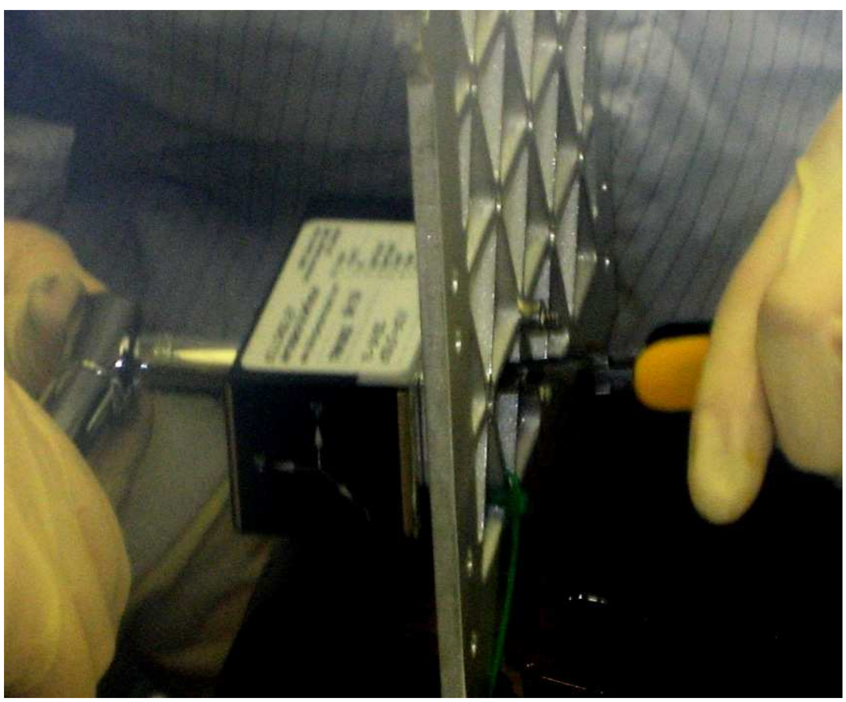


Figure 7.8 Magnetometer Being Attached to Side Panel

A very important lesson that could be the solution of the other challenges mentioned previously was to bring numerous detailed pictures into the clean tent. The assembly procedures were required but the pictures helped immensely. The CAD model pictures of the assembled satellites allowed for a check to be performed at various points during the integration. Had there been detailed pictures of each subassembly, panel, and component, the assembly process would have encountered far fewer challenges. The parts could have been checked against the drawings and prevented the magnetometer issue, along with many other time saving challenges. Another way to solve this would be to include pictures in the assembly procedures at each step. During the UMR SAT FCR build, there were many times when the assembly technicians had to request that someone else in the lab print out a picture of a part or subassembly to aid in the process.

A lesson in the system-level build was when attaching the side panels to the bottom panel, on both satellites, it was best to install the bolts through each hole, from the inside, before putting the panel in place. There were many cases where the bolt holes were inaccessible from the outside, especially when there were already other side panels attached. The triangular isogrid holes were not large enough, or in the correct locations, in some instances to allow a bolt to be placed from the outside into the satellite and then navigated through the bolt hole. This was especially true when components from other panels interfered. The propulsion tank presented an issue because it blocked some bolt holes completely, as shown in Figure 7.9. This could have been avoided had the bolts been placed through the holes ahead of time.

The best way to solve this problem would have been to design the structure to not require nuts. Then the bolts could have been inserted from the outside and torqued directly into the panels. Designing the structure without nuts would have required the use of locking helicoils in each hole, which would increase cost and introduced cycle issues, but would have saved complications with assembly.

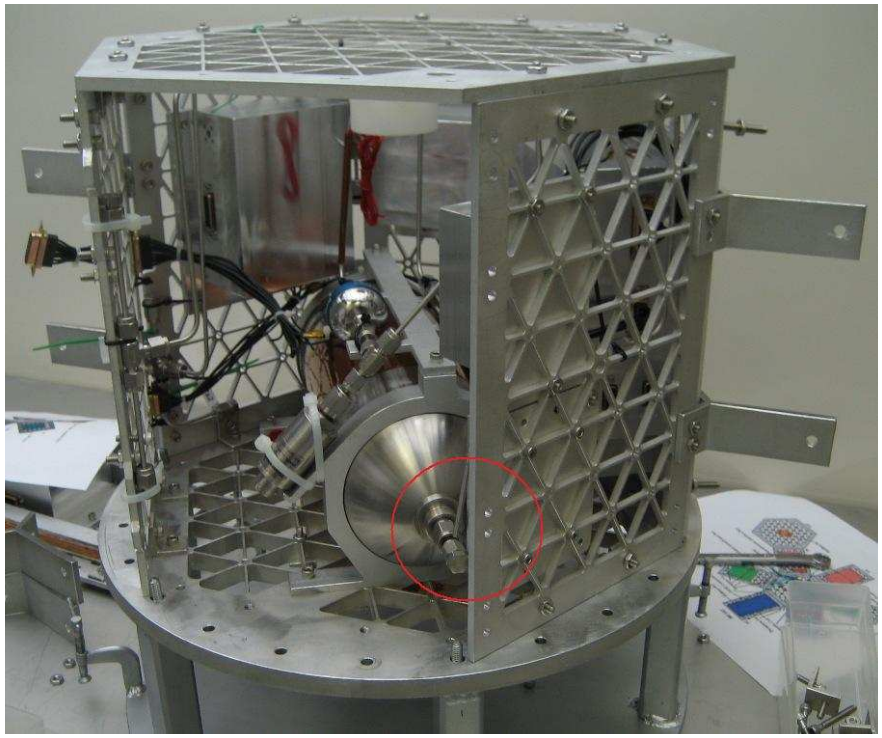


Figure 7.9 MR SAT with Tank Blocking Bolt Hole Locations

The final lesson that was learned during assembly was not to torque any bolts until the entire satellite was built. There were many times when bolts had to be loosened to allow other bolts to fit into place. Had the bolts all been hand tightened only, time could have been saved in arranging the other bolts to line up correctly.

The assembly and integration of the UMR SAT satellites in preparation for the UNP Flight Competition Review was met with many challenges. The lessons learned and recommendations for the future have been discussed. The most important lesson learned was to find ways to save time wherever possible and not wait to start preparing for assembly. Many of the challenges could be overcome with simple solutions and proper planning.

8. SUMMARY REMARKS

This thesis documents the development of the UMR SAT configuration, including the design of the component boxes and the layout of all components within the satellites. The resulting configuration, which was assembled for the UNP Nanosat-4 Flight Competition Review, met the requirements placed on the project. Lessons learned during the manufacture, assembly, and integration were discussed in detail. Many of the challenges met by the UMR SAT team are likely typical to those of any small satellite program. Other universities and small satellite developers can use the lessons learned during the configuration, manufacture, assembly, and integration of the UMR SAT satellites.

Future work to be completed by the UMR SAT team includes further development of the Flat Sat, detailed thermal and structural analysis, and completion of assembly and integration procedures. The lessons learned during the University Nanosat Program Competition should be incorporated into the future plans of the UMR SAT project.

APPENDIX A

MR SAT AND MRS SAT MASS BUDGETS

Document Name:	MR SAT Mass Budget
Document Number:	01-001
Revision:	I
Created By:	Lori Ziegler
Date Created:	7/19/2005
Date Modified:	9/26/2005
Date Modified:	12/2/2005
Date Modified:	1/18/2006
Date Modified:	1/27/2006
Date Modified:	3/3/2006
Date Modified:	4/25/2006
Date Modified:	7/27/2006
Date Modified:	9/6/2006
Date Modified:	2/19/2007
Date Modified:	10/23/2007

Subsystem	Component	Designed Part Mass (g)	Actual Part Mass (g)	Quantity	Designed Mass (g)	Actual Mass (g)	Designed Subsystem Mass (g)	Actual Subsystem Mass (g)
Structure							**12094.4**	**11030.4**
	Isogrid Side Panel 1	313.0	311.4	1	313.0	311.4		
	Isogrid Side Panel 2	313.0	316.1	1	313.0	316.1		
	Isogrid Side Panel 3	313.0	317.0	1	313.0	317.0		
	Isogrid Side Panel 4	313.0	318.2	1	313.0	318.2		
	Isogrid Side Panel 5	313.0	316.9	1	313.0	316.9		
	Isogrid Side Panel 6	313.0	317.4	1	313.0	317.4		
	Isogrid top panel	760.0	815.7	1	760.0	815.7		
	Isogrid bottom panel	2000.0	2500.0	1	2000.0	2500.0		
	Bracket 120 degrees	13.0	11.3	4	52.0	45.2		
	Bracket 90 degrees	6.0	6.1	24	144.0	146.4		
	Bracket Corners	24.0		12	288.0	0.0		

	Honeycomb Al panels	296.0	261.0	6	1776.0	1566.0		
	#10 bolts & nuts	6.0	4.3	144	864.0	619.2		
	#8 bolts & nuts	5.0	3.2	46	230.0	147.2		
	Spacers	0.6	0.4	24	14.4	9.6		
	Starsys Qwknut 3K	205.0		1	205.0	0.0		
	Qwknut Adaptor plate	75.0		1	75.0	0.0		
	Magnetometer Adaptor Plate	18.0	25.2	1	18.0	25.2		
	Transmitter Adaptor Plate	60.0	145.0	1	60.0	145.0		
	Component box- Battery Lid	400.0		1	400.0	0.0		
	Component box- Battery Bottom	1000.0		1	1000.0	0.0		
	Component box- GPS Lid	100.0	161.0	1	100.0	161.0		
	Component box- GPS Bottom	200.0	227.2	1	200.0	227.2		
	Component box- Magnetometer Lid	150.0	201.4	1	150.0	201.4		
	Component box- Mag. Bottom	250.0	217.3	1	250.0	217.3		
	Component box- Computer Lid	350.0	469.2	1	350.0	469.2		
	Component box- Computer Bottom	800.0	962.8	1	800.0	962.8		
	Component box- Receiver Lid	120.0	249.8	1	120.0	249.8		
	Component box- Reciever Bottom	200.0	371.9	1	200.0	371.9		
	Component box- Bluetooth Lid	60.0	97.7	1	60.0	97.7		
	Component box- Bluetooth Bottom	100.0	155.6	1	100.0	155.6		
GSE							**672.0**	**546.4**
	Lightband bolts	8.0		24	192.0	0.0		
	GSE Tabs	60.0	68.3	8	480.0	546.4		
Power							**2170.0**	**1800.0**
	Solar array	150.0		1	150.0	0.0		
	Wiring harness	500.0		1	100.0	0.0		
	Ni-Cd Battery	160.0	150.0	12	1920.0	1800.0		

ADAC							**1017.0**	**1665.0**
	Magnetometer	117.0	100.0	1	117.0	100.0		
	Magnetic Coil with side mount	350.0	890.0	1	350.0	890.0		
	Magnetic Coil on battery box	200.0		1	200.0	0.0		
	Magnetic Coil with bottom mount	350.0	675.0	1	350.0	675.0		
Orbit							**80.0**	**70.0**
	GPS receiver	40.0	22.0	1	40.0	22.0		
	GPS interface	40.0		1				
	GPS antenna	40.0	48.0	1	40.0	48.0		
Communication							**493.7**	**276.0**
	RX-145 receiver	40.0	48.0	1	40.0	48.0		
	Spacequest TX-435 UHF Trans.	210.0	224.0	1	210.0	224.0		
	Modem	80.0		1	80.0	0.0		
	Communications Power Board	80.0		1				
	Receive antenna	20.0		1	20.0	0.0		
	Transmit antenna	20.0		1	20.0	0.0		
	Bluetooth antenna	20.0		2	40.0	0.0		
	Bluetooth Transceiver	1.9	2.0	2	3.7	4.0		
	Shielded coaxial cables	20.0		4	80.0	0.0		
C&DH							**352.0**	**0.0**
	Magnetometer board	40.0		1	40.0	0.0		
	Magnetic coils board	40.0		1	40.0	0.0		
	Propulsion board	40.0		1	40.0	0.0		
	One-Wire board	40.0		1	40.0	0.0		
	Power board	96.0		1	96.0	0.0		
	Arcom Viper computer	96.0		1	96.0	0.0		
Propulsion							**4112.0**	**3932.2**

Cold Gas Thruster:	Tank	1500	2097	1	1500	2097.0		
	Tank Mount A	215	170	1	215	170.0		
	Tank Mount B	179	225	1	179	225.0		
	Propellant	500		1	200	0.0		
	Fill/Drain Valve	100	42	1	100	42.0		
	Thrusters	100		8	800	0.0		
	Prop- iso Valve		48	2	0	96.0		
	Carl- prop Valve		7.09	8	0	56.7		
	AXES_TUBE		22.1	3	0	66.3		
	PROP_WELDTUBE		0.232	16	0	3.7		
	PROP_SMALL_30_TUBE		0.161	3	0	0.5		
	PROP_SMALL_90_TUBING		0.446	10	0	4.5		
	PROP_SMALL_60_TUBING		0.285	1	0	0.3		
	PROP_SMALL_45_TUBING		0.26	2	0	0.5		
	PROP_OFFSET_TUBE		0.333	8	0	2.7		
	PROP_LONG_SMALL_TUBE		0.91	2	0	1.8		
	Tube connections: Tee	40	30	7	280	210.0		
	PROP_SWAGELOK_SMALL_TEE		44.44	6	0	266.6		
	PROP_TRANS_BRANCH_TEE		49.9	1	0	49.9		
	PROP_TRANS_RUN_TEE		48.695	1	0	48.7		
	Tube connections: cross	40	38	1	40	38.0		
	Tube connections: swagelok/AN	40	14	2	80	28.0		
	Tube connections: Tank Connector	40		1	40	0.0		
	Regulator	550	176	1	550	176.0		
	Heater - Tank	30	60	1	30	60.0		
	Heater - Lines	8	8	1	8	8.0		
	Heater - Valves	0.29		0	0	0.0		
	MLI	250		0	0	0.0		
	Transducer (Pressure)	45	140	2	90	280.0		
Thermal							**280.0**	**0.0**

	DS 75 sensors	5.0		8	40.0	0.0		
	Wire for sensors	10.0		24	240.0	0.0		
	Insulation	250.0		0	0.0	0.0		
						Satellite Mass (g)	**21271.1**	**19320.0**

Document Name:	MRS SAT Mass Budget
Document Number:	01-002
Revision:	I
Created By:	Lori Ziegler
Date Created:	7/19/2005
Date Modified:	9/25/2005
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Date Modified:	3/3/2006
Date Modified:	4/25/2006
Date Modified:	7/27/2006
Date Modified:	2/18/2007
Date Modified:	10/23/2007

Subsystem	Component	Designed Part Mass (g)	Actual Part Mass (g)	Quantity	Designed Mass (g)	Actual Mass (g)	Designed Subsystem Mass (g)	Actual Subsystem Mass (g)
Structure							**5899.8**	**5981.7**

Isogrid side panel 1	190.0	208.6	1	190.0	208.6
Isogrid side panel 2	190.0	207.6	1	190.0	207.6
Isogrid side panel 3	190.0	208.0	1	190.0	208.0
Isogrid side panel 4	190.0	206.8	1	190.0	206.8
Isogrid side panel 5	190.0	208.4	1	190.0	208.4
Isogrid side panel 6	190.0	207.4	1	190.0	207.4
Isogrid top panel	640.0	682.2	1	640.0	682.2
Isogrid bottom panel	650.0	684.9	1	650.0	684.9
Honeycomb Al side panels	90.0	98.0	6	540.0	588.0
Honeycomb Al top panel	140.0		1	140.0	0.0
#8 bolts & nuts	6.0	3.2	30	19.2	96.0
#10 bolts & nuts	5.0	4.3	136	21.5	584.8
Spacers	0.6	0.4	28	11.2	11.2
Bracket 120 degrees	12.8	12.8	2	25.7	25.7
Bracket 90 degrees	6.4	6.4	12	76.6	76.6
Bracket corners	3.8		12	45.6	0.0
Magnetometer Adapter Plate	30.0	23.5	1	30.0	23.5
Blot Retractor Mechanism	160.0		1	160.0	0.0
Component box- Battery Bottom	600.0		1	600.0	0.0
Component box- Battery Lid	200.0		1	200.0	0.0
Component box- Bluetooth Bottom	140.0	152.0	1	140.0	152.0
Component box- Bluetooth Lid	80.0	89.3	1	80.0	89.3
Component box- Mag. Bottom	180.0	206.1	1	180.0	206.1
Component box- Magnetometer Lid	100.0	188.8	1	100.0	188.8
Component box- Lg Computer Bottom	350.0	366.6	1	350.0	366.6
Component box- Lg Computer Lid	150.0	254.3	1	150.0	254.3
Component box- Sm Comuter Bottom	200.0	230.4	1	200.0	230.4
Component box- Sm Computer Lid	100.0	142.3	1	100.0	142.3
Component box- GPS Bottom	200.0	199.7	1	200.0	199.7
Component box- GPS Lid	100.0	132.5	1	100.0	132.5

GSE							**200.0**	**290.0**
	GSE Tabs	50.0	72.5	4	200.0	290.0		
Power							**950.0**	**750.0**
	Solar array	50.0		1	50.0	0.0		
	Wiring harness	200.0		1	100.0	0.0		
	Ni-Cd Battery	160.0	150.0	5	800.0	750.0		
ADAC							**517.0**	**990.0**
	Magnetometer	117.0	100.0	1	117.0	100.0		
	Magnetic Coil with side mount	150.0	380.0	1	150.0	380.0		
	Magnetic Coil on battery box	100.0		1	100.0	0.0		
	Magnetic Coil with bottom mount	150.0	510.0	1	150.0	510.0		
Orbit							**82.0**	**70.0**
	GPS receiver	22.0	22.0	1	22.0	22.0		
	GPS Interface	40.0		1	40.0	0.0		
	GPS antenna	20.0	48.0	1	20.0	48.0		
Communication							**63.7**	**4.0**
	Bluetooth antenna	20.0		2	40.0	0.0		
	Bluetooth Transceiver	1.9	2.0	2	3.7	4.0		
	Shielded coaxial cable	20.0		1	20.0	0.0		
C&DH							**312.0**	**0.0**
	Magnetometer board	40.0		1	40.0	0.0		
	Magnetic coils board	40.0		1	40.0	0.0		
	One-Wire Board	40.0		1	40.0	0.0		
	Power board	96.0		1	96.0	0.0		
	Arcom Viper	96.0		1	96.0	0.0		

Propulsion							**0.0**	**0.0**
						0.0		
Thermal							**175.0**	**0.0**
	DS 75 sensors	5.0		5	25.0	0.0		
	Wire for sensors	10.0		15	150.0	0.0		
	Insulation	100.0		0	0.0	0.0		
						Satellite Mass (g)	**8199.5**	**8085.7**

APPENDIX B

UMR SAT QUALITY ASSURANCE DOCUMENT

Quality Assurance Document for Manufactured Parts

Drawing Number: ______________________

Part Description: _______________________

Drawn By: ____________________________ Date: ______________

Manufactured By: ______________________ Date: ______________

Is the following information included on the drawing?

	Initials	Date
Material:	______	__________
Surface Finish:	______	__________
Process:	______	__________
Checked by at least 2 people:	______	__________

Visual/Measurement inspection completed?

Measurements within tolerance:	______	__________
Surface Finish:	______	__________

List any discrepancies here in detail: (continue on back if necessary)

Signatures		Date
Structure Lead	_______________________________	_____________
Integration Lead	_______________________________	_____________
Chief Engineer	_______________________________	_____________

APPENDIX C

ASSEMBLY PROCEDURE FORMAT EXAMPLE:
16-04-003 PROPULSION CORE HARDWARE AND TANK ASSEMBLY

University of Missouri – Rolla Satellite Team

Document Title:

Assembly Procedures for Propulsion Core Hardware and Tank

Document Name:	Assembly Procedures for Propulsion Core Hardware and Tank
Documentation Number:	16-04-003
Status:	FCR Ready
Date:	2-1-07
Revision:	-

Revision Summary

Rev	Release Date	Brief Description/Reason For Change	Effective Pages
-	2/1/07	Initial release	All

Signature Page

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Approval:

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Table of Contents

1. Introduction

1.1. Scope/Objective

This procedure covers the assembly of the Propulsion Core Hardware and Tank.

1.2. Applicable Documents

- UN-1007-1050, Rev B, NS4 Sample Box Assembly Procedure
- UN-0001, NS4 User's Guide Rev A
- UN-0002, NS4 CM Plan

2. General Considerations

2.1. Pass/Fail Criteria

All results and applicable data will be recorded directly on this assembly procedure. Pass/Fail criteria for each assembly is based on successful completion of the specific assembly with all steps followed per the assembly procedure. Any additional observation or notes completed by the operator may be handwritten in the procedure and made part of the final data package.

Any problems or failures must be dispositioned through a Problem/Failure Report (PFR).

2.2. Safety Compliance

For operations during normal duty days, all accidents and hazardous incidents shall be reported to Dr. Hank Pernicka, Faculty PI (573-341-6749). During non-standard hours, all accidents and incidents shall be reported to Dr. Pernicka on the next working day.

2.3. Hazardous Operation

No hazardous operations occur during assembly of this part. This procedure only involves hand tools and parts weighing less than 2-kg.

2.4. Quality Assurance (QA) Provisions

A Quality Assurance representative shall perform the following functions:

- Inspection of the initial assembly setup and all assembly procedures.
- In the event of a component failure or suspected assembly error, QA shall initiate a Problem/Failure Report (PFR).
- Visual inspection of the test articles at points indicated in this procedure, including visual damage.
- Review data and accept at completion of this procedure.

The Quality Assurance representative can be any technical team member other than the person performing the assembly. The QA representative must be present and witness all steps in the procedure.

2.5. PFR and Non-Conformance List

The following is the current list of Non-conformance items and PFR's that are outstanding against this assembly.

Table 2-1: PFR and Non-Conformance List

Document Number	Summary of Discrepancy

This list has been reviewed as to the effect these items may have on the execution of this procedure.

______/________

ENG / Date

______/________

QA / Date

3. Resource Requirements

3.1. Facilities

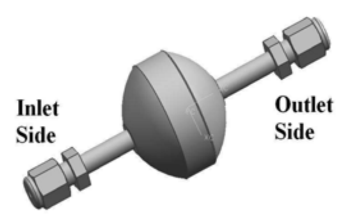
This procedure shall be performed at the Space Systems Engineering Lab, University of Missouri-Rolla. Work is to be performed in the lab clean tent. Proper attire is to be worn in the clean tent at all times. Refer to document 00-009 for details.

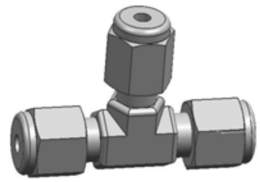
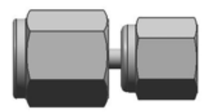
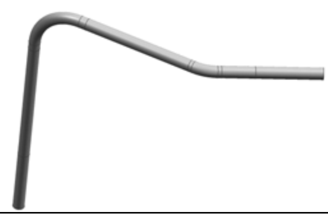
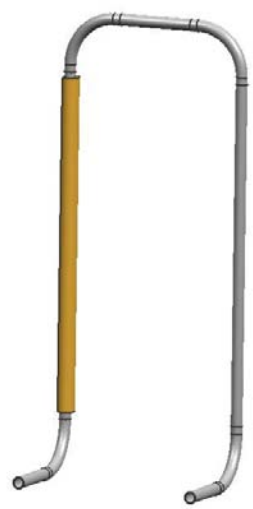
3.2. Materials and Equipment

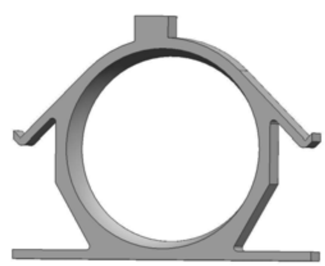
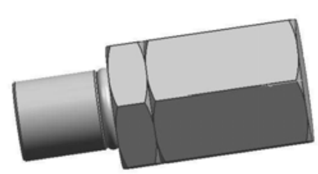
Table 3-1 lists the materials required for this assembly. Table 3-2 lists the equipment required for this assembly. Drawings for the Propulsion Core Hardware and Tank assembly can be found in the following documents:

1. 04-P-101 Tank Mount A Part drawing
2. 04-P-102 Tank Mount B Part drawing
3. 04-P-103 Mount Bridge Part drawing

Table 3-1: Materials for Assembly

Item	Description	Picture	Quantity
1	Tank Tk01		1
2	Transducer PtML01/PtML02		2
3	Regulator RML01		1
4	Valve VML01		1

5	Tank Connector ESML01		1
6	Tee Fitting TML01/TML02		2
7	Coupling CpML01/CpML02		2
8	Tubing ML01		1
9	Tubing ML02		1
10	Tubing with Heater (HML01) attached ML03		1

11	Tubing ML04		1
12	Tubing ML05		1
13	Coupling CpFD01		1
14	Tank Mount TMFD01		1
15	Tank Mount TMML01		1
16	Fill/Drain Valve VFD		1

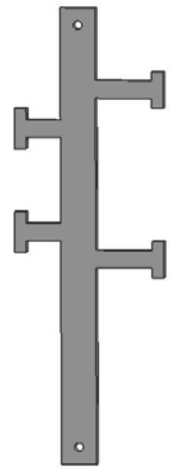
17	Fill/Drain Valve Cap VFDC		1
18	Mount Bridge MB		1
19	8-32 x 1/2" socket head screws		2
20	MLI		1
21	MLI Tape		1
22	Zip-ties		20
23	Arathane 5753		1

Table 3–2: Equipment for Assembly

Item	Description	Picture	Quantity
1	Torque Wrench		1
2	Wrench		1
3	Allen Wrench Set		1
4	Zip-Tie Cutter		1

3.3. Personnel Requirements

Quality Assurance and Assembly Technician shall participate in conducting this assembly procedure. QA shall primarily support the assembly verification and review. There must be two people present at all times in which assembly is being performed.

4. Assembly Setup

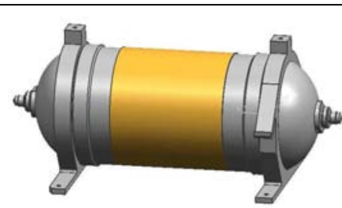
Assembly is to be completed in a class 100,000 or better ESD controlled environment, see document 00-009 for reference. Place all of the parts and tools from Tables 3-1 and 3-2 on a clean work area.

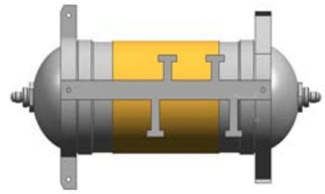
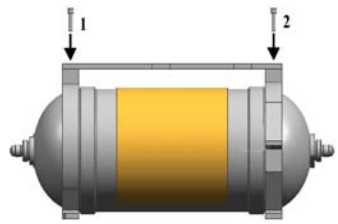
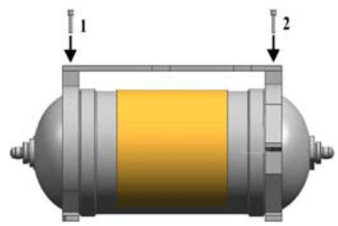
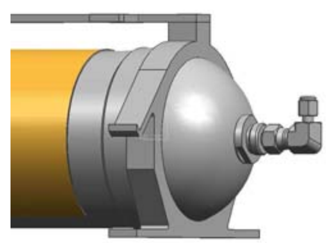
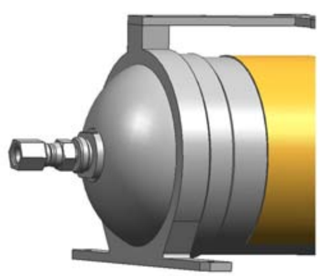
5. Assembly Procedure

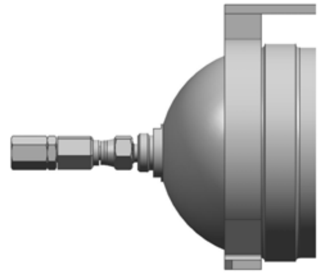
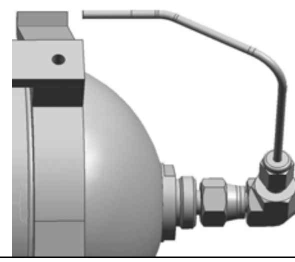
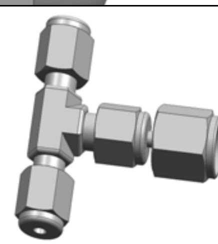
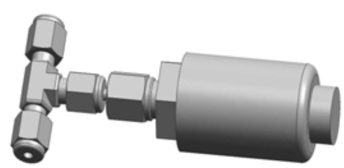
Propulsion Core Hardware and Tank will undergo the following steps for assembly.

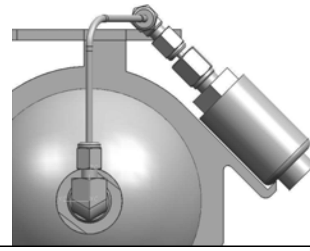
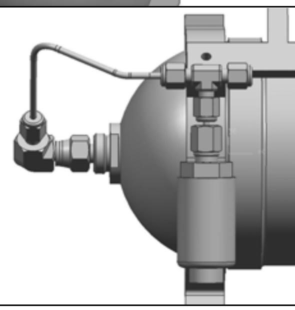
1. Cleaning and Inspection
2. Connect Fittings, Mounts, and Bridge to Tank
3. Connect first Valve, and Regulator using Tubing
4. Assemble Transducers, Couplings, and Tee Fittings
5. Connect first Valve and Regulator assembly to Transducer assemblies
6. Position core hardware onto mounting surfaces
7. Connect core hardware to Tank
8. Zip-tie components to Mounts
9. Pot all Zip-tied components with Arathane 5753

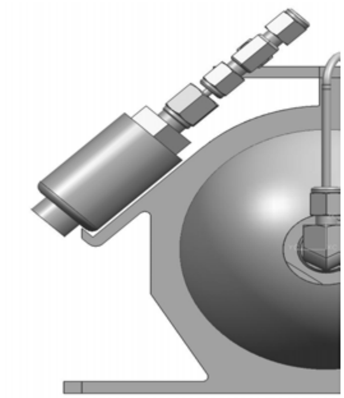
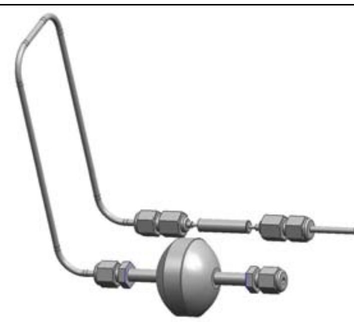
5.1. Assembly

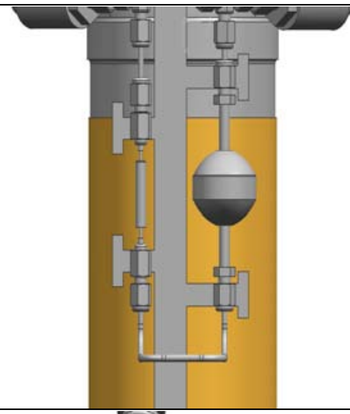
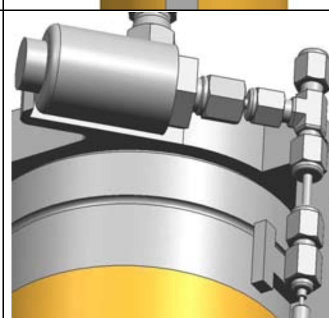
Step #	Activity	View	Performer Initials/ Date	QA Initials/ Date
PCHT-01	Inspect all personnel for proper clean room attire and safety prior to entering the clean room.			
PCHT-02	Place Tank Mounts TMFD01 and TMML01 on Tank. TMML01 must be on the outflow side of tank as indicated.			

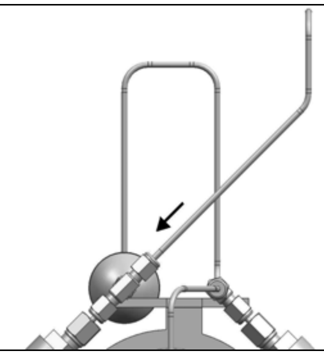
PCHT-03	Align Mount Bridge on top of Tank Mounts as shown.			
PCHT-04	Insert 8-32 x 1/2" screw into first hole on top of mount bridge and torque to ### in-lb +- 1 in-lb. Record actual torque.			
PCHT-05	Insert 8-32 x 1/2" screw into second hole on top of mount bridge and torque to ### in-lb +- 1 in-lb. Record actual torque.			
PCHT-06	Wrap Tank Tk01 in the MLI.			
PCHT-07	To join the two ends of the MLI, place a strip of MLI tape along the seam.			
PCHT-08	Connect side 1 of Tank Connector ESML01 to end 2 of Tank (outflow side of tank).			
PCHT-09	Using the wrench, apply a turn of 1-1/4 to side 1 of Tank Connector.			
PCHT-10	Connect side 2 of Coupling CpFD to end 1 of Tank (inflow/fill side of tank).			
PCHT-11	Using the wrench, apply a turn of 1-1/4 to side 2 of Coupling CpFD.			

PCHT-12	Connect side 2 of Fill/Drain Valve VFD to side 1 of Coupling CpFD.			
PCHT-13	Using the wrench, apply a turn of 1-1/4 to side 2 of Fill/Drain Valve VFD.			
PCHT-14	Verify if Fill/Drain Valve Cap is attached to side 1 of Fill/Drain Valve VFD. If not, reattach.			
PCHT-15	Connect end 1 of Tubing ML01 to side 2 of Tank Connector ESML01.			
PCHT-16	Connect side 1 (Swagelok side) of Coupling CpML01 to side 2 of Tee Fitting TML01.			
PCHT-17	Using the wrench, apply a turn of 1-1/4 to side 1 of Coupling CpML01.			
PCHT-18	Connect Pressure Transducer PtML01 to side 2 of Coupling CpML01.			
PCHT-19	Using the wrench, apply a turn of 1-1/4 to Pressure Transducer.			

PCHT-20	Position the fully assembled Transducer, Coupling, and Tee Fitting length over the Tank Mount TMML01 location as shown.			
PCHT-21	Connect end 2 of Tubing ML01 to side 1 of Tee Fitting TML01.			
PCHT-22	Using the wrench, apply a turn of 1-1/4 to side 2 of Tank Connector ESML01.			
PCHT-23	Using the wrench, apply a turn of 1-1/4 to side 1 of Tee Fitting TML01.			
PCHT-24	Connect side 1 (Swagelok side) of Coupling CpML02 to side 3 Tee Fitting TML02.			
PCHT-25	Using the wrench, apply a turn of 1-1/4 to side 1 of Coupling CpML02.			
PCHT-26	Connect Pressure Transducer PtML02 to side 2 of Coupling CpML02.			
PCHT-27	Using the wrench, apply a turn of 1-1/4 to Pressure Transducer.			

PCHT-28	Position the fully assembled Transducer, Coupling, and Tee Fitting length over the Tank Mount TMML01 location as shown.			
PCHT-29	Connect end 2 of Tubing ML02 to side 1 of Valve VML01.			
PCHT-30	Using the wrench, apply a turn of 1-1/4 to side 1 of Valve VML01.			
PCHT-31	Connect end 1 of Tubing ML03 to side 2 of Valve VML01.			
PCHT-32	Connect end 2 of Tubing ML03 to side 1 of Regulator RML01.			
PCHT-33	Using the wrench, apply a turn of 1-1/4 to side 2 of Valve VML01.			
PCHT-34	Using the wrench, apply a turn of 1-1/4 to side 1 of Regulator RML01.			

PCHT-35	Connect end 1 of Tubing ML04 to side 2 of Regulator RML01.			
PCHT-36	Using the wrench, apply a turn of 1-1/4 to side 2 of Regulator RML01.			
PCHT-37	Position Swageloks of Valve VML01 and Swageloks of Regulator RML01 over Bridge tines as shown.			
PCHT-38	Connect end 1 of Tubing ML02 to side 3 of Tee Fitting TML01.			
PCHT-39	Connect end 2 of Tubing ML04 to side 2 of Tee Fitting TML02.			
PCHT-40	Using the wrench, apply a turn of 1-1/4 to side 3 of Tee Fitting TML01.			
PCHT-41	Using the wrench, apply a turn of 1-1/4 to side 2 of Tee Fitting TML02.			
PCHT-42	Zip-tie Pressure Transducer PtML01 to Tank Mount TMML01 in such a manner to prevent movement.			

PCHT-43	Zip-tie Pressure Transducer PtML02 to Tank Mount TMML01 in such a manner to prevent movement.			
PCHT-44	Zip-tie Swageloks of Valve VML01 to Mount Bridge tines in such a manner to prevent movement..			
PCHT-45	Zip-tie Swageloks of Regulator RML01 to Mount Bridge tines in such a manner to prevent movement.			
PCHT-46	Connect end 1 of Tubing ML05 to side 1 of Tee Fitting TML02.			
PCHT-47	Using the wrench, apply a turn of 1-1/4 to side 1 of Tee Fitting TML02.			
PCHT-48	Pot Pressure Transducer PtML01 using Arathane 5753 to Tank Mount TMML01.			
PCHT-49	Pot Pressure Transducer PtML02 using Arathane 5753 to Tank Mount TMML01.			
PCHT-50	Pot the Swageloks of Valve VML01 using Arathane 5753 to Mount Bridge tines.			
PCHT-51	Pot the Swageloks of Regulator RML01 using Arathane 5753 to Mount Bridge tines.			

5.2. Assembly Clean-up

Step #	Activity	Picture	Performer Initials/Date	QA Initials/Date
PCHT-1	Move core hardware and tank assembly to clean room storage location			

PCHT-2	Dispose of all trash appropriately			
PCHT-3	Put away tools			
PCHT-4	Note any conditions relevant to the next stage of assembly or testing			
PCHT-5	This procedure is complete			

BIBLIOGRAPHY

[1] Air Force Research Laboratory, "University Nanosat Program," May 2007. http://www.vs.afrl.af.mil/UNP/index.html

[2] Leitner, Jesse. "Distributed Space Systems: Mission Concepts, Systems Engineering, and Technology Development" Systems Engineering Seminar. April, 2002.

[3] University of Missouri – Rolla Satellite Team, "00-003 Executive Summary," Rev E, March 2007.

[4] University of Missouri – Rolla Satellite Team, "00-005 On-Orbit Operations Plan," Rev B, March 2007.

[5] Sarafin, Thomas P. Spacecraft Structures and Mechanisms - From Concept to Launch. Microcosm Inc and Kluwer Academic Publishers, 1995.

[6] AFRL/VS, University Nanosat-4 Program, "Nanosat-4 User's Guide," (Limited Release) UN4-0001 – Rev A, University Nanosat Program Office, Kirtland AFB, NM, June 2006.

[7] Larson, Wiley J. and James R. Wertz. Space Mission Analysis and Design. 3rd ed. Microcosm Inc and Kluwer Academic Publishers, 1999.

[8] Launius, Roger D. " Sputnik and The Dawn of the Space Age," July 2007. http://inventors.about.com/library/inventors/blsatellite.htm

[9] "The History Behind Small Satellites," July 2007. http://www.aero.org/publications/crosslink/winter2001/04_sidebar2.html

[10] Jilla, Cyrus D. and Dr.David W. Miller. "Satellite Design: Past, Present and Future," International Journal of Small Satellite Engineering, 1997.

[11] Surrey Satellite Technology Limited, "Small Satellites Home Page, Satellite Classification," November 2006. http://centaur.sstl.co.uk/sshp/sshp_classify.html

[12] Surrey Satellite Technology Limited, "The Company: History," July 2007. http://www.sstl.co.uk/index.php?loc=25

[13] Kitts, Christopher A. and Robert J. Twiggs. "The Satellite Quick Research Testbed (SQUIRT) Program," September 2007. http://ssdl.stanford.edu/ssdl/images/stories/papers/1994/ssdl9401.pdf

[14] Luu, Kim, et al. "Microsatellite and Formation Flying Technologies on University Nanosatellites," AIAA Space Technology Conference, 1999.

[15] Cubesat, "Mission Statement," September 2007. http://cubesat.atl.calpoly.edu/pages/home/mission-statement.php

[16] INSAT 2, "India and Earth Observation Systems," October 2007. http://www.fas.org/spp/guide/india/earth/insat2_eo.htm

[17] Katti, V.R. et al. "Assembly, Integration & Testing of INSAT-2A & 2B," Journal of Spacecraft Technology, January 1994. vol. IV, 154-172.

[18] Griffin, Michael D. and James R. French. Space Vehicle Design. American Institute of Aeronautics and Astronautics, Inc., 1991.

[19] Yee, Terrance. "Key Elements of Rapid Integration and Test," 3rd Responsive Space Conference, 2005. RS3-2005-4001.

[20] University of Missouri – Rolla Satellite Team, "01-001 MR SAT Mass Budget," Rev H, March 2007.

[21] University of Missouri – Rolla Satellite Team, "01-003 MR SAT Volume Budget," Rev H, March 2007.

[22] University of Missouri – Rolla Satellite Team, "05-021 MR SAT Wiring Harness," Rev H, March 2007.

[23] University of Missouri – Rolla Satellite Team, "05-022 MRS SAT Wiring Harness," Rev H, March 2007.

[24] AFRL/VS, University Nanosat-4 Program website, "Nanochat Forum topic-Containment/EMI Boxes" January 2006. http://www.universitynanosat.org/NS5/?q=node/192

[25] NASA. Marshall Electromagnetic Compatibility Design and Interference Control (MEDIC) Handbook. January 1995.

[26] Mironer, A. and Regan, F. "Venting of Space-Shuttle Payloads," Shuttle Environment and Operations Meeting, Washington, DC, October 31-November 2, 1983, Collection of Technical Papers (A84-10926 01-16).

[27] OMAX Precision Abrasive Waterjet Systems, "Equipment Specifications 2652," October 2007. http://www.omax.com/pdfs/2652_207.pdf

VITA

Lori Ann Ziegler was born in St. Louis, Missouri on September 10, 1982 to Thomas and Charlotte Ziegler. She has an older sister, Amy, and a younger brother, William. Lori graduated from Rockwood Summit High School in May, 2000 and enrolled in St. Louis Community College – Meramec in August, 2000. She graduated in May, 2002 with an Associate's in Arts Degree. She then enrolled at the University of Missouri – Rolla (UMR) and graduated Summa Cum Laude in May, 2006 with a Bachelor's of Science Degree in Aerospace Engineering. She continued at UMR and graduated with a Master's of Science Degree in Aerospace Engineering in December, 2007.

While an undergraduate at UMR, Lori was President of Tau Beta Pi (the Engineering Honor Society) and Sigma Gamma Tau (the Aerospace Engineering Honor Society), Chair of the UMR section of the American Institute of Aeronautics and Astronautics (AIAA), and a member of Student Council, Omega Sigma Service Organization, and the Society of Women Engineers (SWE). She received the Sigma Gamma Tau North Central Region Undergraduate Honor Award and the Academy of Mechanical and Aerospace Engineers Student Excellence Award. While a graduate student, Lori received the Chancellor's Fellowship, was a Graduate Teaching Assistant for the Mechanical Engineering senior design course and served as a representative for the Council of Graduate Students.