open space

Satellite Manufacturing Inside Out

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1. Front Matter

1.1 Executive Summary

1.1.1. Context

A configure-to-order spacecraft is like a piece of art—unique, but expensive and time-consuming to produce. Once a satellite is launched, it cannot be sent back to a repair shop, so manufacturers do extensive testing to make sure they get it right the first time. This testing is actually one of the most important, time-consuming, and expensive parts of satellite manufacturing, and it does not always go smoothly. In approximately 75% of manufactured satellites, some internal component will require replacement late in the process. This can often take several months and millions of dollars since the entire satellite must be disassembled and retested to reach the internal component that needs replacement.

Lockheed Martin Space Systems presented the challenge to create an innovative structure for geosynchronous (GEO) communication satellites that is affordable, producible, testable, scalable, and modular. The design team, composed of three students from Stanford University and four from Universidad Nacional Autónoma de México (UNAM), created a new structure that will dramatically reduce the manpower, time, and cost required for assembly and testing efforts throughout the manufacturing process. Although many users will ultimately come in contact with the final product, the main focus will be on assemblers and test engineers, who must endure all current consequences of late box replacement.

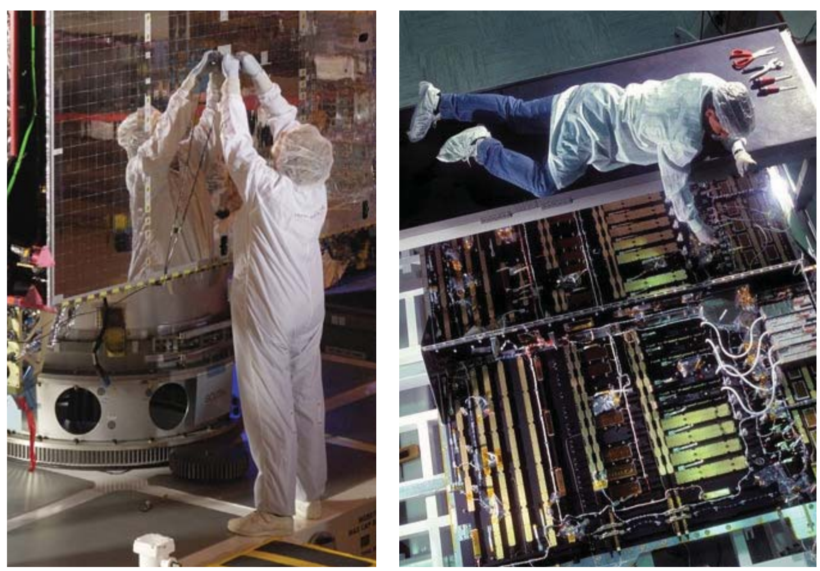

Figure 1 *Current methods of satellite testing often involved a lot of reaching—whether standing in front of a vertical surface or even lying down above the panel to reach components in the center. These working positions are not ergonomic for the assemblers and test engineers.*

1.1.2. Solution—Open Space

The Open Space satellite structure decreases the cost associated with late box replacement from several months to a few weeks and reduces cost by several million dollars. This dramatic improvement in efficiency is achieved by a folding panel design. When a test goes wrong, the panel containing the malfunctioning component can be folded down instead of being disconnected, which greatly reduces retesting since wires remain connected at all times.

This innovative communication satellite structure (Figure 2) has a hexagonal base. Four of its edges are attached to large panels that can fold down during assembly, and the two remaining sides are left open to accommodate satellite antennas during launch. In addition to saving cost during late box replacement, the foldable panels also provide more ergonomic work conditions. The 5-foot wide panels (which are 35% narrower than current panels) allow users to reach components easily, and the working surface is horizontal so that users can assume a sitting position during assembly and testing.

Figure 2 *The Open Space structure has narrower panels that can fold down to allow for easy access to components while also providing users with an ergonomic, horizontal working surface.*

Figure 3 *A physical prototype of the full-scale joint in real materials provided a model for the wire-twisting and heat pipe thermal interface solution concepts.*

Several technical challenges also had to be addressed during the development of Open Space. Over 200 boxes were arranged onto four panels according to real wiring diagrams and required heat dissipation. The center of mass also had to be considered so that the satellite could be launched without creating unsafe moments. The use of a folding mechanism in this structure also necessitated engineering design to allow wires and heat pipes to cross the foldable joint without damaging them (Figure 3). A pivoting fixture was specified to serve as an external hinge, which allows panel rotation without adding any launch weight.

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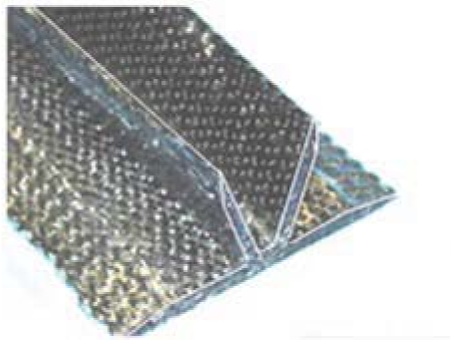
1.5 Glossary

3D preform fasteners- a type of fastener used in composite construction in which a strip with an open slot is attached to one piece so that a tab can be fitted into the slot. Rubber tooling is used to mate the two parts permanently (see Figure 4).



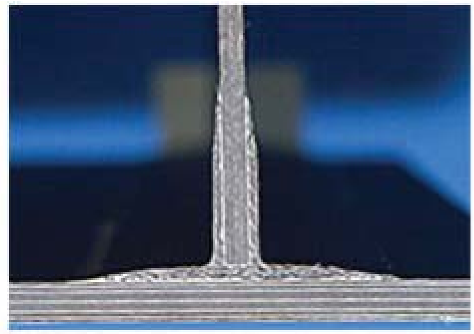


Figure 4 *3D preform fasteners, with a slotted strip (left) that mates with a tab (right).*

Acoustic-Vibe- Acoustic Vibration test,a test in which the entire satellite is subjected to vibrations in all three directions at various frequencies and acoustic waves of several hundred decibels to test for failures or unpredicted vibration modes that would cause problems during launch.

AI&T- Assembly Integration and Test, a commonly used term in manufacturing industries, in this case referring to the attachment of boxes to the structure,construction of the structure,electrical,heat and other connections between boxes the structure,and various stages of testing along the way.

Attach Fitting- a partial-cone shaped fitting specified as part of the Delta IV launch vehicle to which all satellites to be launched must mate mechanically to support their load during launch.

Benchmarking: Examining and/or taking apart existing products in order to understand current solutions.

Boxes: A term used in the satellite industry to refer to the subsystems of a satellite, often manufactured independently.

Brainstorming: Generating large quantities of ideas,usually performed in a group setting.

Bus: The satellite structure which packages subsystems (or boxes), locates payloads, and provides the infrastructure needed to integrate all satellite parts.

CEP: Critical Experience Prototype,a procedure to test an important aspect of the user experience.

CFP: Critical Function Prototype,a contraption built to test an important concept.

COMSAT (Communications Satellite): is an artificial satellite stationed in space for the purpose of telecommunications. Modern communications satellites use a variety of orbits.

CTO (Configure to Order): represents the ability for a user to define the component make-up (configuration) of a product at the very moment of ordering that product, and a vendor to subsequently build that configuration dynamically upon receipt of the order.

Dark Horse: An outlier idea that has high potential for innovation, though it may have low chance of success.

Ergonomics- An applied science focused on designing safer and more comfortable user posture.

GEO (Geostationary Earth Orbit): Geostationary/Geosynchronous Earth Orbit,an orbit pattern approximately 36,000 km from the earth in which satellites orbit at the same rotational rate as the earth so that they appear stationary from a point on the earth s surface.

Geosynchronous Orbit: is an orbit around a planet or moon with an orbital periodthat matches the planet or moon sidereal rotation period.

Late box replacement- An undesirable step in the production process in which several mechanical and electrical components must be de-mated to replace a faulty,inaccessible box. This step is not planned for but occurs at least once on approximately 75% of satellites and can four months and millions of dollars (1).

Payload: The primary functioning components of a satellite like antennas, reflectors and cameras, usually external to the bus. (Contrast to boxes, which perform secondary functions to assist the payloads and are generally internal to the bus).

P.Bot: (Paperbot) A warmup exercise for the begining of winter quarter, every team designed and built a robot that can send and receive messages with others of its kind using a standard protocol.

Rotating Panels: The satellite bus prototype Team LM developed for CFP

SIA (Satellite Industry Association): was formed in 1995 by several major US satellite companies as a forum to discuss issues and develop industry-wide positions on shared business, regulatory and policy interests.

Thermal-Vac: Thermal Vacuum test, a test in which the entire satellite minus solar panels is subjected to vacuum and thermal loads approximating those in space are repeated to test for failures caused by thermal expansion and contraction.

TTeam (Teaching Team): professors,consulting professors and teaching assistants

Team LM (Team Lockheed Martin): The team in charge of the CTO Spacecraft project. It is formed by 3 Stanford students and 4 UNAM students.

Rad-hard (radiation hardened): a term that describes electrical components designed to resist damage or malfunction caused by solar radiation.

Satellite Kit: A set of pieces imagined by Team LM which would be used to ease the plannification and design of a satellite at its very early stages.

SolidWorks: A 3D CAD design software. Used also for analysis and product data management.

Strongbacks: Large sheets of metal used at Lockheed Martin to support panels while on the ground.

X: One prototype that shows the details of the final design concept for one small part of the overall product design

2. Context

2.1 Need Statement

Satellites are a key component in today's lifestyle. They keep people in communication and allow them to survey the planet in real time. In the past few decades, thousands of them have been launched, accomplishing a wide variety of missions. Every satellite in orbit represents a huge human endeavor, but current technologies make it feasible to have a plethora of them in service.

Today's needs demand more satellites. The Satellite Industry Association (SIA) recently reported that "41 commercial geosynchronous orbit (GEO) satellite manufacturing orders were announced in 2009 for future delivery, almost double the orders announced in 2008" (SIA Report 2010). However, these satellites are built as unique, custom platforms for each individual customer. This means that almost every satellite mission starts from scratch, taking from seven to eight years to develop each one. That is a lot of time, but the ultra high costs of putting a satellite in orbit demand it.

Space is a complex environment. Every spacecraft must endure extreme conditions like thermal variations and electromagnetic radiation. Also, launching the satellite to space represents a dangerous stage, because the satellite must resist the vibrations produced by the rocket's motors. Satellites also require complex subsystems like power supply, propulsion, navigation computers, transponders, etc. Integrating such different features in a single structure is a huge challenge. Making satellites is a risky and expensive business.

A lot of people are needed in order to complete a satellite (e.g. design engineers, test engineers, machine experts, etc.), and they need to manage lots of data and expensive equipment. Mistakes are inadmissible, but they happen and need to be solved. In order to reduce the risks intensive tests are done to guarantee a successful mission. If a component fails it needs to be removed and fixed, but this often requires disassembly of other components or even modification of the spacecraft structure, which can cost millions of dollars and several months of work.

Figure 5 *Satellites are like art pieces, they are unique, exotic and expensive.*

The uniqueness of each satellite makes them difficult to develop: custom components, different structures and difficult tests. Is it possible to design a spacecraft structure which supports different payloads? Will this reduce the resources spent in the manufacturing of a satellite? Can a modular satellite improve the integration of different subsystems? Will this lead to a more affordable satellite?

2.2 Problem Statement

Lockheed Martin is aiming to design a new generation of communication satellites that will be configurable, modular and scalable, satisfying different missions with one single structure. This spacecraft design will reduce the time between authorization to proceed to delivery of the satellite to the customer.

The goal of Team Lockheed Martin is to develop an innovative bus structure which will support a predefined set of subsystem components (Boxes). Modularity can be maintained by using a simple connector and bolt pattern or by implementing an extendable box or tank. The structure will be designed to support attachments, cabling, launch loads, and thermal control components, and it must accommodate simple assembly, integration, and testing.

Figure 6 *A CTO Spacecraft would reduce resources spent in Assembly, Integration and Tests..*

2.3 The Design Team

The Lockheed Martin CTO Spacecraft team is composed of three students from Stanford University (SU) and four students from Universidad Nacional Autonoma de México (UNAM).

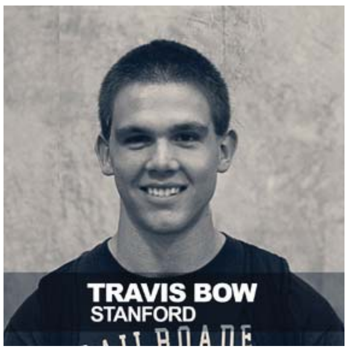
2.3.1. The Stanford Division

Stanford University

Location: Palo Alto, California,USA

Primary Language: English

Fouded: 1891



Travis is a 1st year MS Mechanical Engineering graduate student. He grew up in Reno, NV. He was homeschooled from 5th grade through high school. Out of highschool he won a full ride scholarship to Oklahoma Christian University, heard about Mechanical Engineering program, and decided that was the major for him. He studied there for 4 years, working summers at the University of Oklahoma doing undergraduate research, at Spirit Aerosystems working on business jets, and at Orthocare Innovations working on prosthetics.

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Xiao is a 1st year grad student in Mechanical Engineering. She comes from a traditional Chinese city called Yangzhou. She graduate from Harbin Institute of Technology and get a brand-new start in Stanford as a 1st year graduate student. She majored in Flight Vehicle Design and Engineering and now transfer to Mechanical Engineering for a broader view of Engineering and a more narrow focus on Robotics

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Jessica is a 1st year MS Mechanical Engineering graduate student. Her undergraduate studies were in chemical engineering at UCLA. After a summer internship at Abbott Diabetes Care, where she worked with continuous glucose monitors, she became very interested in medical device design. Since then, she has decided to pursue mechanical engineering with a design and biomechanics focus.

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2.3.2. The UNAM Division

Universidad Nacional Autonoma de México

Location: Mexico City, Mexico

Primary Language: Spanish

Founded: 1910

Isaac is a senior Industrial Design student. He was born in Mexico City in 1985. Before he entered the Industrial Design Career at UNAM, he worked for one year in an architectural design office. There he learnt the importance of design for us, but he was quite bored… He needed more action and the feeling of doing something with his hands. Since he was a kid he has liked solving problems and constructing objects. He enjoys playing guitar, drawing and taking pictures.

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Claudio is finishing the Master of Mechanical Design. He was born in Mexico City and raised in Cuernavaca. He lived two years in Germany, and since 1994, he has been in Mexico City again. He loves reading, drawing, logic problem solving, music listening, dreaming, traveling, food tasting, cooking, Scuba diving, swimming, rock and mountain climbing.

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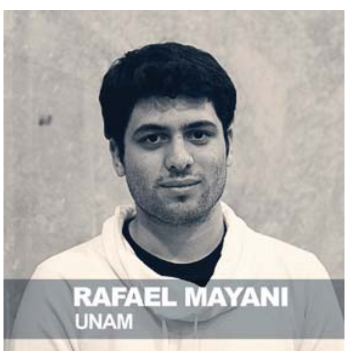

Rafael is an Industrial Design student. He was born in Mexico City, but lived the first 6 years of his life in Vancouver. Since 2006, he has studied at the UNAM University in Mexico City, 1 year of Architecture and almost 4 years of industrial design. Studying Industrial Design has given him a new way of seeing the world and he has always tried to combine his studies with a more artistic part of creativity. For 2 years he has been a freelance graphic designer and photographer.

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Luis is a 1st year Mechanical Design Master student. He is a mechatronic engineer from UNAM. His career has been dedicated to the design of prototypes. He worked at the Center for Applied Sciences and Technological Development (CCADET), and there, he participated in many projects, which were presented at national conferences and some at international conferences. He has taken many courses to complement his vocational training. Some of these courses have been about robotic, design, oratory, and so forth.

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2.4 Corporate Sponsor

Headquartered in Bethesda, MD, Lockheed Martin is a global security company that employs about 136,000 people worldwide and is principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products and services. It has 4 business areas: Aeronautics, Electronic Systems, Information Systems & Global Solutions and Space Systems.

Lockheed Martin Space Systems Company designs, develops, tests, manufactures and operates a full spectrum of advanced-technology systems for national security, civil and commercial customers. Chief products include human space flight systems; a full range of remote sensing, navigation, meteorological and communications satellites and instruments; space observatories and interplanetary spacecraft; laser radar; fleet ballistic missiles; and missile defense systems.

Figure 7 *Some developments by LM: (from left to right) The X-33 Venture Star, the space shuttle's external tank and the A2100 GEO spacecraft.*

2.4.1. Corporate Liaisons

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3. Design Requirements

The project goal is to make satellites more affordable, producible, testable, scalable and modular. Through the course of the past six months this general goal has been decomposed into specific design requirements. These requirements have been broken down into four categories: guidelines, goals, constraints, and considerations. Guidelines are general, high-level requirements (generally given by the liaisons) that narrow the design focus, but aren't necessarily targets to be met with a measurable spec (for example, the satellite will be a communications satellite). Goals are the specific, driving functions that define the design and describe the objectives that must be reached for success (i.e. the satellite must improve box access). Constraints are limits on the design that must be addressed to validate the design (i.e. the satellite must integrate the given set of boxes). Finally, considerations are issues that need to be addressed IF the new design keeps existing solutions from working (for example, wire management must be addressed if the design requires a joint, since wire bundles as they are used currently cannot freely bend across a joint).

3.1 Assumptions

Before discussing these requirements, the project assumptions should be made clear.

Assumption 1: The way to meet the affordable, producible, testable, scalable and modular goal is by redesigning the satellite bus. This assumption was determined by the language of the project proposal and points the design direction toward designing a new satellite infrastructure that will locate the payloads and integrate the various subsystems.

Assumption 2: The subsystems or "boxes" that must be packaged (computing, communication, data handling, switches, etc.) will be limited to a list of currently used boxes with given dimensions, masses, and required connections (see Appendix 1). This assumption was given by the liaisons and provides the specific packaging requirements that shape the bus design.

Assumption 3: The boxes used will be rad-hard and thus need no protection from solar radiation. This assumption was also given by the liaisons and again keeps the design focus on the bus itself, not the boxes.

Assumption 4: Boxes will be electrically connected using wires (bundles, ribbons, etc.). Lots of time and effort has been and is being put into designing wire-less energy & signal transfer, but the team has chosen to assume that wires are (for the time being) inevitable.

Assumption 5: Heat pipes will be used to transfer heat from one side of the satellite to the other. This is Lockheed's currently preferred method of getting rid of heat (since it is difficult to shed head on the sunny side of the satellite, transferring it to the other side allows it to be radiated away more easily). Some satellites employ deployable radiators to avoid having to transfer heat from side to side, but due to the team's lack of experience with radiators and Lockheed's preference this option was ruled out.

3.2 Requirements Overview

Table 1 shows an overview of the guidelines, goals, constraints and considerations the team discovered to guide the design.

Table 1: Requirements Overview

Guidelines	**Goals**	**Constraints**	**Considerations**
General high-level requirements that narrow the design focus, but aren't necessarily addressed by a specific measurable.	*Functions that define the design, objectives that must be reached.*	*Limits on the design, issues that must be addressed to validate the design.*	*Issues that need to be addressed with conceptual solutions if the design keeps the current solutions from working.*
• Communication satellite • Geostationary Earth Orbit • Boxes on interior • Fits current production method	• Allows box access until full system test • Reduces electrical de-mates necessary for box replacement. • Allows for parallel production.	• Integrates given boxes • Lightweight • Made of flat panels and cylinders • .Delta IV volume envelope • Delta IV center of mass envelope • Delta IV minimum resonant frequencies • Delta IV launch loads • User Safety	• Wire management • Heat management • Delta IV attachment • Withstands space temperatures • Solar Panels • User Ergonomics • Fuel Storage

Table 2 *Requirements Overview*

3.3 Guidelines

The following are general, high-level requirements that narrow the design focus but aren't necessarily targets to be met with a measurable spec.

Specification	Metric	Rationale
Communication satellite	Used for relaying television, radio, internet, and other communication signals.	Specified by liaisons to limit project scope.
Geostationary Earth Orbit	35,786 km from Earth, fixed with respect to a point on the earth.	Specified by liaisons to limit project scope.
Boxes on interior	Boxes should be inside the satellite (not exposed to the sun).	It is very difficult to maintain box temperatures if they are exposed directly to ambient temperature fluctuations (-100 °C to +200 °C).
Fits current production method.	Design can utilize current facilities and employees with a tolerable change of +/- 10%.	Box attachment is done in LM's Pennsylvania facility, core structure construction is done in a Mississippi facility, and the two are joined in Sunnyvale.

Table 3 *Requirements Guidelines*

3.4 Goals

The following are the specific, driving functions that define the design and describe the objectives that must be reached for success.

In the autumn quarter the team discovered that costs and time associated with assembly, integration and test (AI&T) were the best places to focus the design to reach the ultimate goal of affordability. In the winter quarter the focus was further narrowed to a specific operation, late box replacement, which can add up to four months and millions of dollars to the cost of production and has not been addressed in any meaningful way by current bus designs.

Late box replacement occurs at Lockheed Martin's facility in Sunnyvale, CA after the two primary structures of the satellite are mated (see Appendix 3 for details). Although extreme efforts are made to have all boxes in place and working properly before this point, about 75% of the time a box has to be replaced (1). Sometimes a hole is drilled in the external panels to access the box, but often the entire structure has to be taken apart to get to the box, which requires de-mating mechanical fasteners and wiring harnesses. Retesting these fasteners and harnesses when they are mated again is a huge cost for Lockheed Martin. Therefore the team has decided to focus on this specific problem by specifying a design that A) reduces the cost of late box replacement and B) does not negatively affect other assembly costs.

Specification	Metric	Rationale
Improves box access	Up until the point when assembly is "locked" and full system tests begin, any box can be accessed without cutting a hole in the structure or requiring users to assume ergonomically undesirable positions.	Currently 75% of satellites suffer from lack of access late in the assembly, which can cost up to 4 months & millions of dollars. Boxes are rarely replaced after full system tests begin.
Reduces electrical de-mates necessary for box replacement.	Only 1 electrical de-mate is needed to replace a box.	Huge amounts of time are spent re-mating and re-testing wires that had to be unplugged to access a faulty box.
Allows for parallel production.	Boxes can be simultaneously assembled on N different subsets of the structure before combining the subsets into the full structure, where N > 1.	Slow satellite construction is often very linear (one must complete step 1 before moving on to step 2). Lockheed currently produces two panels in parallel, a standard that must be met at the minimum (and exceeded if possible).

Table 4 *Goals*

3.5 Constraints

The following are limits on the design that must be addressed to validate the design.

Specification	Metric	Rationale
Integrates given boxes	Supplied boxes must fit inside and connect to one another based on given wiring diagrams.	One of the structure's main purposes is to carry boxes in space. The size envelopes, masses, and heat dissipations of the boxes are given in Appendix 1.
Lightweight	Cost of launching any increased mass should be < 50% of the savings generated by the design (mass cost ~ $36k/kg) (2).	The goal is to use the wiggle room created by lower mass costs to generate AI&T (Assembly, Integration and Test) savings. The mass increase should be significantly less cost than the savings generated.
Made of flat panels and cylinders	>90% of structure mass is made from panels or cylindrical pieces.	Industry standard for low cost; see Lockheed A2100 or SS/L communication satellites.
Delta IV volume envelope	The satellite must fit within a cylindrical envelope, diameter=5.131 m, height=13.075 m, (see Figure A2.1, Delta IV-H).	The inside of the rocket fairing minus a margin for vibratory deflection (1).
Delta IV center of mass envelope	The satellite center of mass must be within a maximum vertical distance from the satellite bottom (2m to 3.4m depending on satellite weight, see Figure A2.3.)	If the center of mass is too far from the attachment fitting at the bottom it will create unsafe moments on the fitting when being launched (1).

Specification	Metric	Rationale
Delta IV minimum resonant frequencies	Axial/Lateral directions: minimum resonance = 30Hz/8Hz respectively (see Figure A2.4, Delta IV Heavy).	Avoiding low frequencies keeps the satellite from coupling with the modes of the launch vehicle and/or deflecting enough to hit the fairing (1).
Delta IV launch loads	Withstands axial body acceleration (between 4.5 and 5.4 g, depending on satellite mass (see Figure A2.5).	Highest loading condition is during launch (1).
User Safety	Zero increase in recordable injuries caused by design changes.	Cost savings do not justify increased danger to workers.

Table 5 *Constraints*

3.6 Considerations

The following are issues that need to be addressed IF the new design keeps existing solutions from working.

Specification	Metric	Rationale
Wire management	Allows equivalent of two 3" diameter wire bundles to run to all installed boxes with >5cm of space between boxes.	Lockheed's preferred wiring method uses two 3" wire bundles for power. Other conduction solutions (besides wire harnesses) were excluded to limit project scope.
Heat management	Allows embedded heat pipes (heat transfer capacity according to boxes specified) to carry box-generated heat from one side of the satellite to the other.	This is Lockheed's preferred method for managing heat; other solutions like deployable radiators were not employed because of time/knowledge constraints.
Delta IV attachment	Attaches to one of five available circular attachment fittings (diameters = 1.566m, 1.194m, 0.937m, 1.664m, and 4.394m, see Figure A2.2).	Boeing requires satellites to interface with one of their standard interfaces (1).

Specification	Metric	Rationale
Withstands space temperatures	Temperatures fluctuations (-100 °C to +200 °C) do not cause static or fatigue failure.	Structure can't be repaired in service.
Solar Panels	Allows two solar arrays of two to five panels each to be attached and deployed.	Solar energy is standard for satellites.
User Ergonomics	Maximum reach = 25", minimum arm space = 4", minimum finger space = 1", maximum unassisted lift weight = 7lb, maximum time spent leaning/crouching = 1 min/hr (3,4).	Ergonomics are important to improve user experience and product quality.
Fuel Storage	The current volume available for fuel storage must be maintained without introducing >10% extra weight caused by containers, fasteners, etc.	Fuel must be carried stably and is often a large part of the satellite's weight, affecting the center of mass and total mass drastically.

Table 6 *Considerations*

4. Design Development

A variety of satellite buses have been designed and applied in the satellite industry. A typical hexagonal satellite bus is shown in Figure 8. After the tour to Lockheed Martin Space Systems in Sunnyvale, CA, the LM Team gained a more comprehensive understanding of the current Configure-To-Order (CTO) satellite structure used at Lockheed Martin, which is the A2100 satellite as shown in Figure 9. The structural components marked in red make up the satellite bus, which mainly consist of a U-shape panel assembly that hosts the various satellite components, a core structure that supports panels and divides fuel tank zones, and a transitional structure that connects the satellite to the launch vehicle.

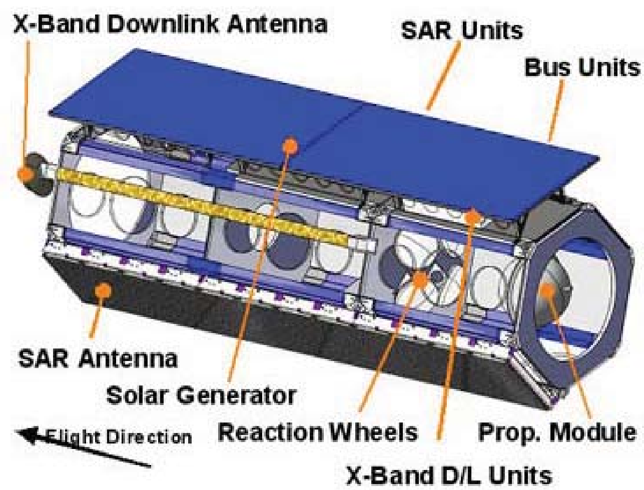


Figure 8 *Bus from TanDEM-X satellite*

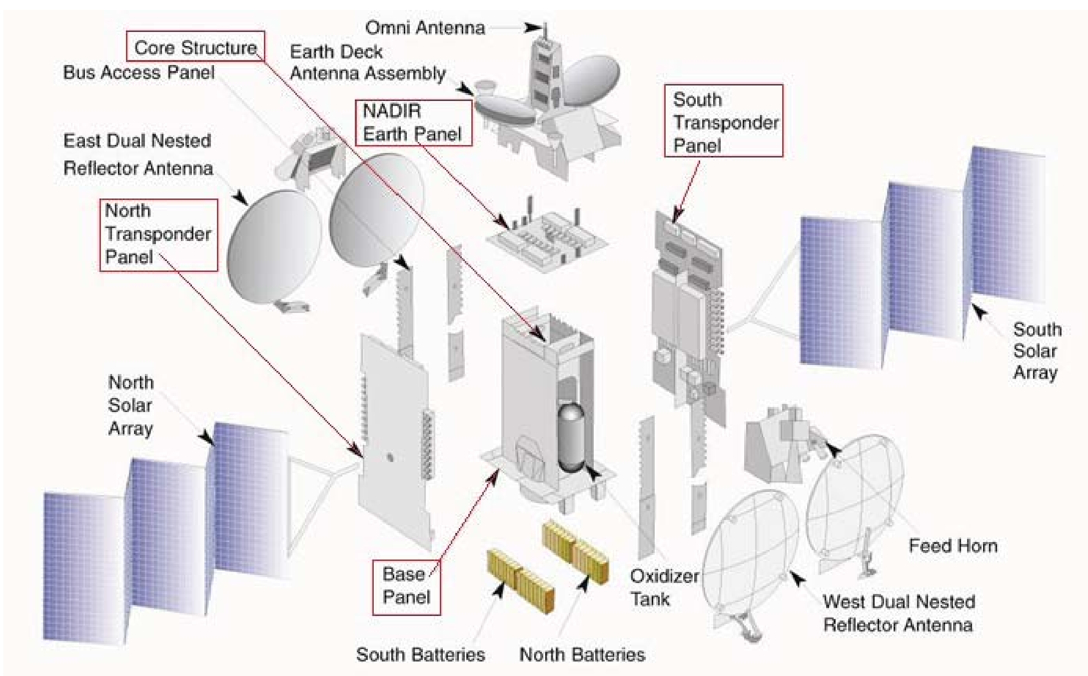


Figure 9 *Decomposed graphic of LM A2100 satellite shows bus structure marked in red*

In the Fall Quarter, Team LM focused on understanding the problem statement presented by Lockheed Martin and benchmarking the current state-of-the-art technology that surrounds CTO Spacecrafts. Learning who the potential users were and creating a “Persona,” a character that represents them, was the first approach for understanding CTO’s Satellite context. The second approach was to learn about basic satellite configuration. Team LM also worked on Critical Function Prototypes in order to attack the problem from different sides. The knowledge obtained from this process was used to better formulate the project requirements and vision.

In the Winter Quarter, Team LM has dived into the project with a deeper understanding of satellite manufacturing, specifically the manufacturing of the A2100 satellite structure. More comprehensive understanding of the current satellite bus structure was developed through design iterations and weekly meetings with the Lockheed liaisons. After several discussions and prototypes, the LM Team decided to narrow down the focus from addressing both wiring and accessibility difficulties to designing a satellite bus structure for better accessibility. The design development of a CTO satellite bus has begun to successfully converge to a potential solution. Computer-aided analysis and more detailed design of the satellite structure are the next steps for Spring Quarter.

4.1 Need-finding and Benchmarking

In the Fall Quarter, Team LM did plenty of Brainstorming, Need-finding and Benchmarking, which broadened our view and opened the door to multiple opportunities and challenges.

To learn more about satellites, the Team looked towards a variety of resources for information and interviewed some people that worked in satellite-related areas, including multiple Boeing © test engineers as well as three professors and students who have been working with Pico-satellites named Cubesats. These experts gave the Team LM important information related to different challenges they had to face when building, assembling or testing new satellites. Team LM also took a tour of Space System Loral © to learn more about the subsystems that satellites have and the current manufacturing process. From these need-finding expeditions, the LM Team concluded that design engineers desired improvements in wiring and collaboration, while test engineers desired improvements in wiring and accessibility. These insights led to the Team’s decision to focus on addressing wiring and accessibility problems through the design of the main satellite bus structure.

In the Fall Quarter, to explore potential opportunities for the project, the Team LM went to IKEA in search of various ways to modularity and easy connections are implemented in existing products. The collapsible/deployable solutions applied in home storage equipment inspired the Team with ways of improving accessibility. Desktop computer disassembling sparked ideas for ways to assemble electrical components. It also raised questions for us, such as how to enhance accessibility and distribute workspace for electronics for satellite manufacturing. To learn more about user experiences regarding configure-to-order products, the LM Team searched for some brands that allowed users to “design” the product that they were going to buy—namely LEGO and Nike websites. This experience helped the LM Team understand the importance of interaction and communication between the customer and the product provider.

In the Winter Quarter, the LM Team continued Need-finding and Benchmarking through weekly Skype meeting with liaisons and references to satellite-related websites. The LM Team also toured Aeromexico's aircraft maintenance hangar to learn more about the manufacturing process and work distribution in high-order vehicle industries. A tour to Lockheed Martin in Sunnyvale, CA, was also very useful for getting more information regarding current satellite manufacturing. These experiences presented more important issues regarding satellite bus design and pushed the LM Team to narrow down the specific area of focus for this project.

4.2 Critical Function Prototypes

4.2.1. Rotating Panels Concept

Will it work to build the bus with various levels of panel that can spin out? The idea of Rotating Panels for the satellite's main structure was inspired by innovative architectural designs and furniture as shown in the Figure 10:

Figure 10 *Collection of Rotating Architecture and Furniture*

The idea development process of the Rotating Panels design for the satellite bus is shown in Figure 11, a diagram depicting how the design team consolidated information from benchmarking, need-finding and prototyping to making the CFP. Figure 12 shows the design of Rotating Panels which basically consists of a main supporting column with multiple rotating panels attached at adjustable intervals.

Compared to current satellite buses, the possible advantages of applying the rotating-panels structure to satellite bus are:

- It saves space by closing panels during transportation and launch.
- The cylindrical bus structure maximizes use of space specified by cylindrical launch vehicle.
- It distributes subsystems to horizontal panels of different levels of height, combining both horizontal and vertical space.
- It has adjustable panels to flexibly change spacing according to different sizes of subsystems.

- It enables easy access by allowing a specific panel to be rotated out when users work on that panel.
- It can either stand upright or be hung from the main column, depending on whether users need to work on the panels vertically or horizontally.
- Panels can be deployed to different directions according to subsystem needs while in orbit.
- The wiring can be simplified by wiring through the main column to different levels of panels.
- It may allow for better dissipation of heat by spinning out panels to improve heat transfer.

Based on the prospective advantages of rotating panels, the LM Team decided to build the Rotating panels bus for the CFP. Due to time constraints and test conditions, the LM Team decided to focus on one important aspect of the design, specifically the wiring experience with this bus structure.

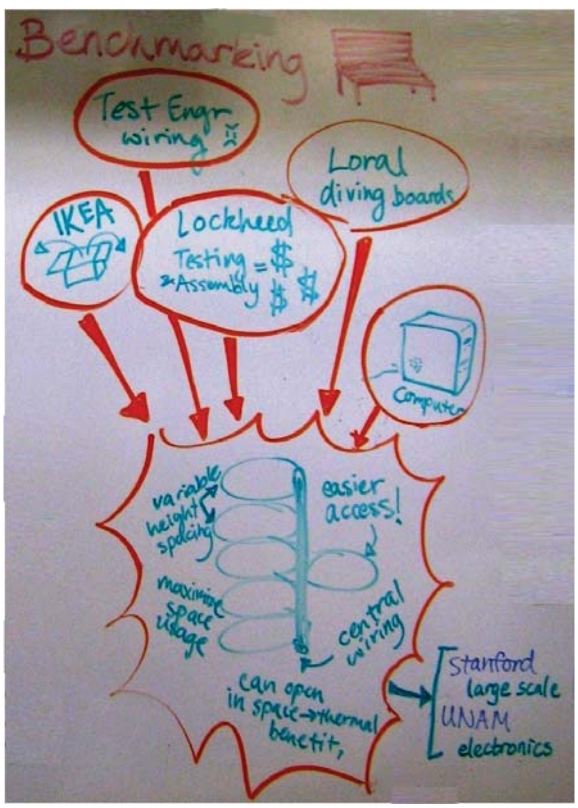


Figure 11 *Design development Chart of Rotating Panel for CFP*

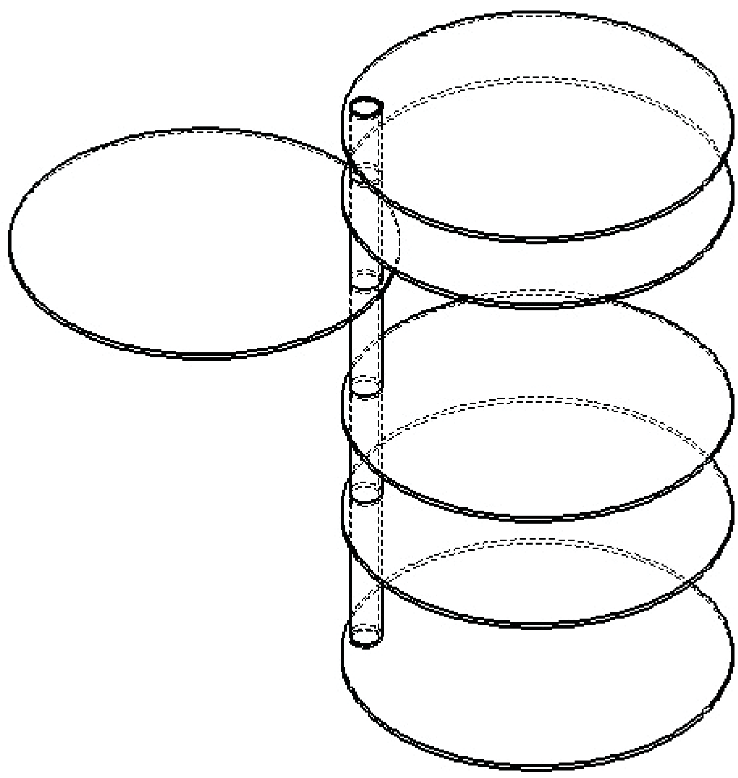


Figure 12 *Sketch of Rotating Panels idea for CFP*

4.2.2. Large Rotating Panels Prototype Construction

4.2.2.1. The Materials

In real satellite manufacturing, the materials for the bus are highly reliable and can withstand the harsh environment in outer space. The LM Team learned during Winter Quarter that the current bus structure of the A2100 is made of honeycomb aluminum material. However, as an initial prototype, materials for the CFP were chosen based on functionality and availability in local hardware stores. Therefore, the main columns were made of PVC pipes, and the panels were made of insulation foam board. The materials used for the CFP prototype are presented in Figure 13.

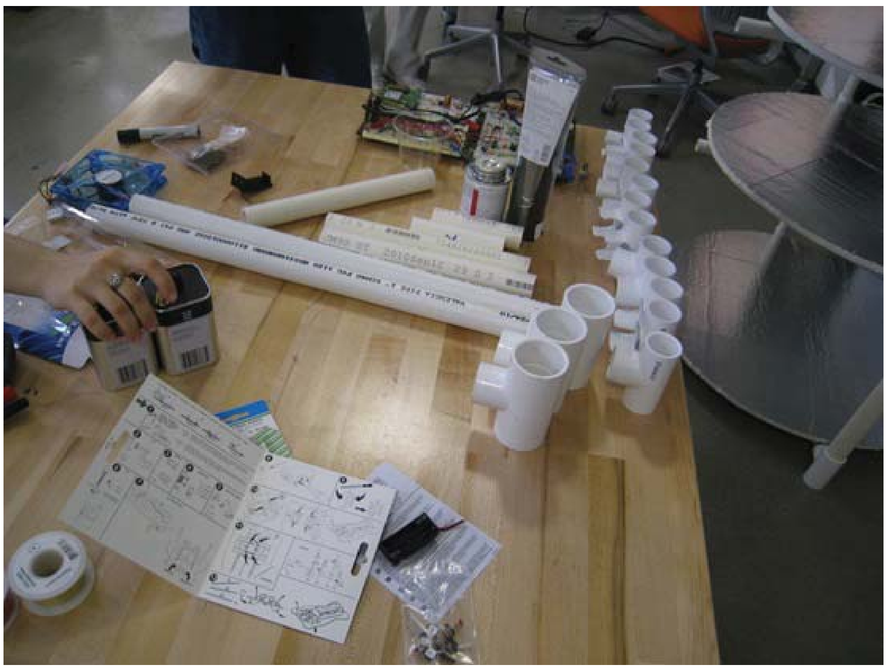


Figure 13 *Construction materials: PVC pipes, foam panels and T connectors*

4.2.2.2. The Attachment

Since one focus of the CFP was to design a wiring system with easy connections and high reliability, the LM Team decided to use a simple attachment mechanism as shown in Figure 14. The distance between panels were different in order to model height adjustability, which can be customized to the size of the boxes on each panel. To stabilize and support the panels, two extra columns were added, as shown in Figure 15. Cross pipes were used to connect the panels with the main column. In order to best test the user experience, some cross pipes were placed under the panels while others were placed above them, as shown in Figure 16.

4.2.2.3. Wiring Test

To test wiring through the main column to different panels, the LM Team came up with the idea of connecting string to the wires to pull the wires through pipes. This process is shown in Figure 17. There were crossed PVC pipes, either below or above each panel, which were connected to the main column. The idea of central wiring was brought up in order to take advantage of this hollow supporting structure. To aid the wiring process, holes were drilled at each intersection of pipes, and several loops of string were used, represented as the dashed blue lines shown in Figure 17. The loops of string were made tight or loose for testing different user experiences. To move wires from one panel to another, one end of the wire was tied to the string corresponding to that panel. As the string is pulled in the right direction, the wire would be pulled through the pipe. When the wire came out from the next intersection of pipes, it would be tied to the next loop of string. This same process was repeated until the wire arrived at the desired panel.

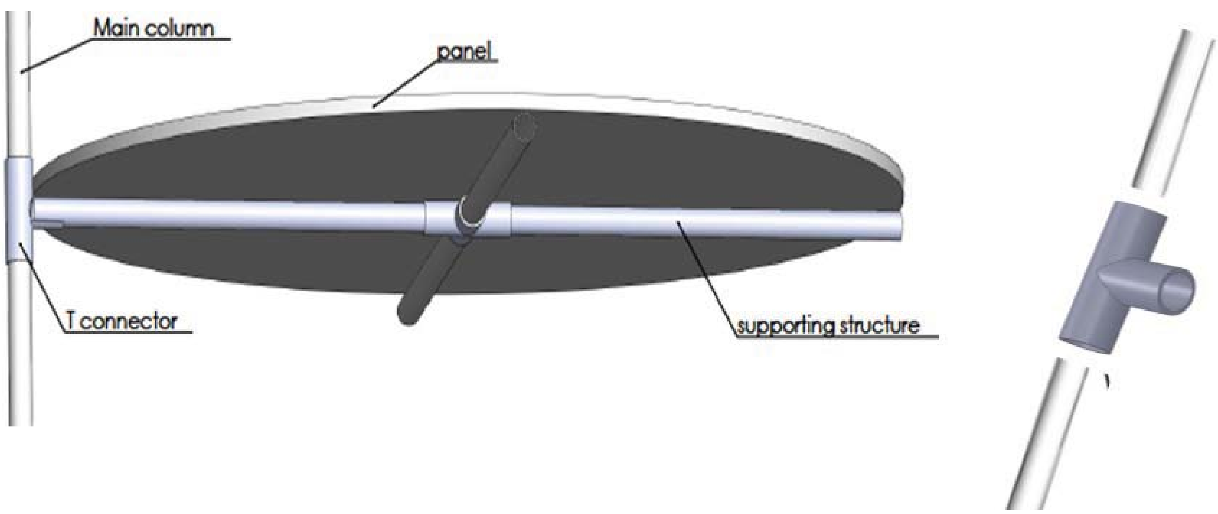


Figure 14 *Panel Attachment and Column connection design for CFP Prototype*

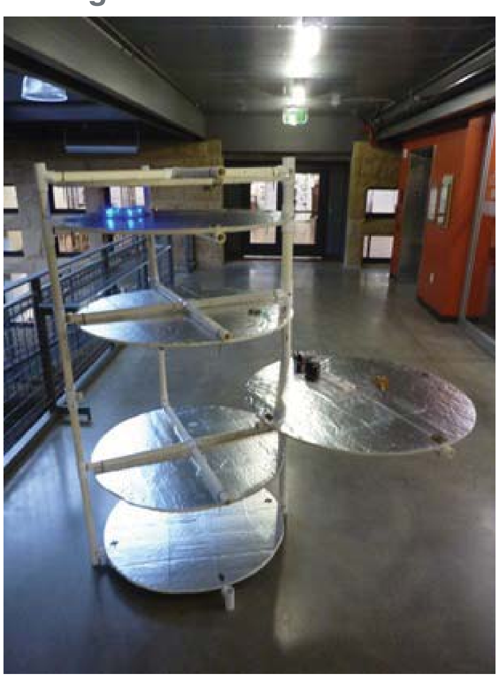


Figure 15 *Large Rotating Panels CFP Prototype*

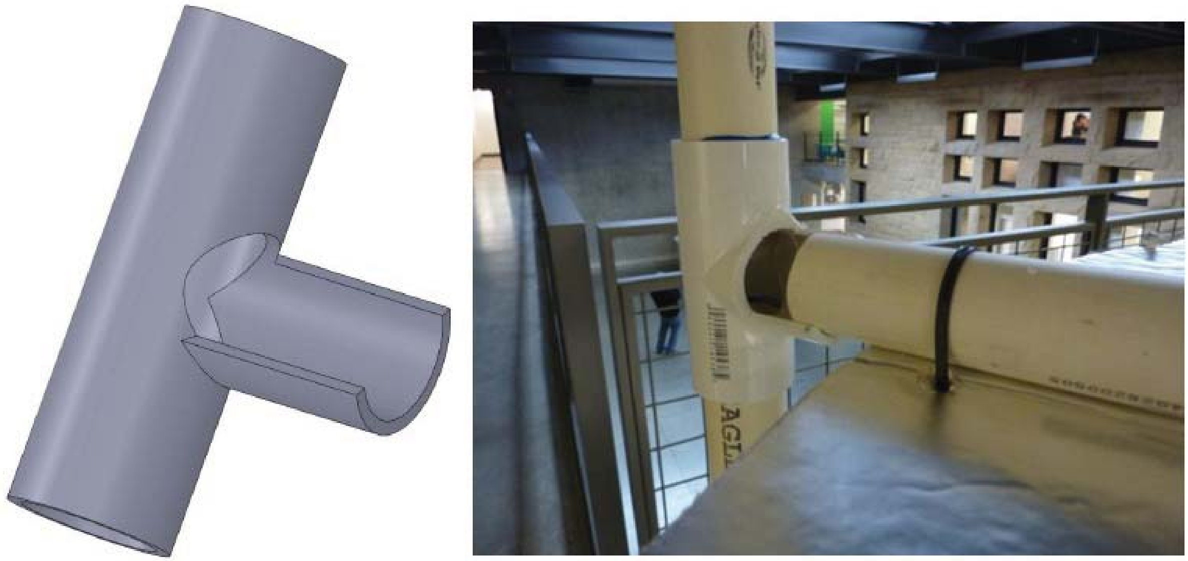


Figure 16 *Adjusted connector enables strong connection and easy release*

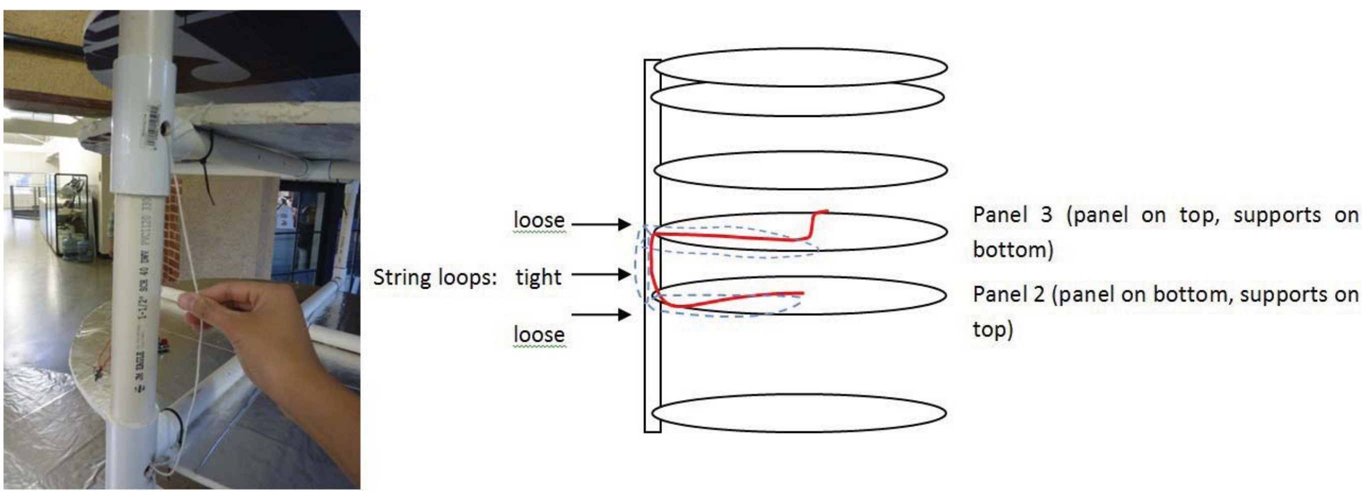


Figure 17 *Graphic interpretation of wiring strategy with help of strings*

4.2.2.4. Large-scale CFP Conclusion

During construction of the Rotating Panels structure design for the CFP, the LM Team encountered several challenges, but new insights were discovered and new thoughts were also generated. and the orientation to build the Rotating Panels became clearer. A summary of what was learned from building this CFP include:

- It was easier to install components on panels before putting panels on frame.
- Wiring through the tubing is more difficult than expected.
- An outer tube covering may be used for larger/thicker cables.
- Small wood pieces are useful to protect the foam board.
- This structure is not very balanced—it needs support beams.
- Many shapes are possible for support beam notches.

4.2.3. Small Rotating Panel Prototype

4.2.3.1. Motivation for the Computer Chassis with Rotating Panels

A satellite is basically a main bus structure that has several components attached to it, called the payload. When the LM Team was still wondering what kind of prototype could provide some answers regarding modularity, the Team had no concept of what type of components these were. So, the the first question that the LM Team decided to address was, “Given a ‘satellite’ with particular components attached, can the structure be rearranged in some way to allow the maintenance technician to have easier access to necessary components?”

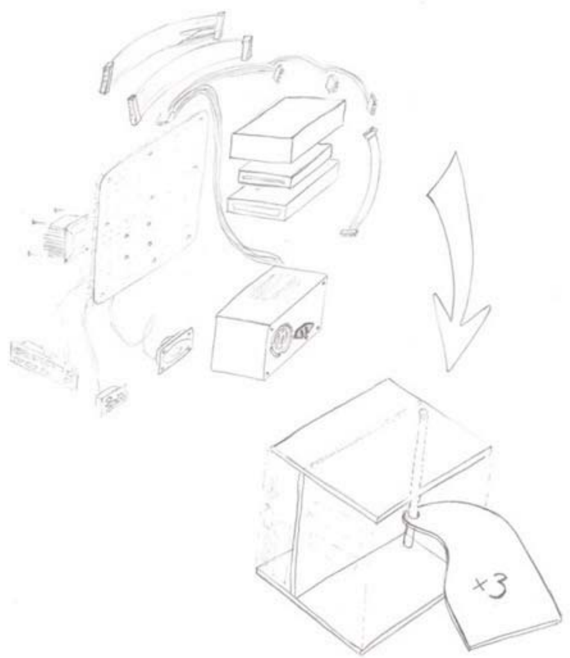


Figure 18 *Rotating solution for computer structure*

LM Team proposed a computer chassis for this experiment and tried to figure out how to rearrange all computer components in a more accessible way. Figure 18.

4.2.3.2. Development of the Computer Chassis with Rotating Panels

The Team began to have some configuration difficulties while working with the computer parts, because it was discovered that there were not very many possibilities for rearranging the components. The cables were too short and tangled, the ventilation system had to be put in a particular position, and it was necessary to install the user interfaces at the front of the structure.

Several tests were made to try to resolve these problems. With the computer already disassembled, the Team began to play with the components and try to understand its behavior. Some of them had to be put together—not necessarily on the same panel, but somewhere nearby. Others had more mobility, because of their cable length and could therefore be put anywhere. The PC board could not be cut, so it necessitated a fixed minimum dimension. After analyzing some ideas, the Team arrived at a final rotating panel configuration. Figure 19 shows a CAD assembly of the final solution.

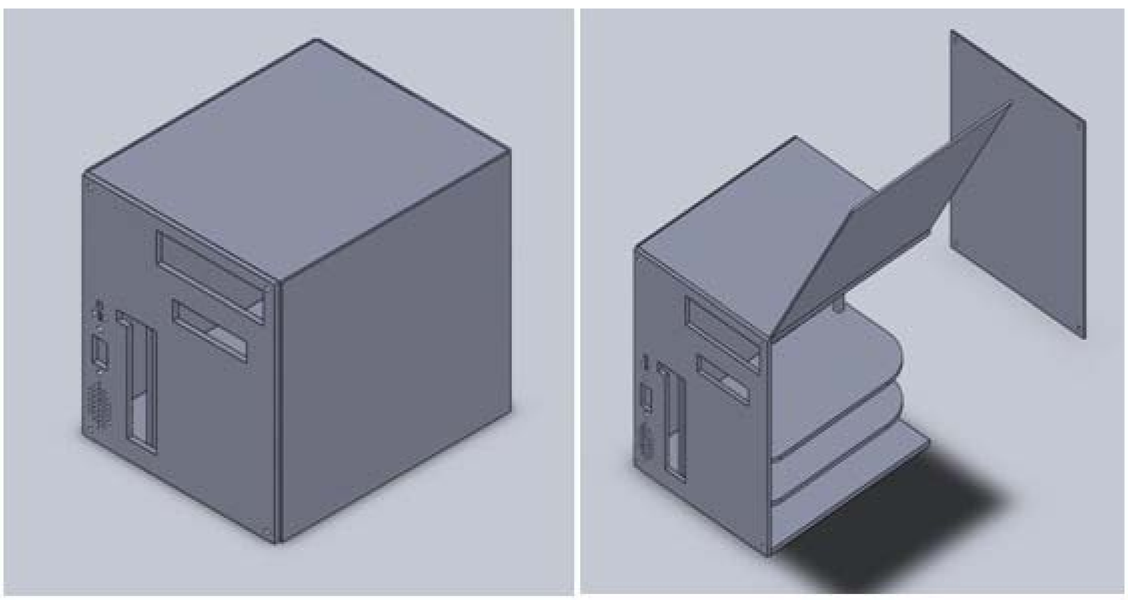


Figure 19 *model of CFP -- Small Rotating Panels*

TM Team took measurements of the computer board, the CPU, the Disc Lector, the bolt holes and locations, and other specific dimensions. The computer board was the largest dimension of all components, so space considerations were made regarding the possibility of adapting other cards to the board, asis expected in a computer. Figure 20 shows some examples of the work in progress.

The prototype was built using wood, because it is easy to work with and not conductive, thus reducing the likelihood of a short circuit. An attempt was made to test the panels to verify that everything worked. The Team found that the wires did not have enough room to move when the panels rotate, so to correct this problem, a slot was made on the panels. Some pieces of PVC pipe were used to provide spacing between the rotating panels.

After the structure was finished, a shell of cardboard was made for the outside of the computer, so that the new dimensions could be compared to the original chassis. Figure 21 shows the exterior and interior of the new structure design.

Figure 20 *Construction Process for Small Rotating Panels*

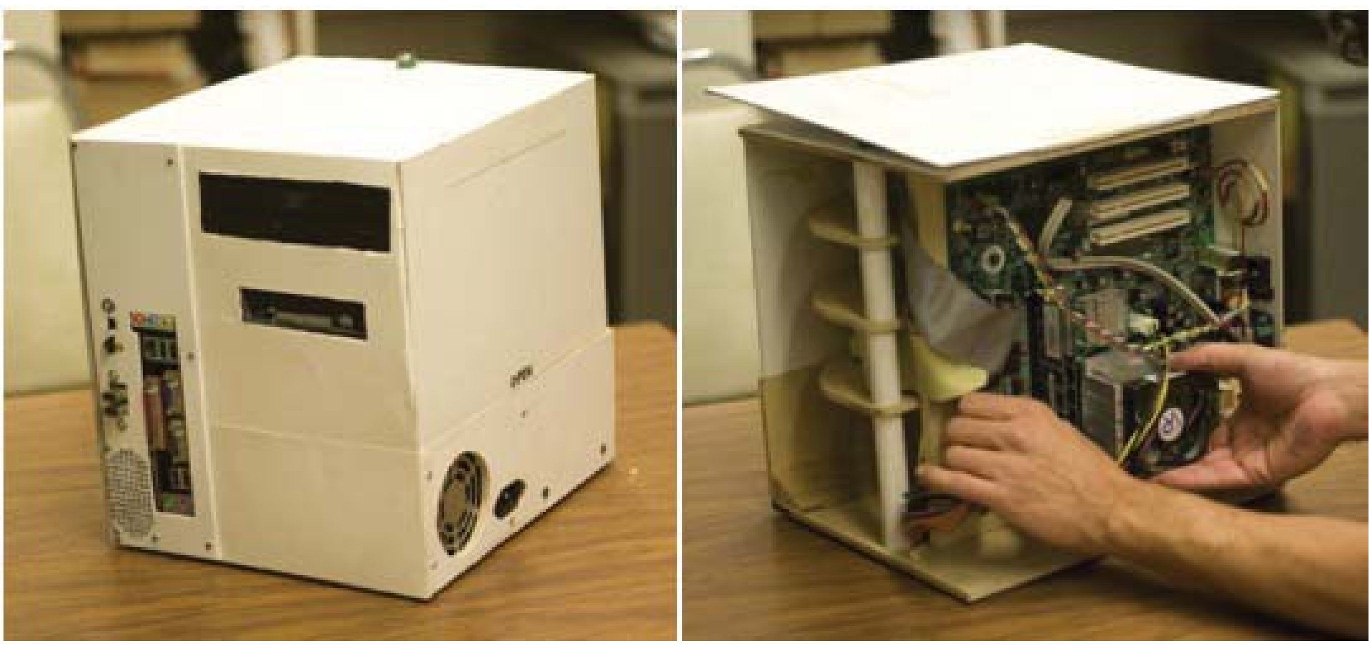


Figure 21 *CFP prototype -- Small Rotating Panels*

After exploring many ideas and many possibilities, the team decided to focus on two areas of the satellite this quarter: the connection between the different elements of the satellite and the design of the main structure. After analyzing the various complications that arise during satellite development and manufacturing, these two specific areas seemed to have the most opportunity for decreasing the time necessary to build and test the satellite.

4.3 Dark Horse Prototype

The Dark Horse Prototype was intended to have a slightly lower success probability but a high potential for return. After observing the wiring difficulties during the construction and testing of the Rotating Panels design in the Critical Function Prototype, Team LM attempted to try to find a better way to connect the components and to eliminate external wire harnesses by putting wires into the structure itself. The potential solution was building a giant PCB and imbedding conductors into the connection points, which became the two main explorations of the Dark Horse prototype.

One of the ideas was to build a breadboard-like panel, which provides an easier and faster way to connect the different elements, or boxes, of the satellite, similar to a standard breadboard that is used for electronic circuits.

To build this prototype, the team first performed benchmarking using PCBs and breadboards, as shown in Figure 22. The team decided to use cables and terminal blocks to build the giant breadboard.

The structure for this prototype was an octagonal base with foldable panels; the wires and terminal blocks were laid on the panels, as shown in Figure 23. Users could connect each terminal block to a component that belongs on the panel.

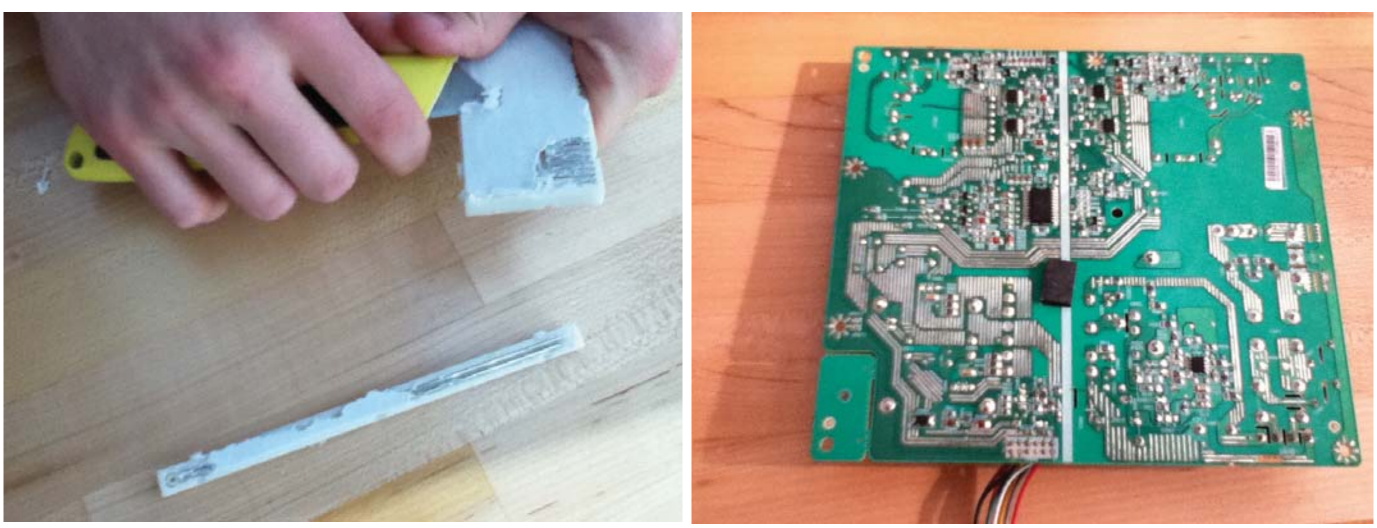


Figure 22 *Explorations on PCBs and Breadboards*

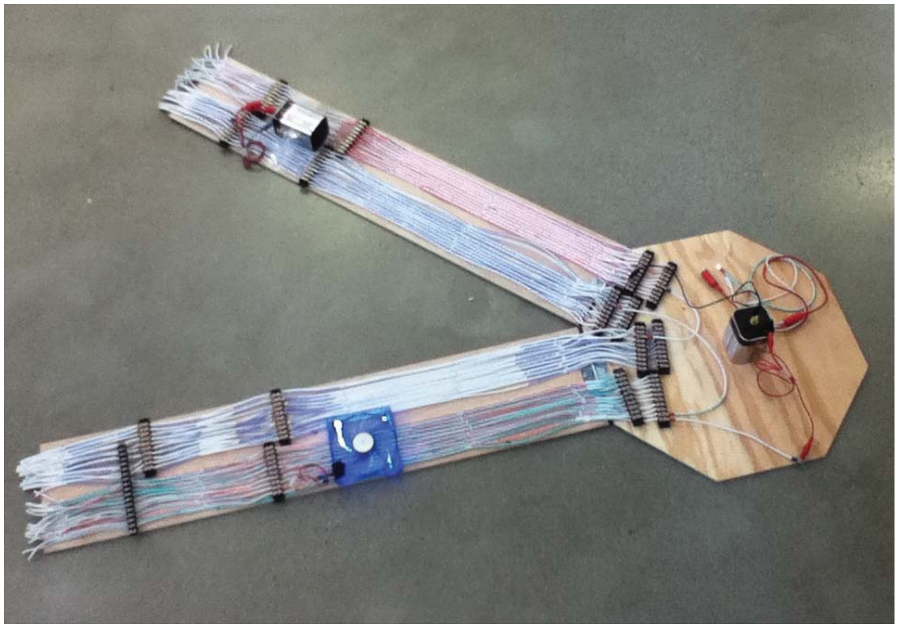


Figure 23 *Dark Horse prototype of a giant breadboard satellite panel with terminal blocks used to connect components.*

The other idea was to develop a universal connector that could be integrated in the structure of the satellite. The goal of this prototype was to allow users to connect multiple elements in a single joint. This universal connector was a tube that contains both the cables and terminal block in each end. This terminal block was composed of nine rings of copper, which were located at different heights and were of different diameters in order to isolate the rings and therefore allow for multiple simultaneous connections. This configuration was chosen because the copper rings would allow the universal connector to be rotated without affecting any of the connections.

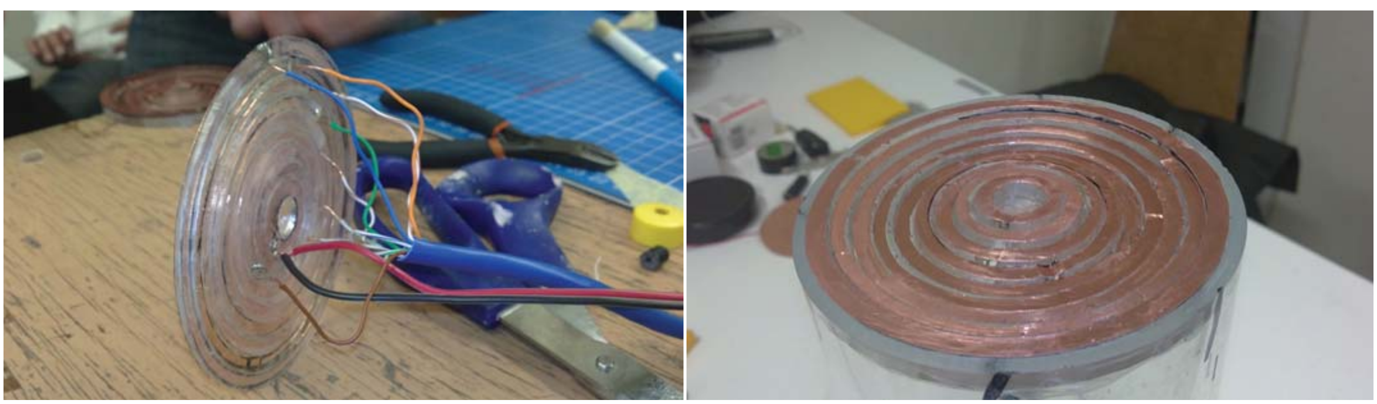


Figure 24 *An image of the terminal block of the universal connector. The nine copper rings allow for nine separate connections to be joined through this one point.*

As in the previous prototype, this idea also explores a structure that integrates the wiring connectors. The idea behind this structure was that each universal connector was part of the tubular structure, and each end of the tubes could be connected to a component on one of the satellite panels.

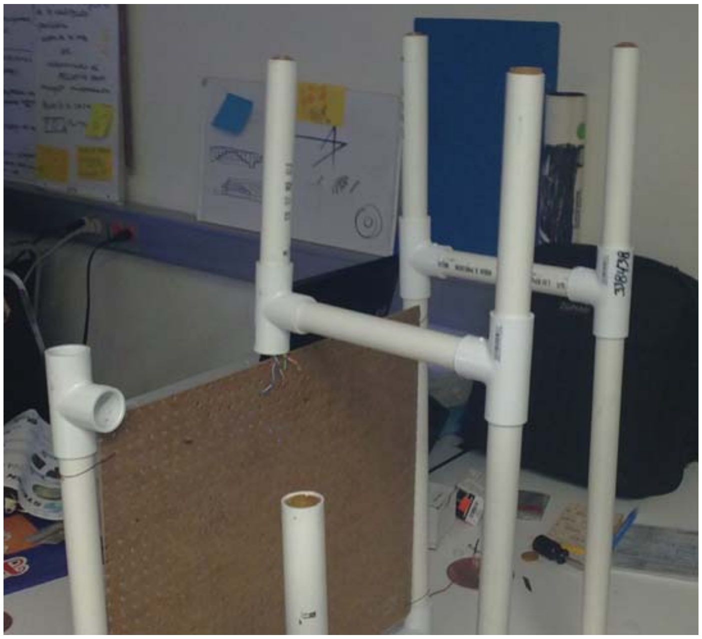


Figure 25 *The concept of the universal connector was to be able to rotate any pivot point while still maintaining electrical connections.*

At the end of these Dark horse prototypes, Team LM learned that wiring issues were much more complicated than originally anticipated, but at the same time, the folding structure design seemed to present a good area of opportunity. Some problems found in the first prototype were that all the unused cables presented unnecessary extra weight, and in the universal connector prototype, Team LM realized that the connections were not stable and would often fail.

The key insights discovered during the Dark horse prototype are summarized in the following table.

Prototype 1: wires integrated into folding panels	Prototype 2: wires routed through structural tubes with rotatable connection
Layout or wires makes it possible to connect boxes to each other and/or to the middle.	Not a robust or versatile electrical connection method
Making integrate panels is difficult.	Manufacturing difficult.
There could be safety issues	The type of connection is unstable
Bending wire at frame must consider how the wires move when panels are readjusted.	A welding system would be necessary
since connectors are larger than wires, they must be staggered	It is necessary to know if the connection is working
Might extra weight	Possible interference betwen cables
Need strips or other no-wired section to mechanical mount the boxes	Structure is easier to build when already wired
Heat dissipation could be a issue	

Table 7 *Key insights discovered during the Dark Horse prototypes.*

4.4 Funky Prototype

The next step was the Funky prototype, a quick and low-cost prototype used to start the converging phase of design development through making something functional, despite unrealistic materials. Based on previous learnings, Team LM focused design efforts on developing a structure based on folding panels that could be scalable and modular, while also allowing easy accessibility to the components.

For the Funky prototype, the team delved into two related ideas, one of these was based on folding panels and the other on flexible/rigid connectors. The purpose of the first prototype was to transform a 3D structure into a 2D version in order to improve accessibility of the internal components.

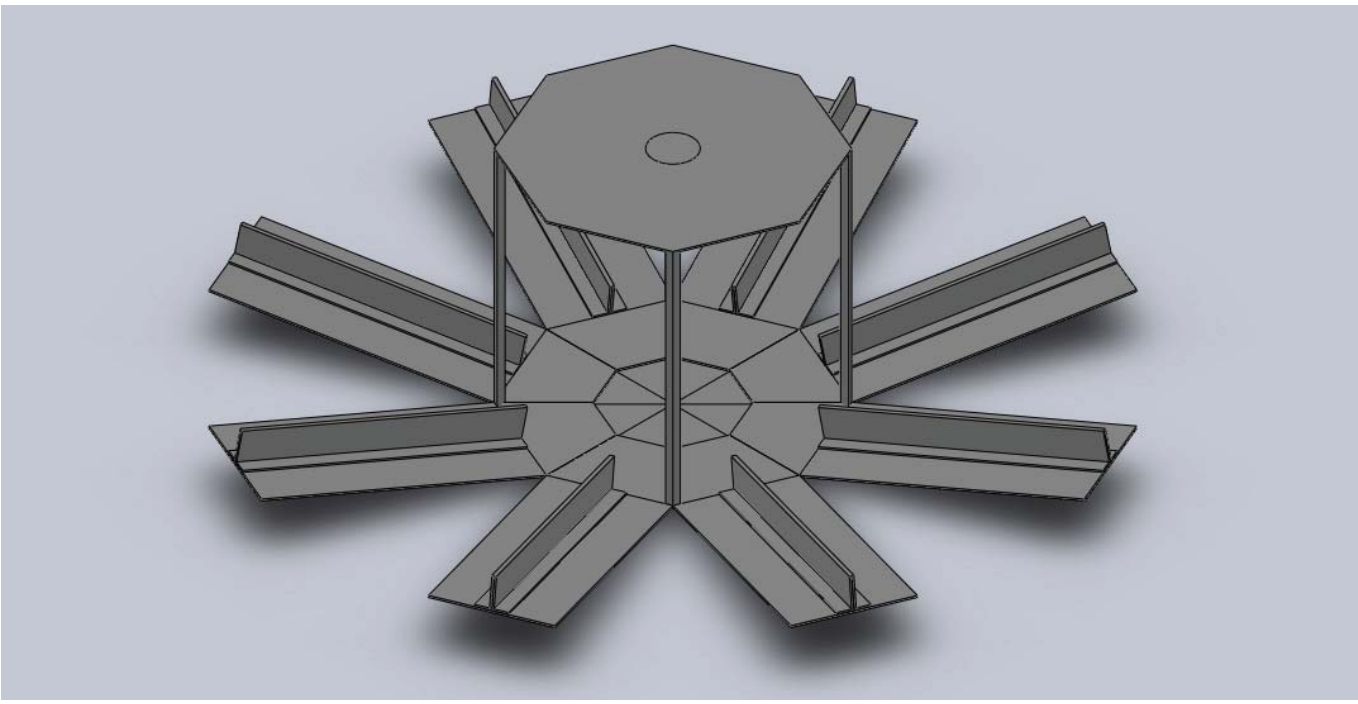


Figure 26 *A SolidWorks rendering of one component of the Funky prototype. The 3D structure can be opened to allow the panels to lay flat for easy access to internal parts.*

For this prototype, the team decided to divide the structure into three modules that could be stacked to form the full structure. The idea was to allow each module to be assembled and worked on in parallel, thereby reducing the overall required production time. The form of the structure was again octagonal, and this prototype was built in a 1:5 scale. At the same time, the team drew the satellite subsystem components in SolidWorks. These boxes were then made physically such that they could be rearranged on the panels.

The panels of this prototype were made of cardboard and the structure was made with PVC tubes. Only one level of the structure was built because the other two levels would be virtually the same, so it was unnecessary to build all three levels in this phase of the design.

The principal function of this prototype was that the components can be accessed without unplugging, which represents a critical advantage through decreased time of testing and repairs.

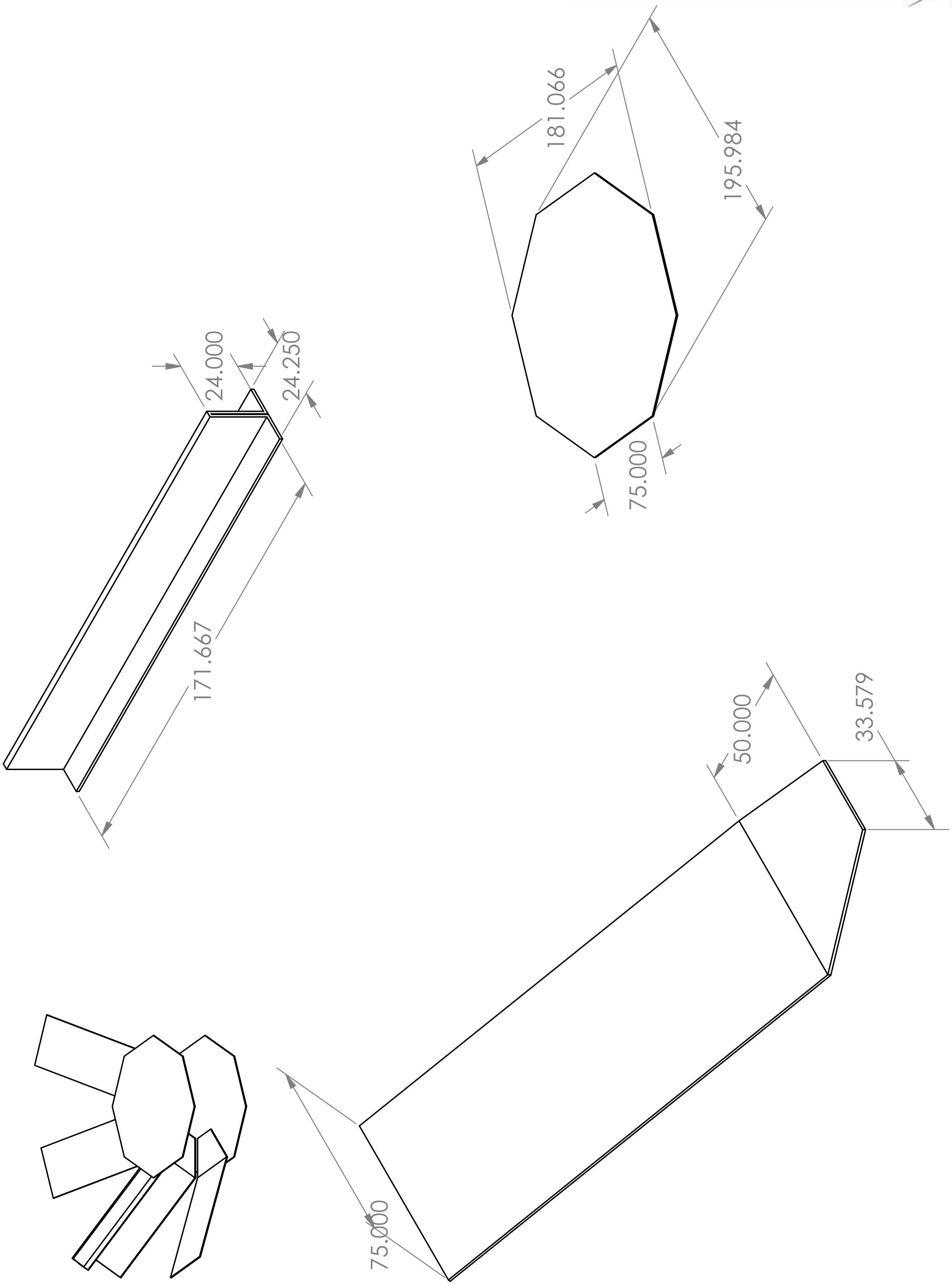


Figure 27 *Part dimensions*

Figure 28 *The Funky prototype constructed out of PVC pipes, cardboard, and duct tape.*

The second prototype explored quite a different way of making foldable panels. The idea for this prototype was to create a structure that could be scalable while also being easy to assemble and rearrange. To achieve these goals, Team LM developed panels that could be attached to adjacent panels along the each edge. Two different connectors were available—one rigid and the other flexible. The purpose of these connectors was that the rigid connectors could be used to create larger flat faces, while the flexible connector could be used to create edges. For this prototype, Team LM did not need an extra supporting structure, because the individual small panels could be combined to build the structure itself.

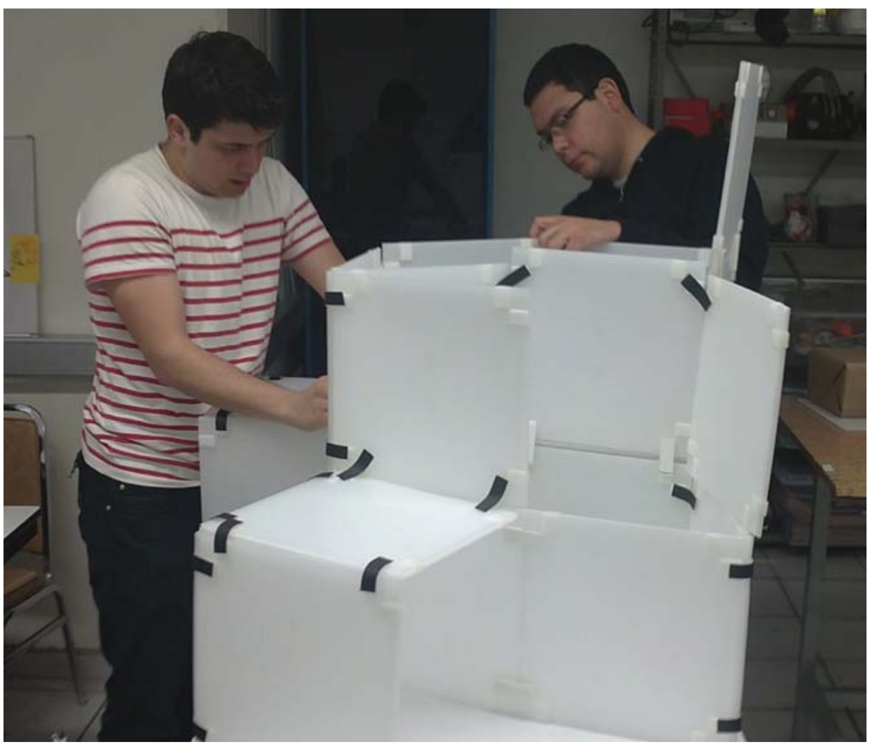


Figure 29 *The second Funky prototype that has both rigid and flexible connectors to customize the shapes and sizes of each side of the structure.*

The panels were made of Coroplast (corrugated plastic sheet), and each sheet had eight pieces of Velcro, one in each corner. The pieces of Velcro were part of the connectors, and these connectors allowed panels to be attached either flat or bent, forming different unions between panels.

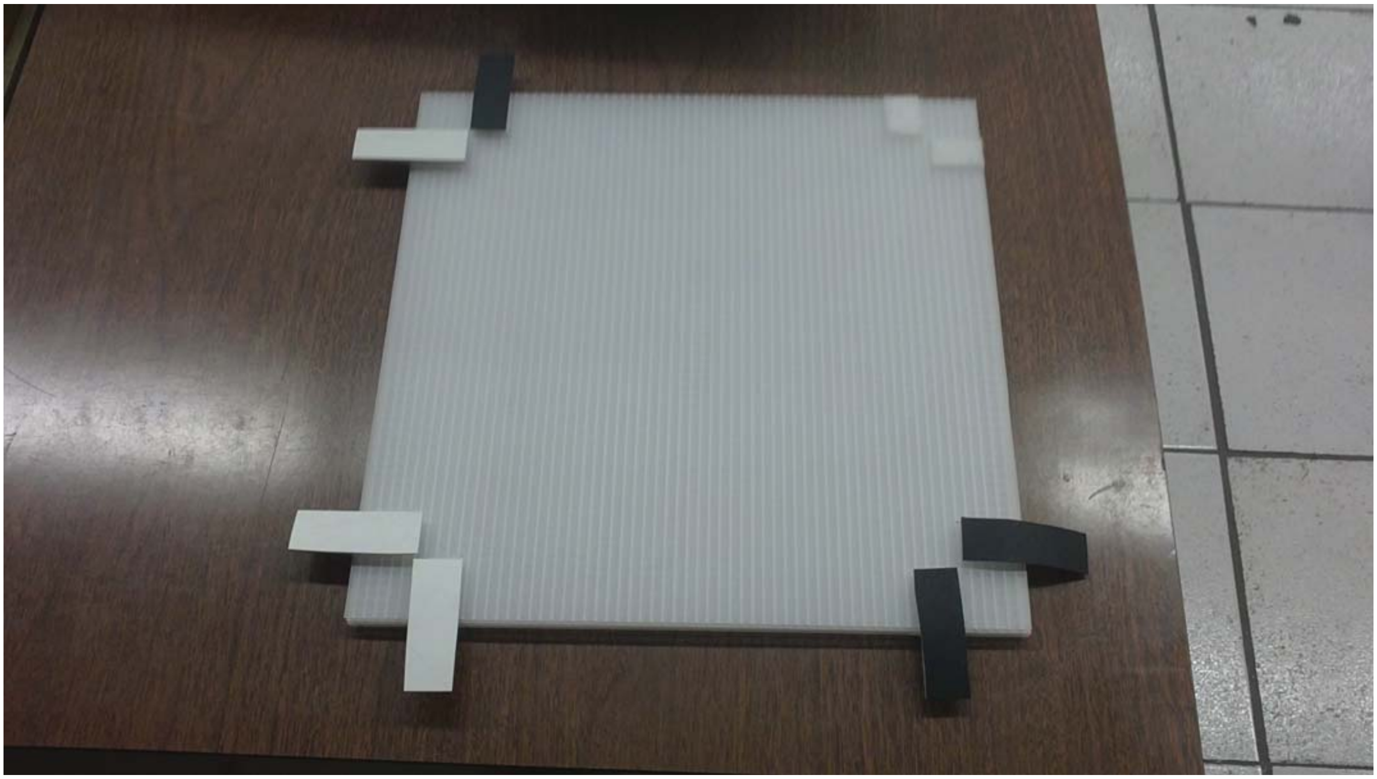


Figure 30 *One unit panel showing eight Velcro connection points. The white ones are rigid, The black are made of Velcro.*

The following table shows key insights gained from the two Funky prototypes built:

Prototype 1: octagon with eight folding panels, 1:5 scale	Prototype 2: unit size panels with flexible/rigid connectors
Space needed for given boxes is less than we thought.	Inter-connectable panels can be arranged into an enormous variety of shapes.
“Wasted” space in the center.	The modular structure allows it to be scalable.
Narrower panels would benefit users (assemblers & testers).	Larger faces can be created by connecting several panels.
Need to address material considerations (composite panels).	Big boxes can be attached to the structure.
Accessibility & wiring seems to be improved.	Accessibility is improved, because every panel can be opened by removing some of the connectors.

Table 8 *Key insights gained from the two Funky prototypes*

4.5 Functional Prototype

The Team's work culminated with the Functional System Prototype—the "Bow Tie" structure, a name derived from its open configuration. This design addresses the problem of late box replacement by decreasing the required time from four months to one week, which will lead to a cost reduction of several hundred thousand dollars. This dramatic improvement in efficiency is achieved by the folding panel design that allows access to satellite components with fewer necessary disconnections, and therefore fewer retests.

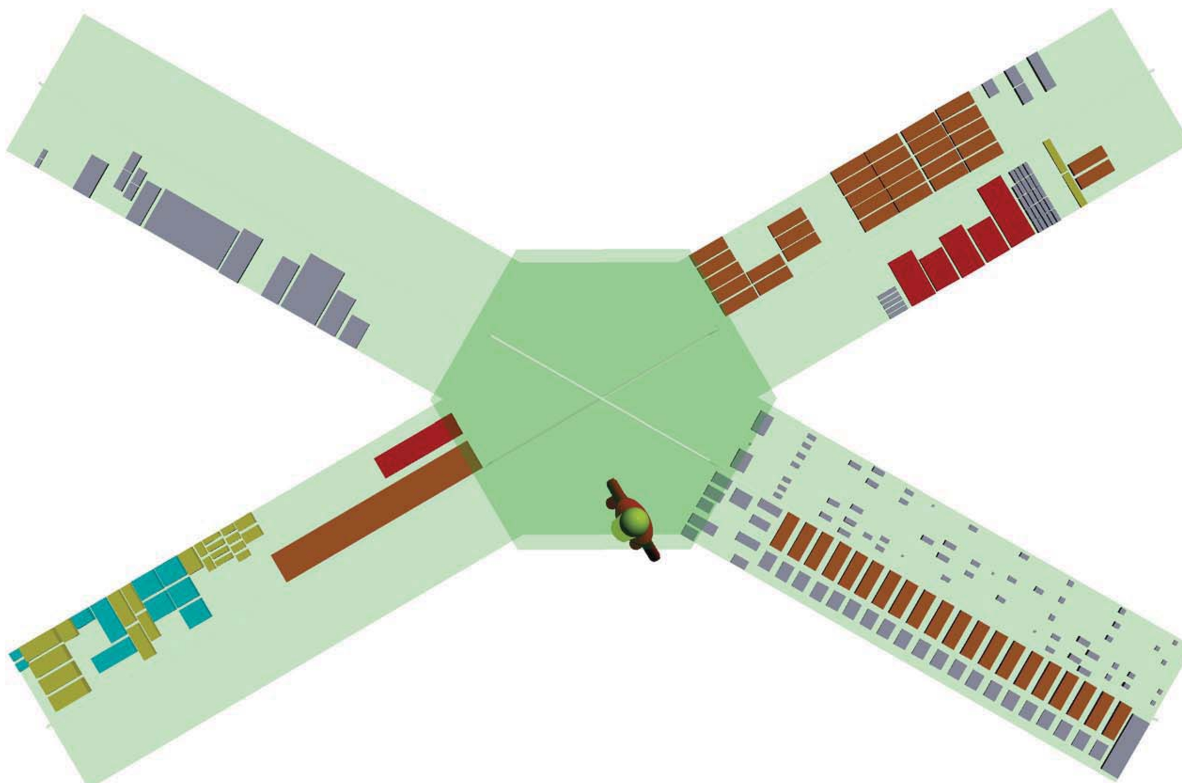


Figure 31 *This SolidWorks rendering shows the top view of the open configuration of the "Bow Tie" satellite structure, which has a hexagonal base and four large foldable panels. The subsystem components are attached to the panels, while the two open sides allow for folding of the satellite antennas during launch*

For the Functional System Prototype challenge, LM team focused on two components of the functional system prototype—panel assembly and hinge design. The purpose of this prototype was to address the problem of late box replacement. Other benefits of this structure included flat panels for simple manufacturing, narrow panels for easy reach of components, a central supporting structure for attachment of panels, and hinges that allow panels to rotate and lock. The use of more realistic materials directed the Team towards practical implementation considerations such as the use of cranes for lifting the large panels.

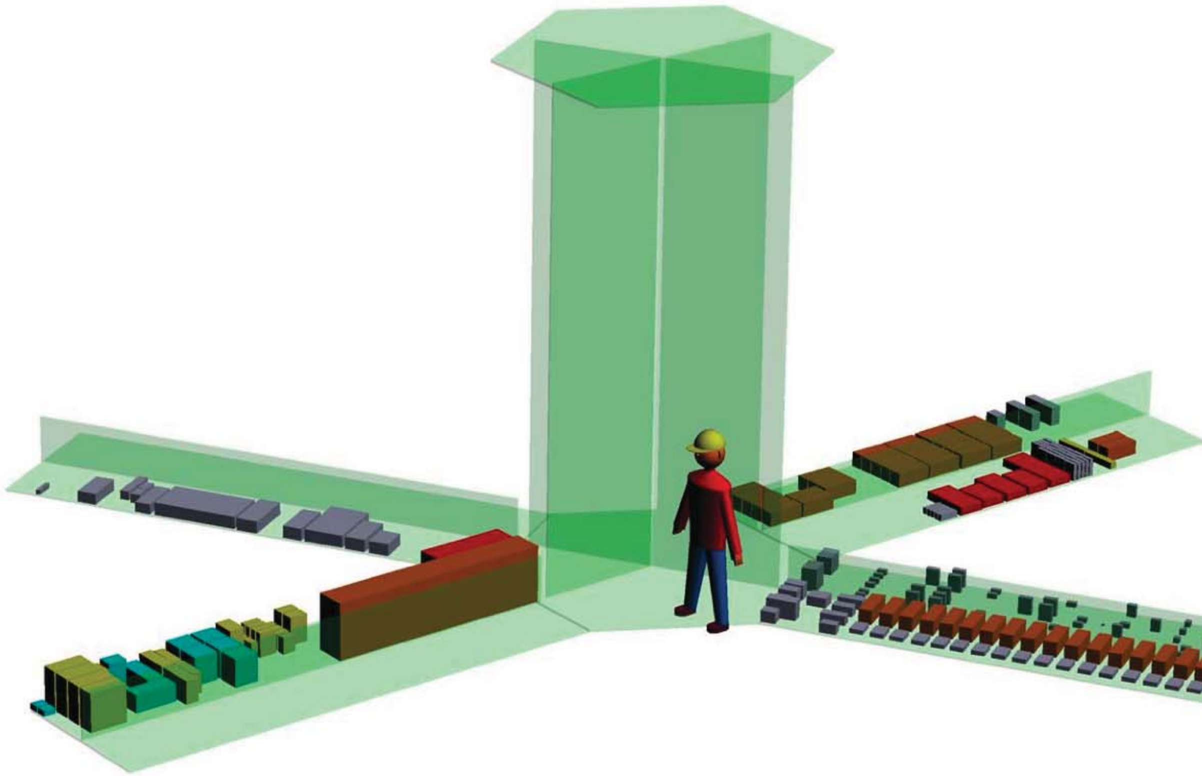


Figure 32 *This SolidWorks rendering of the Functional System prototype shows a 16-foot tall structure with a diameter of 5 feet. For scale, a 6-foot-tall person is included in the model.*

This prototype was made in a more realistic scale of 1:2, and the folding panels were made of 1/2-inch thick polyisocyanurate foam insulation (Rmax brand). The structure of this prototype was a hexagonal prism supported by an “x” shaped core structure that connects the top and bottom hexagons. Commercial hinges were used as a place-holder until final hinges are developed. For this prototype, the team built a representative number of boxes to the same 1:2 scale with objective of having a better idea of the density of distribution of the satellite components.

Figure 33 *The "Bow Tie" structure demonstrated the benefits of a folding panel design while also addressing logistical issues through more realistic construction materials. The four panels can be opened for access to components (left), and they can be closed for launch (right).*

Figure 34 *A half-scale version of the "Bow Tie" satellite structure with some representative scaled boxes attached to the panel in the lower right side of the image.*

The second part of this prototype was the design and development of the hinges. The purpose of this innovative hinge design was to allow the structure to be scalable by adding or removing panels, modular by creating many different structures and more accessible by providing access to boxes without disassembling the entire structure.

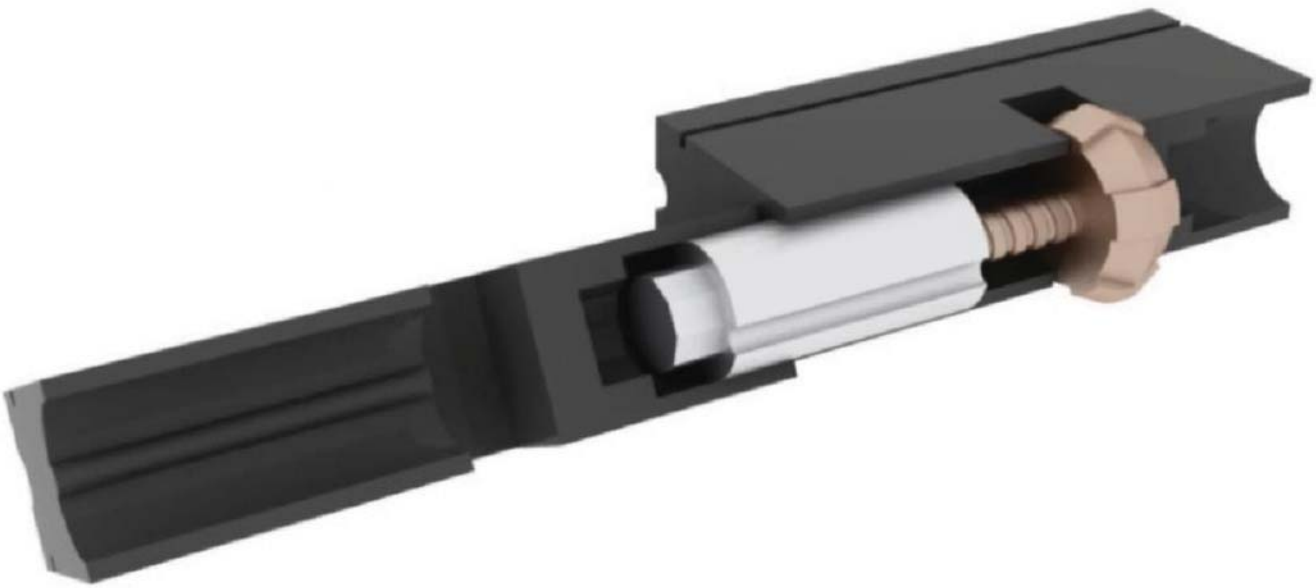


Figure 35 *A SolidWorks rendering of the hinge design that allows panels to be rotated and also locked in various different angles.*

The hinge was made of Nylamid and aluminium and was composed of three parts: the structural part, a roller and a bolt. The main function of this hinge is that it can be used for attaching and detaching panels easily and independently, allowing rotation about the axis when necessary. An additional advantage is that the hinges can also be fixed at a specific angle in order to build different structural configurations. To achieve this, the bolt has two different geometries: one is a normal cylinder, and the other has a hexagonal cross-section; the first cylinder is used to allow rotating about the axis, and the hexagonal cylinder is used to lock the hinge in a specific position.

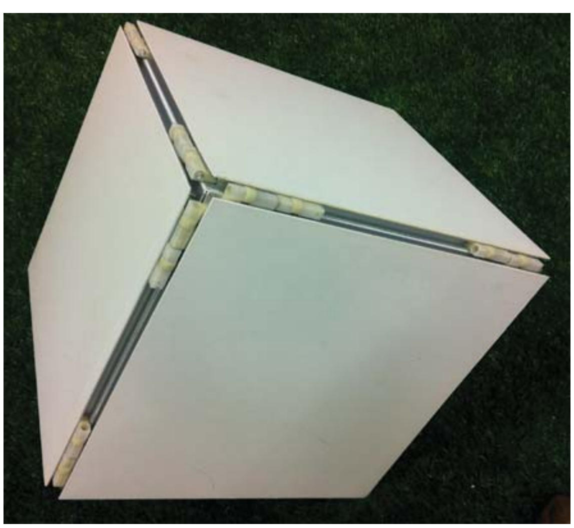


Figure 36 *The physical model of the hinges attached to square panels. With this hinge design, each panel can be rotated and locked at multiple angles. For this prototype, the panels were made of aluminum and sheets of polystyrene.*

Insights from the Functional System prototype are that:

Functional Prototype
A crane will be needed to lift the large panels.
"Strong-backs" and others ground support equipment will be needed when lifting the panels.
Inserts, plates, etc. can be used to attach hinges, bolts, latches, etc.
Glue and bolts on delicate materials works, but it takes time and great care.

Table 9 *Insights from the Functional System prototype*

The next steps for this project include further analysis of the details regarding the "Bow Tie" structure design.

4.6 The Wooden Joint

Following the functional system prototype, the next large hurdle was to determine how the joint would function. Since this hinge is the major difference between existing satellites and the new folding panel idea, a design concept had to be developed to accommodate these alterations.

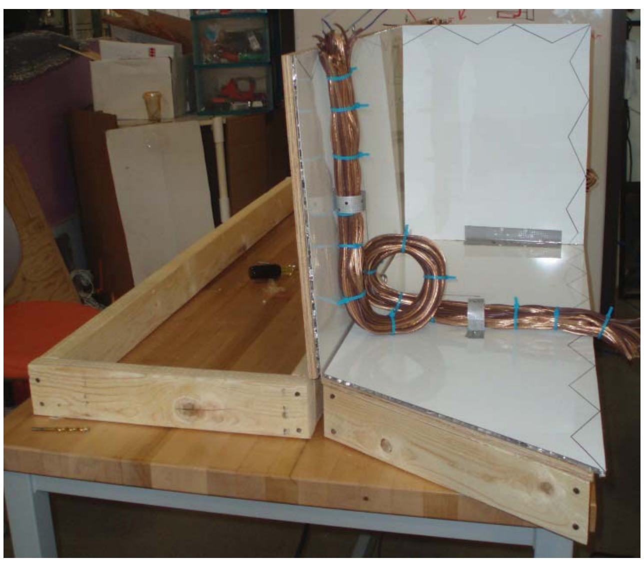


Figure 37 *The wooden strongback supports the panel as it is being folded up or down. The hinge is mounted on the strongback and will not be launched in order to minimize the launch weight. Wire loops are used to decrease the bending forces and reduce the possibility of damage to the wires during bending.*

The "X" prototype (Figure 37) was a high resolution, full scale model of the satellite joint with a wooden strongback and initial conceptual solutions for heat transfer and wiring. It modeled a full-scale cut-out of the satellite (Figure 38). This prototype showed how a hinge can actually be placed on the ground support equipment instead of on the actual satellite. By doing this, the overall weight of the satellite would be decreased, allowing the panel to fold down without greatly increasing the weight-associated cost of the folding design.

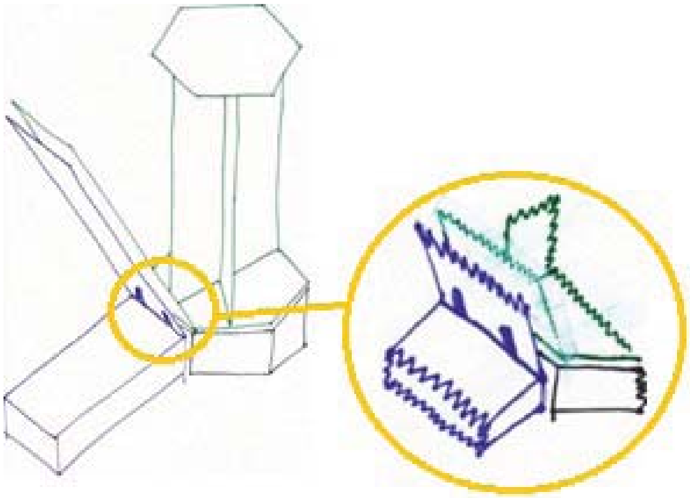


Figure 38 *The hinge is a cutout of the full scale satellite structure, where the green lines show the satellite and the blue lines show the ground support equipment.*

According to the liaisons, a typical satellite has two 3”-thick wire bundles leaving the power source of the satellite. Assuming the wires are divided evenly among four panels, each panel will have two wire bundles that are 1.5” thick. These wires cannot be directly bent because this introduces stresses into the system which can cause the wires to malfunction. Therefore, a design concept had to be developed to reduce the stress on these wires. The initial concept for the wire bundles at this stage of design development was to utilize a loop configuration, as shown in Figure 39 The wires were then attached to the honeycomb panels using wire clamps.

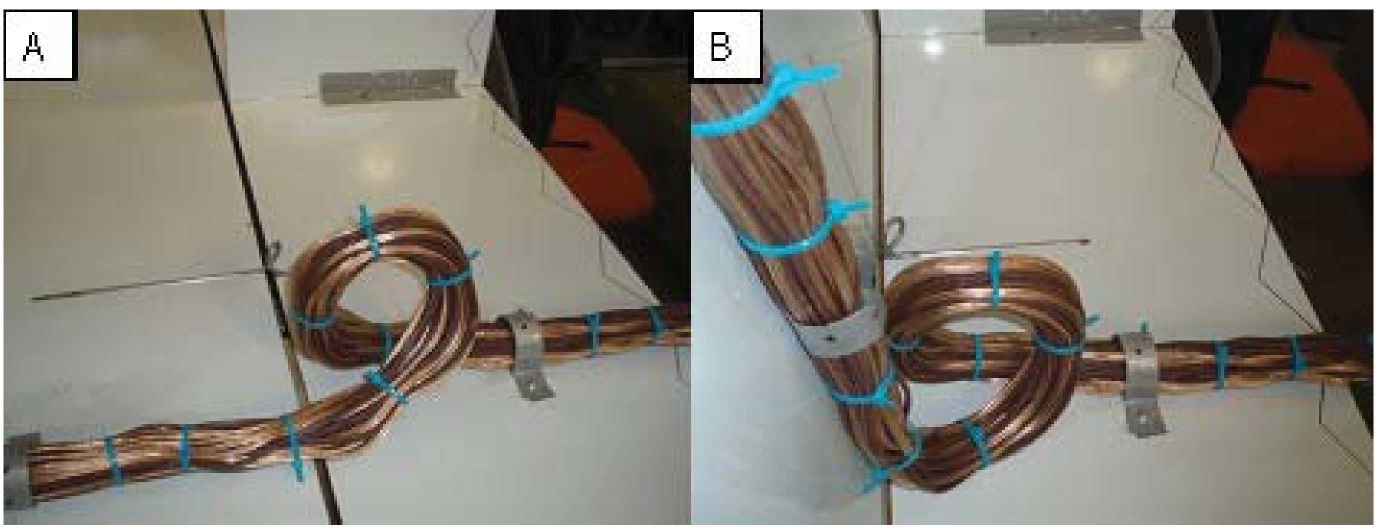


Figure 39 *The hinge in its open configuration (A) and its closed configuration (B) shows how a loop in the wire and the heat pipe may be used to decrease fatigue stresses experienced through opening or closing the joint.*

In the standard A2100, rigid heat pipes are used. Therefore, another design concept needed to be developed to allow for efficient heat transfer across the foldable joint. One option that was explored at this stage of development was the flexible heat pipe, which is technology that already exists (Figure 40). In the prototype modeled, a flexible metal piping was used to show how the heat pipe might look when put into a loop configuration to reduce the stress.

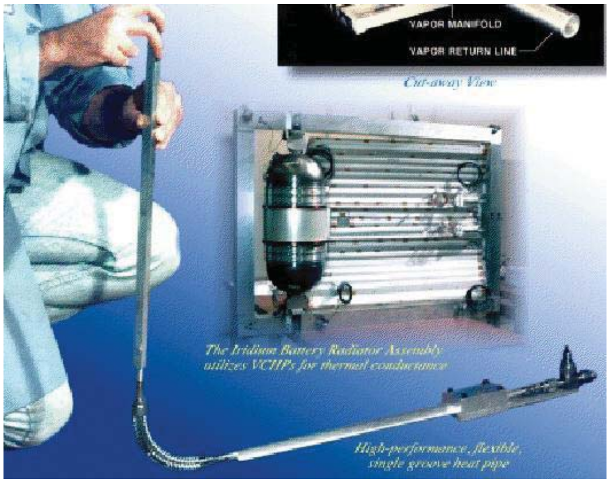


Figure 40 *Lockheed Martin, as well as few other heat management solution companies, have developed flexible heat pipe technologies. These heat pipes are one option for allowing heat transfer across a foldable joint.*

4.7 Cutout Joint Model

After the initial “X” prototype the team made several modifications and improvements. It was at this stage that the core structure was redesigned to have a cylindrical center. This final cutout joint model was made with as many real materials as possible, as if it were cut out from the actual Open Space satellite (Figure 41). Therefore, the foldable panel was made 5 feet wide to match the actual dimensions, and the base was made a partial hexagon. The detailed dimensions are described in Section 5.1.

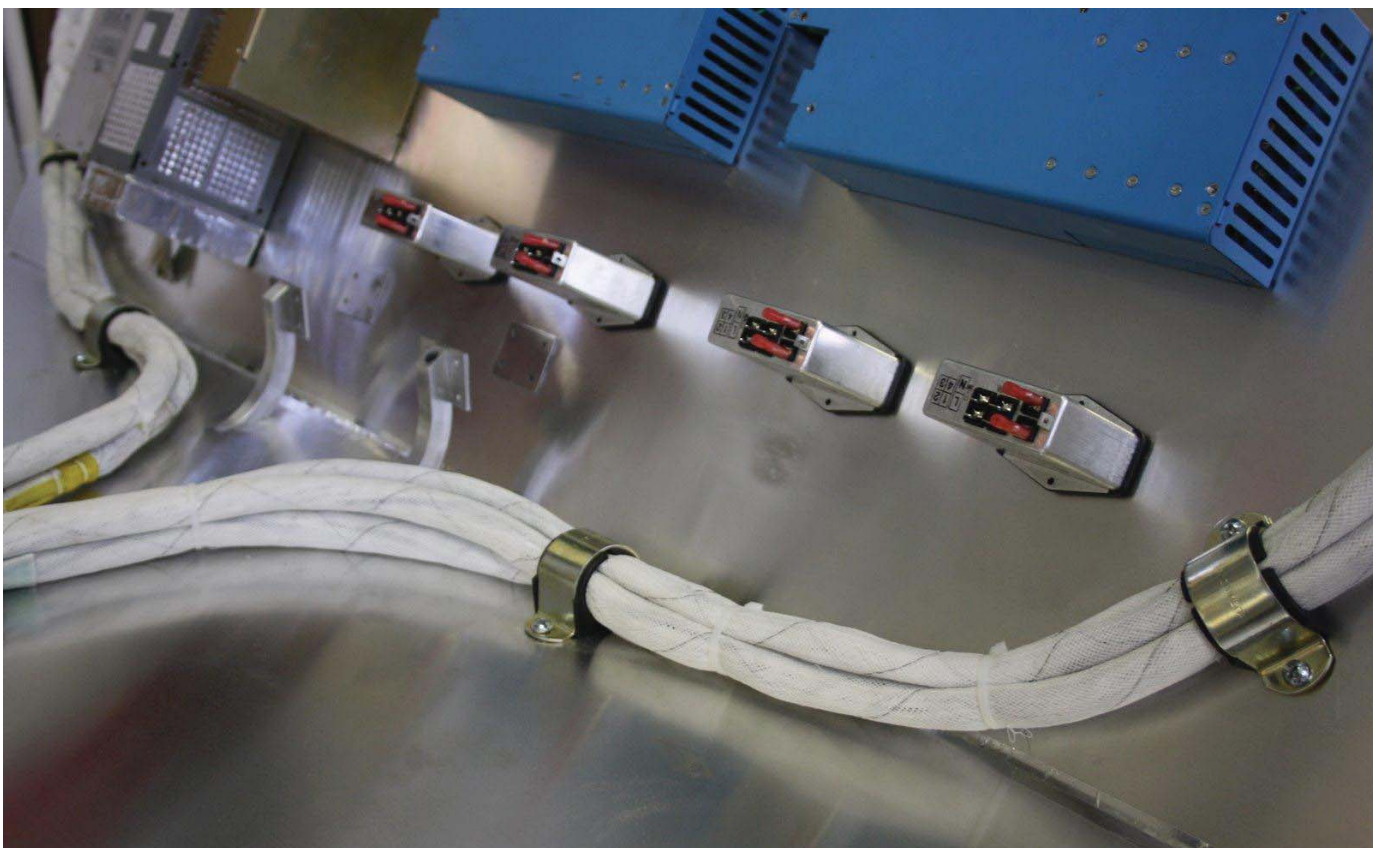


Figure 41 *The cutout joint prototype shows the final concept for wire twisting and thermal conductive heat pipe flange. The electronic components represent real “boxes” that would be attached to the folding panel of the satellite.*

Compared to the wooden "X" joint prototype, this final design prototype had many upgrades. One of the most apparent modifications was the ground support model. To make the cutout joint more realistic, aluminum T-slotted framing was used to replace the wood in modeling the strongback. A CAD model of this construction is shown in Figure 42.

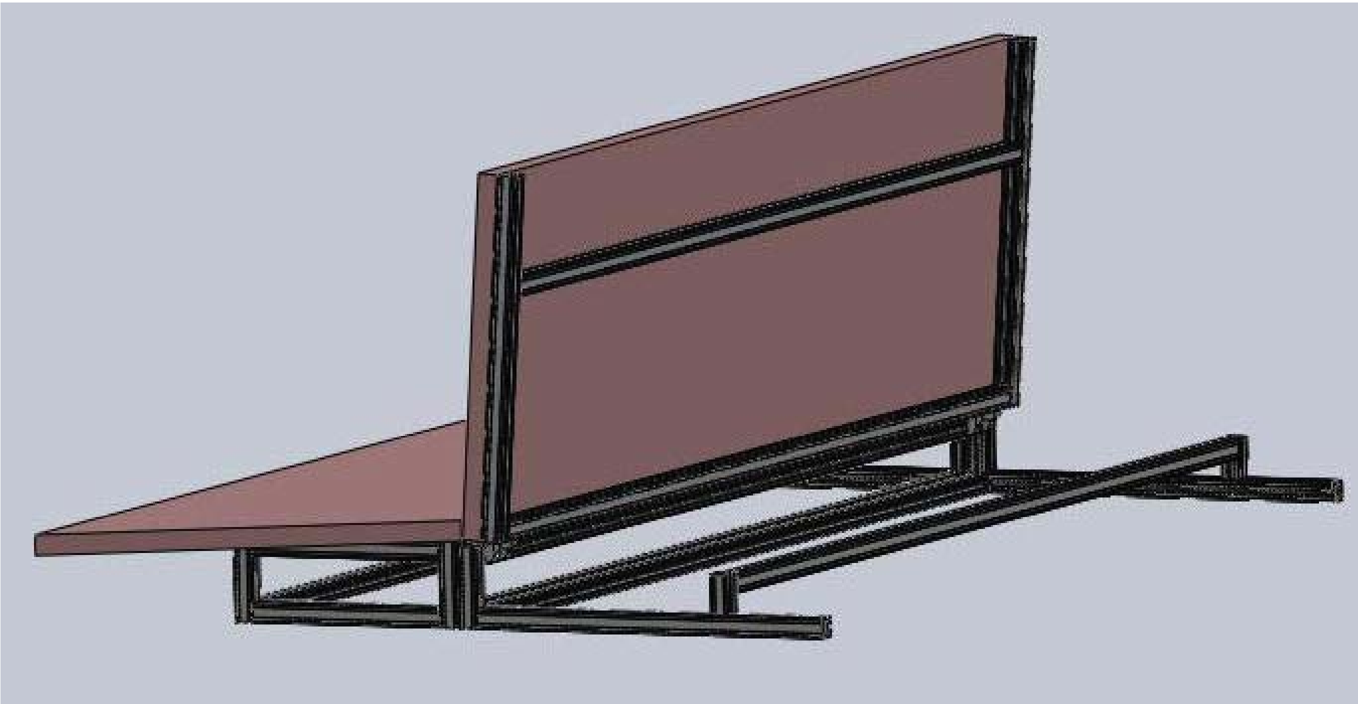


Figure 42 *The CAD model depicts the ground support strongback used to support the cut-out model of the satellite joint. The frame of the strongback is made out of aluminum T-slotted framing.*

A more realistic 1-inch thick honeycomb panel was used instead of the ¼-inch thick honeycomb from the previous model. Also, the design team was able to obtain real satellite wires and a real heat pipe from the Lockheed Martin liaisons, which was ultimately incorporated into this model (Figure 4.9.3). The heat pipes are shown to be embedded in the honeycomb panel, which is the current standard for heat pipe integration. The wires are attached with wire clamps to provide stronger fixation near the joint, since the wires will need to twist every time the joint is folded open or closed. The design reasoning behind the final concept of wiring and heat management is described in sections "4.7.1 Joint Heat Pipes" and "4.7.2 Joint Wiring." A variety of electronic components were also placed on the model to represent the real boxes that would be placed on a satellite panel (Figure 41).

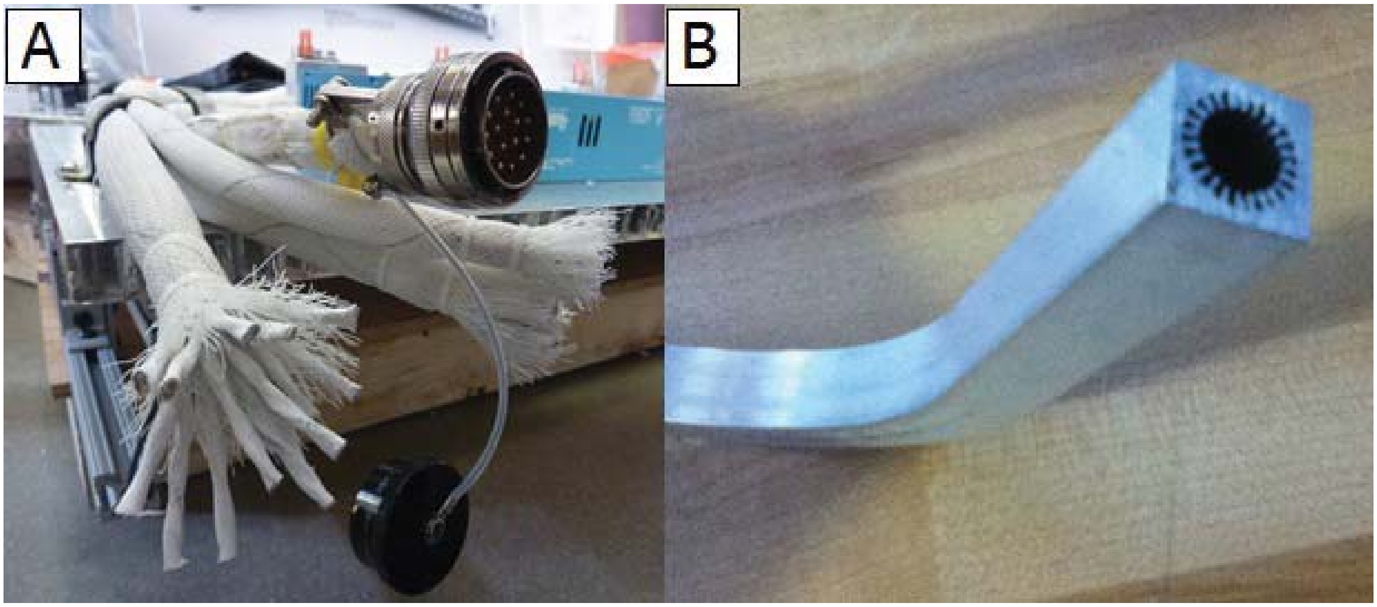


Figure 43 *Real wires used on satellites (A) and real heat pipes (B) were incorporated into our final cutout joint model to add to the realism of the final prototype.*

4.7.1. Joint heat pipe

Heat dissipation is a big issue in satellite thermal control, often driving the performance and life of satellite components. Electronic boxes are mounted inside on satellite panels with heat dissipation ranging from 0 W to as high as 489 W as shown in Table 10 (see Appendix 8.1 also). The current solution to handle heat dissipation in Lockheed Martin's A2100 satellite is to embed heat pipes into panels (which have aluminum facesheets) for thermal control purposes [1]. Team LM decided to take advantage of this current solution and adapt it to fit the Open Space satellite structure. Figure 44 shows how the heat dissipation system works on Open Space. Heat pipes are embedded in panels underneath boxes that need to dissipate heat.

	Operational Phase			Total			Dimensions		
Code	Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)	Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)	Length (in)	Width (in)	Height (in)
CB9.1	0.23	232.1	72.5	2.30	2321.00	725.16	14.57	4.92	5.51
CB9.2	0.23	353.5	110.4	2.30	3535.00	1104.46	14.57	4.92	5.51
CB9.3	0.14	232.1	72.5	1.26	2088.90	652.65	14.57	4.92	5.51
CB9.4	0.19	353.5	110.4	1.90	3535.00	1104.46	14.57	4.92	5.51
CB9.5	0.11	353.5	110.4	1.43	4595.50	1435.80	14.57	4.92	5.51
CB9.6	0.20	152.8	47.7	0.40	305.60	95.48	14.09	2.89	2.53
CB10	0.52	-	-	28.08	-	-	6.69	4.94	1.64
CB11.1	3.57	0.0	489.0	3.57	0.00	489.00	26.05	10.31	3.15
CB11.2	3.93	0.0	216.0	3.93	0.00	216.00	14.86	9.99	3.15
CB11.3	6.68	0.0	339.0	6.68	0.00	339.00	17.88	9.93	3.15
CB11.4	5.10	0.0	224.0	5.10	0.00	224.00	14.05	9.93	3.15
CB11.5	4.83	0.0	377.0	4.83	0.00	377.00	19.07	10.32	3.15

Table 10 *Selected satellite boxes data shows statistically the heat thermal dissipation*

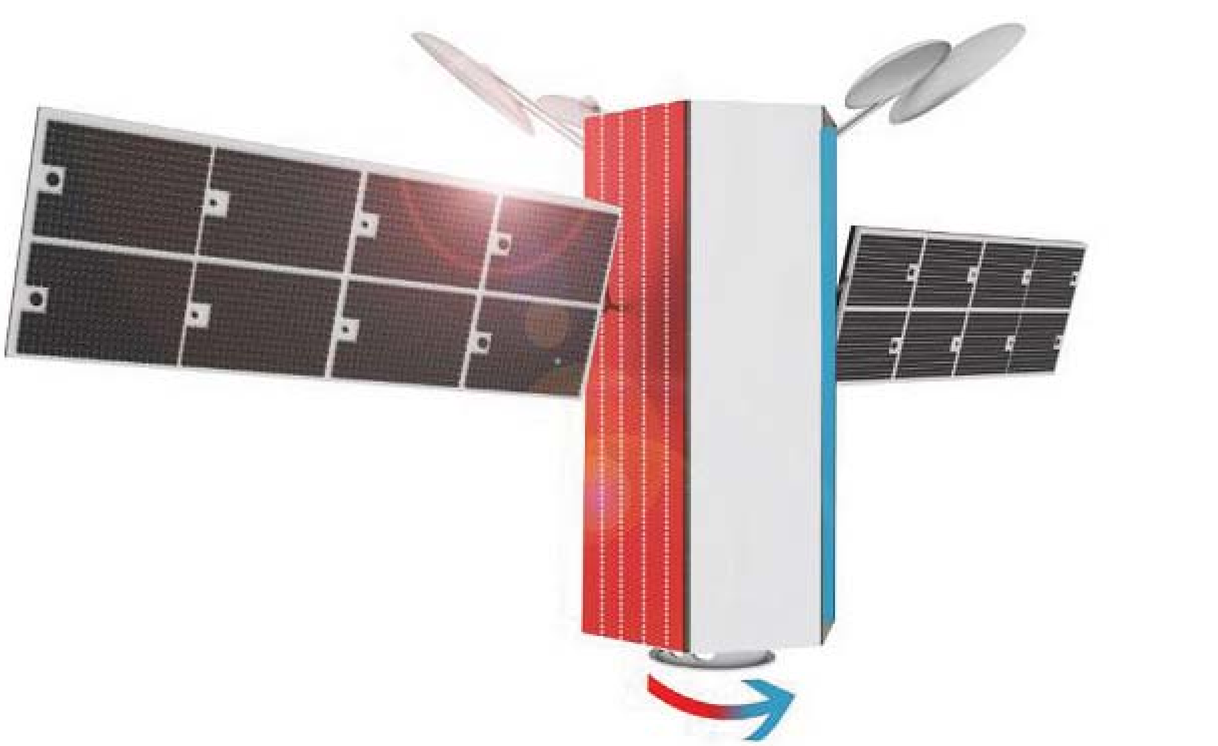


Figure 44 *Heat pipes are embedded in panels to conduct heat from the hot side of the satellite to the cold side*

The thermal dissipation requirement for Open Space satellite is calculated as show below.

1. Total Thermal Dissipation Required: 6763 W
2. Average Thermal Dissipation Required per panel (4 panels): 1691 W
3. Per heat pipe, if 16 heat pipes (4/panel): 422.7 W
4. Per heat pipe, if 20 heat pipes (5/panel): 338.15 W

A heat pipe is a passive, self-contained structure for transferring heat that utilizes capillary forces to pump the working fluid (which is usually ammonia for Lockheed Martin satellites). With heat applied, working fluid is evaporated from the wick, vapor flows to the cooler sections of the pipe, and condenses in the wick. Capillary action returns the liquid to the evaporator, completing the cycle. Figure 45 shows typical heat pipe samples used in satellite industry.

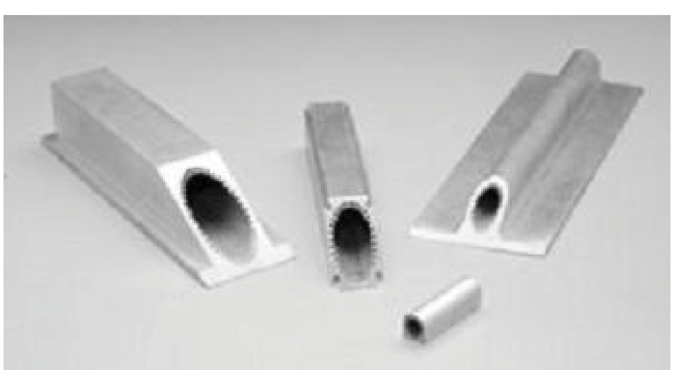


Figure 45 *Cutout heat pipe samples (average outside diameter: 0.5 inches)*

Several ideas of how to realize heat pipe connections at the joint were discussed and justified.

1. **Heat pipe "elbow" joint**

Since the panels are designed to be able to fold open for access during test and assembly, this idea is that the heat pipes would not be joined at the 90 degree bend where the panel meets the base (so that the panel could be rotated without bending the heat pipes). Then, when everything was finalized, the two pipes in the panel and base respectively would be joined with some sort of elbow and charged.

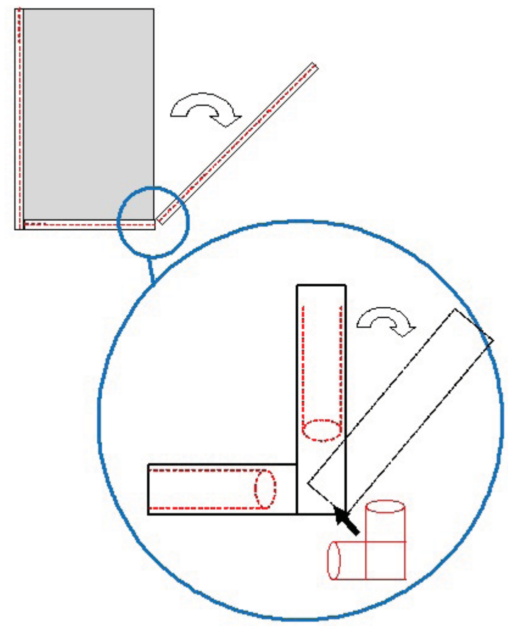


Figure 46 *Sketch of heat pipe "elbow" joint system: a "elbow" is removable from the heat pipes to enable unfolding of the panel during satellite manufacturing*

2. **Flexible heat pipe (FHP)**

Another option considered was to use some sort of flexible heat pipe joint that is sealed/charged through the whole process, but also flexible to allow the panel to rotate. Figure 47 shows a typical flexible heat pipe solution. A typical heat pipe version at ATK (Alliant Techsystems Inc.) has the dimension of maximum diameter ½ inches with flexibility of 90 degrees always and 180 degrees with enough room for curvature. The radius of curvature of these heat pipes is about 2 in. Maximum heat transport capability is about 2500 watt-inches. Each FHP is a separate entity comprised of a flexible bellows mid-section bonded to spiral grooved condenser/evaporator end sections. End-to-end wicking is accomplished with a fibrous mesh running the length of the pipe. Aluminum flanges are bonded to the condenser/evaporator end sections for heat transfer to mating flat surfaces.

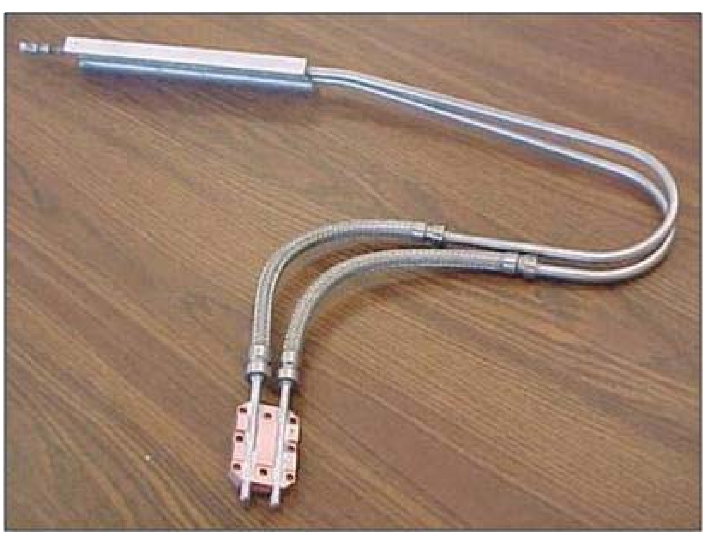


Figure 47 *Flexible Heat pipe*

3. **Loop heat pipes(LHPs)**

LHPs solve difficult thermal challenges for heat acquisition, transport, and rejection. With several meters of pressure head and small diameter tubing, LHPs can provide unique zero gravity thermal management and normal gravity testability with greater orientation independence. LHPs often have flexible couplings to deployable radiators [2]. With the use of LHPs, design of heat pipe connections at the joint would be avoided.

4. **Standard heat pipe with removable conductive interface**

This idea uses the same principle to connect heat pipes as in option 1. However, in this configuration heat pipes would be closed off with an end stub or reservoir that can be interface with another heat pipe during assembly. With a removable conductive interface used, heat pipes can be connected and disconnected easily.

Table 11 shows a comparison between different options of heat pipes.

	Heat pipe with “elbow” joint	Flexible heat pipe	Loop heat pipe	Standard heat pipes with removable conductive interface
Pros	• “Easy” to do because this is the current method • Much cheaper than flexible options	• Has been done before, so we know it works and is flexible enough • Cheaper than loop heat pipes	• Very flexible • High heat transport capability • Can transport longer distances than flexible heat pipes	• Cheaper because heat pipes do not need to be flexible
Cons	• Not able to open boxes after thermal testing	• 20-30% less heat transport capability • Fluid management problem due to liquid collecting in the bellows • Expensive • Damage to heat pipe strength at the joint due to folding/ unfolding	• About 10x more expensive than standard straight heat pipes	• Thermal interface would need to be reapplied each time the panel is opened • Decreased heat transport capability

Table 11 *Pros and Cons of different heat pipes solutions*

Considering the benefits and drawbacks of each option, the standard heat pipes with removable thermal interface were chosen. The price was a major factor because the project goal is to decrease the time and money required for testing and assembly. With the thermal interface option, the extra costs are minimal considering the overall cost savings. The thermal interface only needs to be reapplied if the panel is folded down.

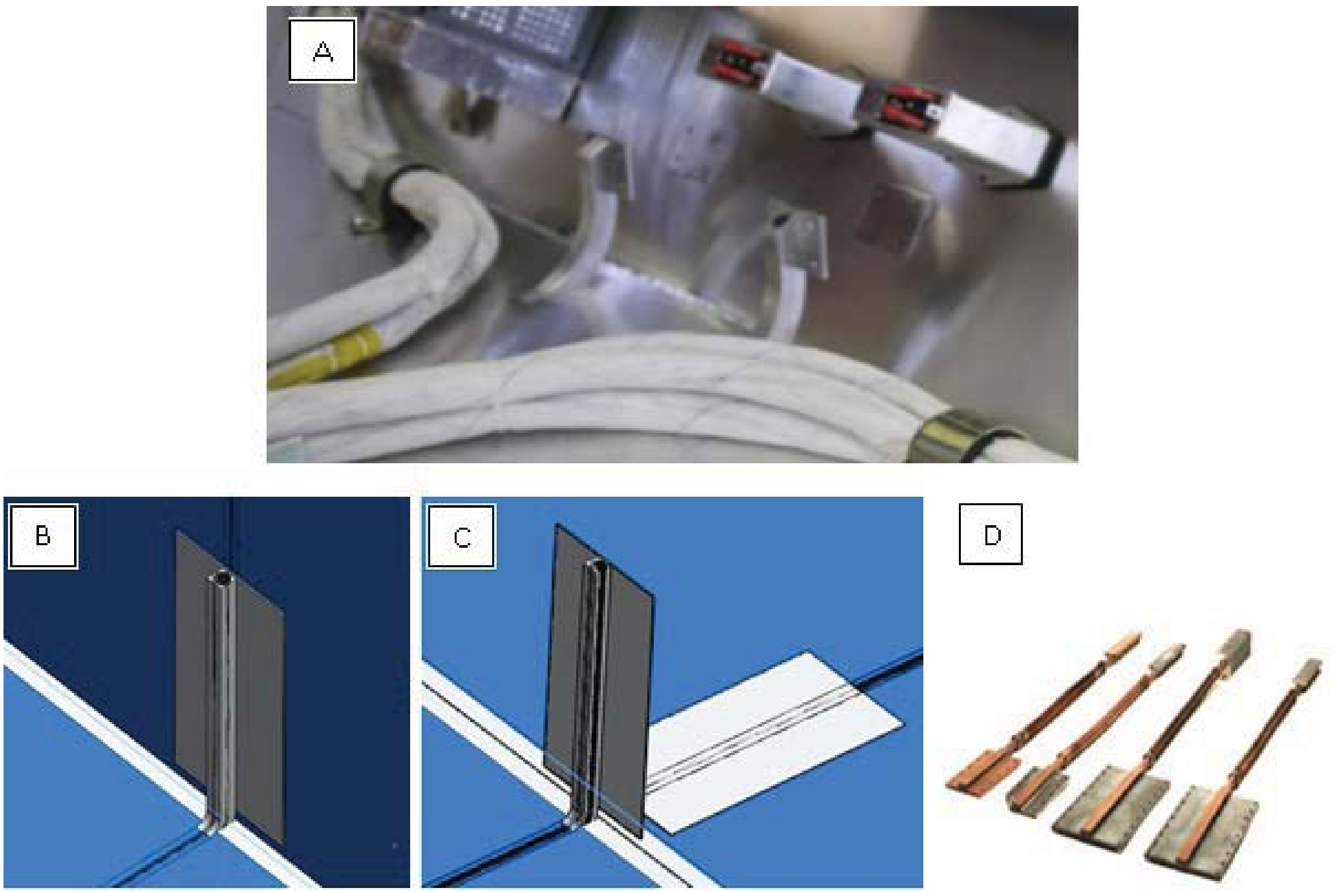


Figure 48 *The thermal interface heat pipe solution is shown closed (B) and open (C). The cutout full scaled joint model shows the heat pipe connections (A). Large flanges are used to aid heat transfer, similar to existing flexible heat pipe flanges (D).*

4.7.2. Joint Wiring Development

One of the biggest challenges in making an opening panel on a satellite is getting wires across the joint without damaging them. Several solutions were considered for making this happen, but before considering any of them it is necessary to understand the specific wiring situation.

At this point in the design process (a high-level, first-concept), the exact gauges and quantities of wires traveling to each panel were not available. To make an good estimate at the amount of wire that would have to cross each joint, the team had several conversations with the liaisons, which revealed that a typical communication satellite has two wire bundles two to three inches in diameter which supply power to all the boxes in the satellite. To assume the worst case, the team chose the case in which two 3” OD cables left the batteries and traveled to each of the panels. The cross sectional area of two 3” OD wire bundles is 18π in2. Dividing this into eight bundles (two per panel) gives a final estimate that two 1.5” OD wire bundles need to cross each joint.

Once the size of the wire bundles crossing the joint had been decided, the next step was to quantify how much the wires could bend. For this purpose a document from NASA that specifies guidelines for routing electrical harnesses (1) was referred to. From this document, three relevant guidelines were discovered. The first is that wire bend radii should be from 3x (minimum) to 10x (optimum) the outer diameter (OD) of the wire harness. For a 1.5” OD bundle, this means that the bend radius should be between 4.5” and 15”.

The second guideline discovered is that the “length of lay” of the harness, which is “the axial length of one complete turn of the helix”, should be between 8x and 16x the OD of the harness. This was relevant because the team considered allowing the wire bundle to twist instead of bending. If the wire bundle could be twisted 360° in 8-16x the OD, it should be able to twist 90° in 2-4x the OD of the harness. Therefore, the wire bundles can twist 90° over a linear distance of 3-6”.

The third guideline discovered was that wire harnesses used in space applications with OD=1”, 2” and 3” weigh about 1 lb/ft, 4.5 lb/ft, and 10.5 lb/ft, respectively. Since a 1.5” OD was to be used, a quadratic regression was fit to this data (along with a point at 0” OD = 0 lb/ft) to yield weight/ft = 1.3*OD2 -.45*OD + 0.04. Using an OD of 1.5” in this equation yields an estimate that the wire harnesses will weigh approximately 2.3 lb/ft.

With these guidelines in mind, the team set out to design a wiring configuration that would allow panels to open reliably without violating the bend radii or twisting length of the wire or putting any other undue stress on it. Three options were considered, and the third option was selected as the final solution.

The first option considered was to simple route the wire across the joint directly, using an appropriate bend radius. However, directly routing the wire across the joint represents a unique challenge best described by referring to Figure 49 below. The left of the figure shows a base panel and closed side panel with a wire bundle crossing with an appropriate radius of curvature. However, since the panels have to pivot around the point shown, when they open they introduce a small gap which would stretch the wire bundles if configured as shown, causing stresses and possible failures.

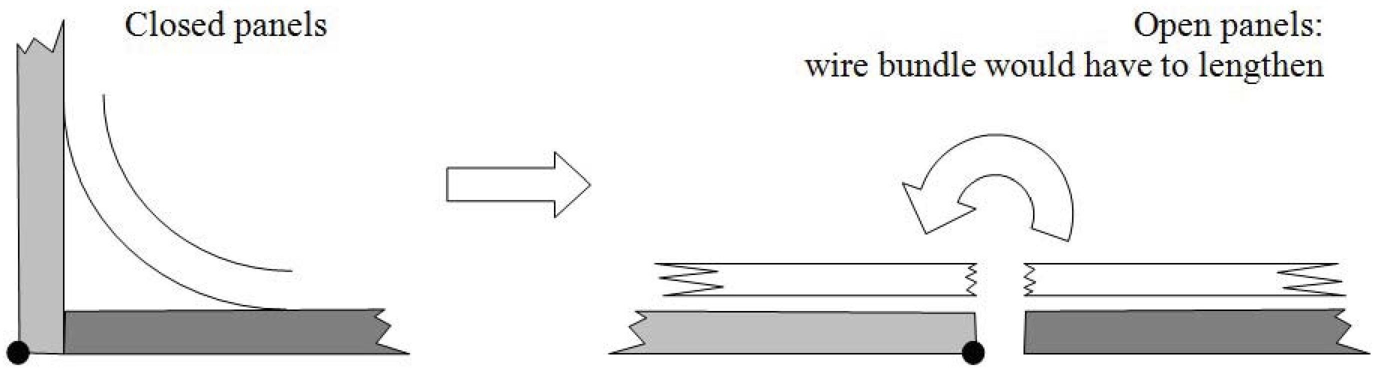


Figure 49 *First option considered to get wire bundle across joint. Fails because joint has to lengthen when opened, pivoting about the corner marked.*

The second option considered was to use a configuration similar to a spring, in which the wire formed a loop at the joint which could expand and contract (see Figure 50 below). A wire loop (similar to a torsion spring) would contract slightly when the panels were opened, allowing a radius to be maintained while still allowing the panels to part slightly on opening. This idea was discarded because the extra weight of the loop is too great and because a fixture would be needed to assure the loop worked properly, which would also add more weight.

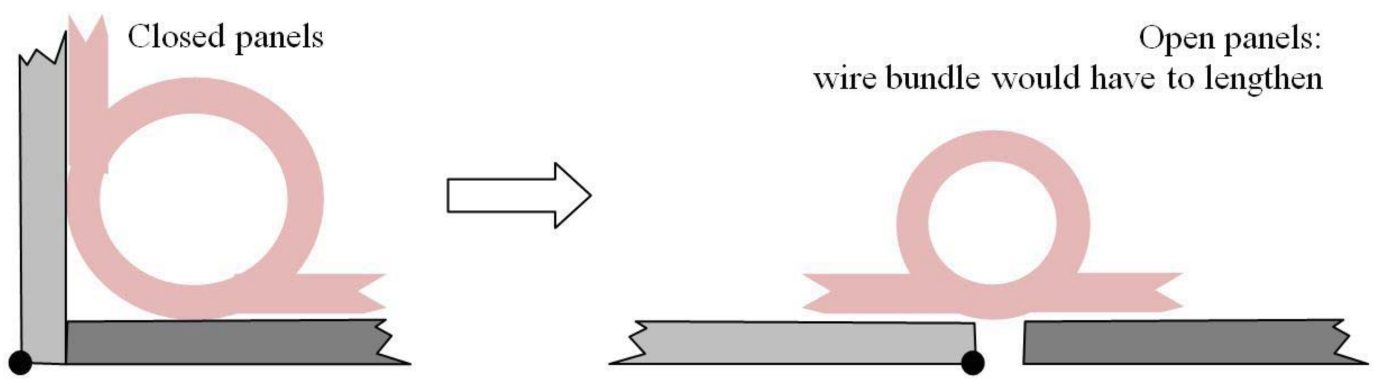


Figure 50 *Second option considered to get wire bundle across joint. Discarded because of excess wire weight and fixture needed to support loop.*

The third option, which was chosen, was initially suggested by one of the teaching team members in a small group meeting, but was forgotten for a while as the loop option was being explored. Later is was picked up again and explored in more depth, and ended up being the best option. Figure 51 shows how this third option works. The wires shown cross the joint parallel to the joint line, which makes them twist instead of bending when the panels fold. This is done over a distance much greater than the required 3-6" of twist length. The required radius of curvature of 4.5" is doubled for a safety factor and maintained at no less than 9". When the panel is folded, the radius of curvature is exactly 9". When it opens, the parallel twisting portion of wire crosses the joint at a diagonal, taking up some of the slack from the bend radii (which actually makes the bend radii larger and thus safer).

This method was tested with real wire bundles, using wire samples provided by the liaisons from Lockheed Martin, and worked very well. It could be done with the force of one hand easily, even with the weight of heavy boxes attached to the folding panel. Fatigue was not considered since the folding would only happen a few times during assembly. More details on the exact dimensions specified can be found in the description in section 5.1.2.u

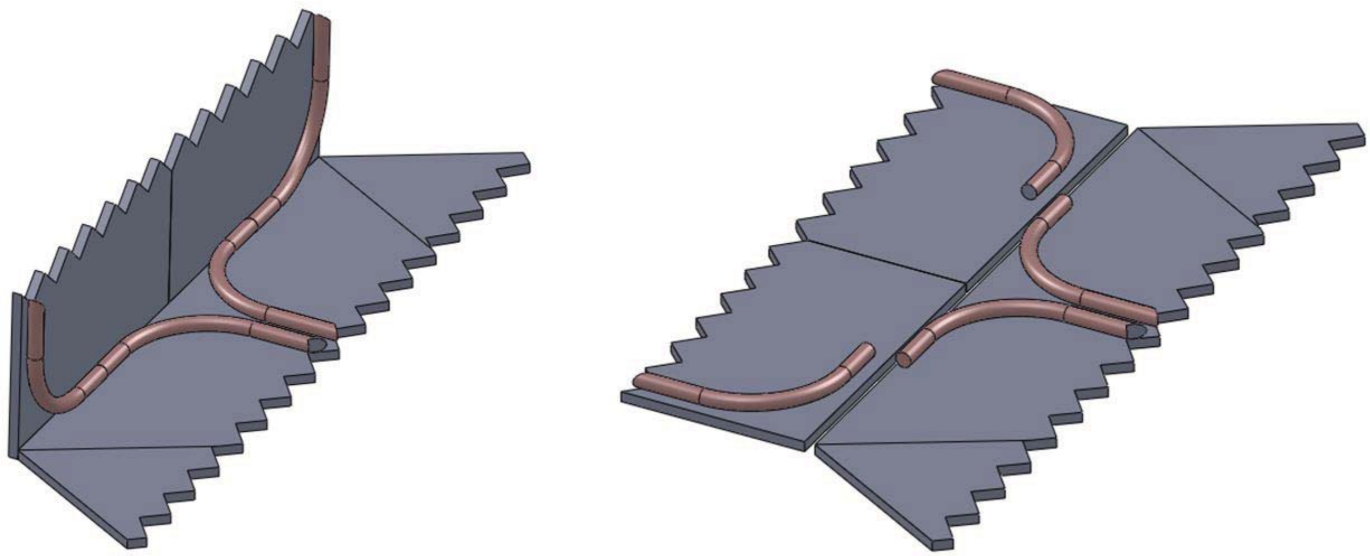


Figure 51 *Third option considered to get wire bundle across joint. Twisting wires allow minimal stress and minimize extra wire weight. Note: wires would not actually separate, but would take up the slack in the radii to form larger radii and angle across the gap.*

This part of the design process addresses the "wire management" requirement, which specifies that the design will allow the equivalent of two 3" diameter wire bundles to run to all installed boxes.

4.8 Scale Model development

With solutions proposed for solving the primary problems in the satellite joint, the next step was to propose a high-level concept for the structure as a whole. A Lockheed Martin A2100 satellite bus is rectangular, with panels approximately 10 ft wide and 16 tall. A hexagonal structure was chosen for the open space satellite so that each panel could be narrower and angled apart. This allows users to reach components on the panel more easily, without having to crawl out over the panel to work on it. The angles of a hexagon also allow adjacent panels to be folded down and accessed from both sides simultaneously. Test engineers and assembly technicians can then access boxes within ergonomic reach while seated as if at a desk. This addresses the requirement that the design be ergonomic.

The core structure was modified from that used in the Functional prototype in the winter quarter, which was found not to be stiff enough torsionally. To solve this problem, a cylinder was proposed for the center of the structure to provide stiffness and double as a space for fuel tanks (an idea borrowed from Space Systems Loral's current methods). In conjunction with radially oriented panels (see Figure 52), it is believed that by adjusting some dimensions a structure of adequate strength and stiffness can be achieved with this configuration.

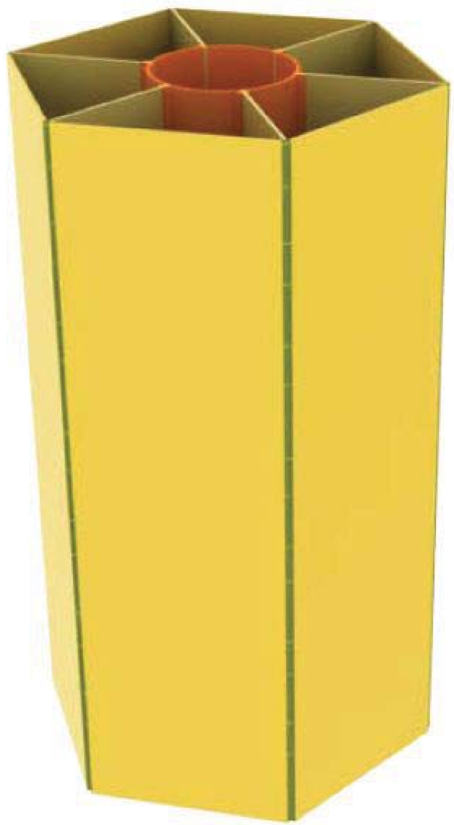


Figure 52 *Rendering of the proposed cylindrical center piece with radial panels to serve as a core structure.*

After all this design process, the team had to decide how to show the final prototype. This decision was perhaps the most complicated, because this final prototype needed to give a clear idea of the project, the solution and the innovation. For all these reasons the team chose to build a complete model of the prototype in addition to the partial model.

The problem with this plan was the size of the satellite, because if the team built a 1:1 scale model it would be too big and heavy. For this reason the team decided to build a 1:3 scale model. This scale was chosen because it is large enough to give a clear idea of how big a real satellite would be, but still easy to build and manipulate.

After choosing the size of the prototype, the next challenge was to chose the material. This material would be light but also strong and easy to work with. The team analyzed many materials and after much consideration chose PVC foam, which is a lightweight yet rigid board of moderately expanded closed-cell polyvinyl chloride (PVC) extruded in a homogenous sheet with a low gloss matte finish. This material easy to work with and readily available at a low cost in Mexico City.

Figure 53 *PVC foam material used to build a1:3 scale prototype.*

In previous prototypes the team had not developed the unions between the panels, but for this prototype it was necessary to do so. These unions needed to be rigid and light, but the most important feature of these unions was the way in which they would connect to the panels. The goal was to have unions that were easy to remove to allow fast access to the boxes inside the satellite. The team analyzed many configurations and many possibilities and tried to find unions with the minimum number of pieces to minimize weight in the satellite. For this reason the LM team decided to design an extrusion with a U-shaped cross section for the union between the internal and external panels and a with an L shape for the union between the internal panels and the core cylinder. These extrusions provided an interface to connect the joint via bolts or screws, an accepted method currently used. (See Figures 54 and 55)

These joints were made of aluminum because this material is rigid and light, and because it is easy to manufacture.

Finally, the core tube was made of PVC, because this tube was too big to be built with another material in an easy way and because this tube had to be rigid and strong to be the central part of the structure.

Another important thing for this final prototype was the way in which to show the inside of the satellite and the arrangement of the boxes. To do this, the LM team decided to show one of the four panels open and all the others closed. The boxes on the open panel were made of translucent acrylic with LEDs of different colors inside to show that some boxes have different temperatures than others. These LED's were red and yellow, and different quantities were put in each box to show different levels of heat.

Finally, the team had to decide how to show all the wires that connect the boxes in the prototype. The team analyzed many possibilities; the goal was to show the complexity of the connections, but at the same time the prototype needed to be finished and neatly assembled before EXPE. For these reasons the LM team decided to show the connections in the easiest way, by printing the arrangement of the boxes with their cables as a wiring diagram on a sheet of paper (see Figure 56) that was pasted on the open panel.

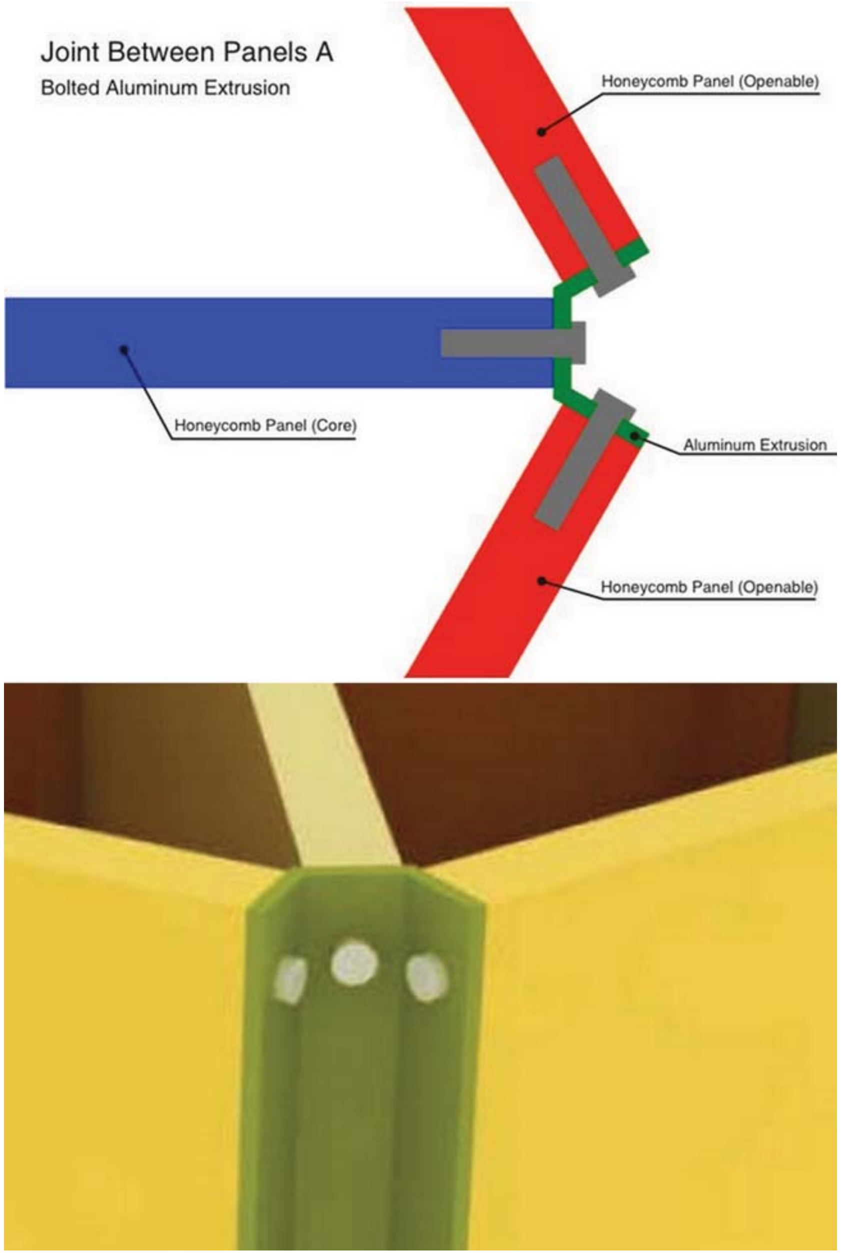


Figure 54 *U-shaped extrusion (green) connecting two folding panels (red) to a core structure panel (blue).*

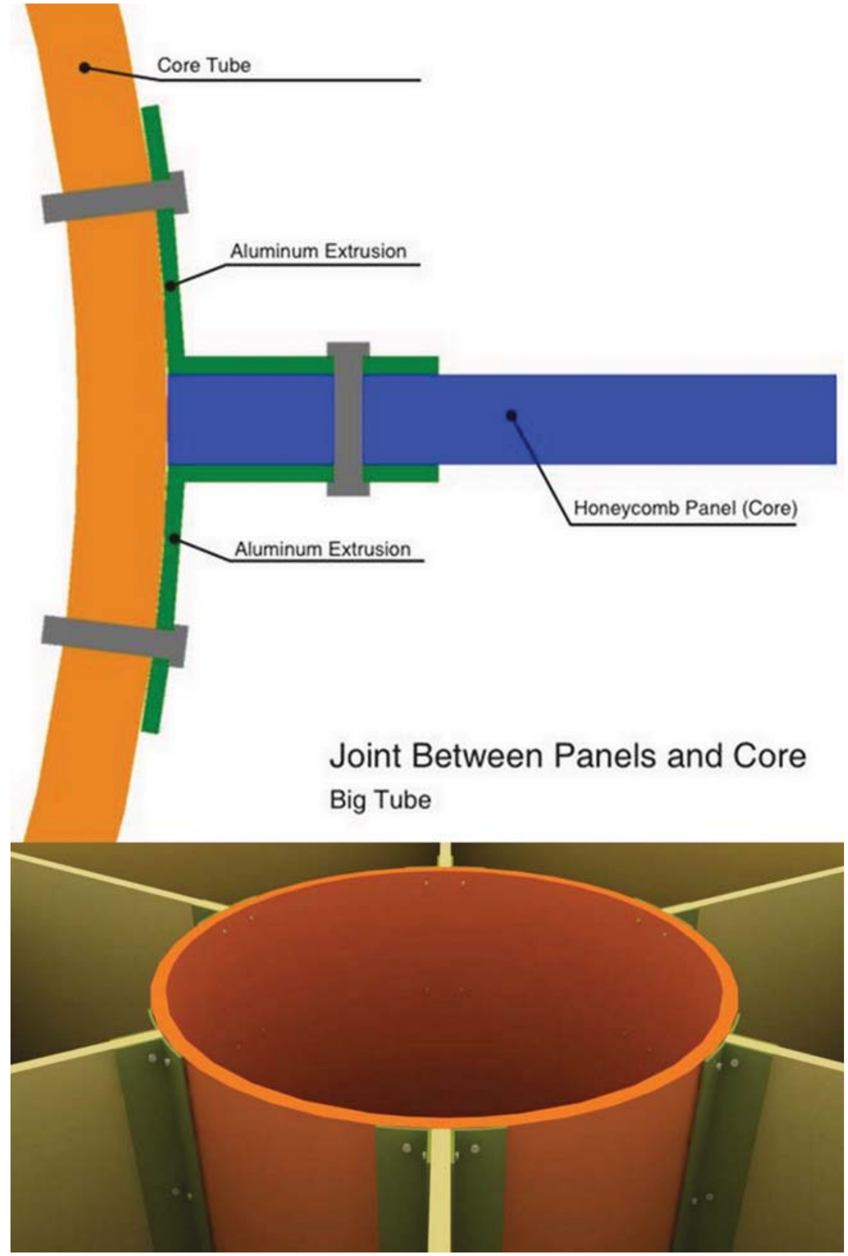


Figure 55 *L-shaped extrusion (green) connecting a core structure panel (blue) to the core cylinder (orange).*

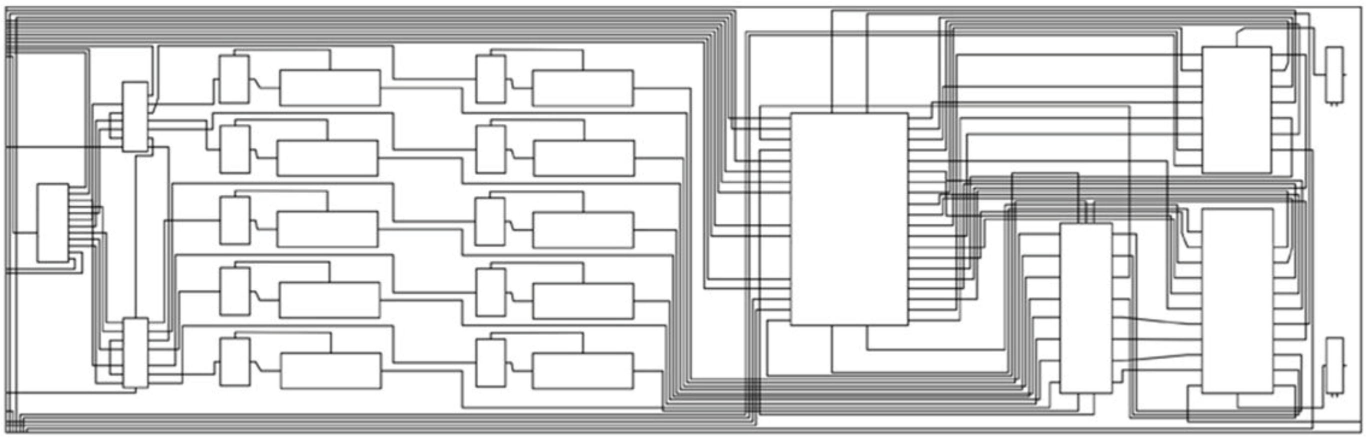


Figure 56 *Wiring diagram printed for 1:3 scale model.*

4.9 Boxes/Wiring/Heat Pipes arrangements

In order to prove whether it was feasible to arrange all the boxes on four panels so that the position and quantity of the heat pipes would be the same for each panel, it was determined to search for a simple modelling solution that could deal with the given information. Some of the solutions proposed were:

- Virtual: use 3D CAD software or a 2D wiring diagram software.
- Physical: build scaled boxes and connect them with strings as wires.

Based on the wiring diagrams provided by the liaisons (see appendix 8.4) and some of the information related to each box (see appendix 8.1), the team decided to use a software that could help to arrange boxes and wires on four panels in an easier way. To achieve this goal, the team required a very flexible program that displayed necessary information in a simple and visual way. Flexibility was needed because boxes had to be moved, oriented, connected and disconnected easily. It was indispensable to be simple to use and visual, so that the information could be easily distinguished, modified, and analysed. The team did some testing with different programs and compared the results. Some of the 3D CAD programs tried by the team, like SolidWorks, were incredibly realistic and could be very helpful for distinguishing if any box was merging with the structure or with another box when closing the panels. Knowing this information was only useful for boxes that would be put near the edges of the panels or were very tall. 3D programs, however, ended up being very slow when moving boxes with many connections. Therefore a 2D program (like Microsoft Visio) that could be used to manage wires and boxes with extra information was preferred. Figure 57 shows the first iteration of the diagram using this program.

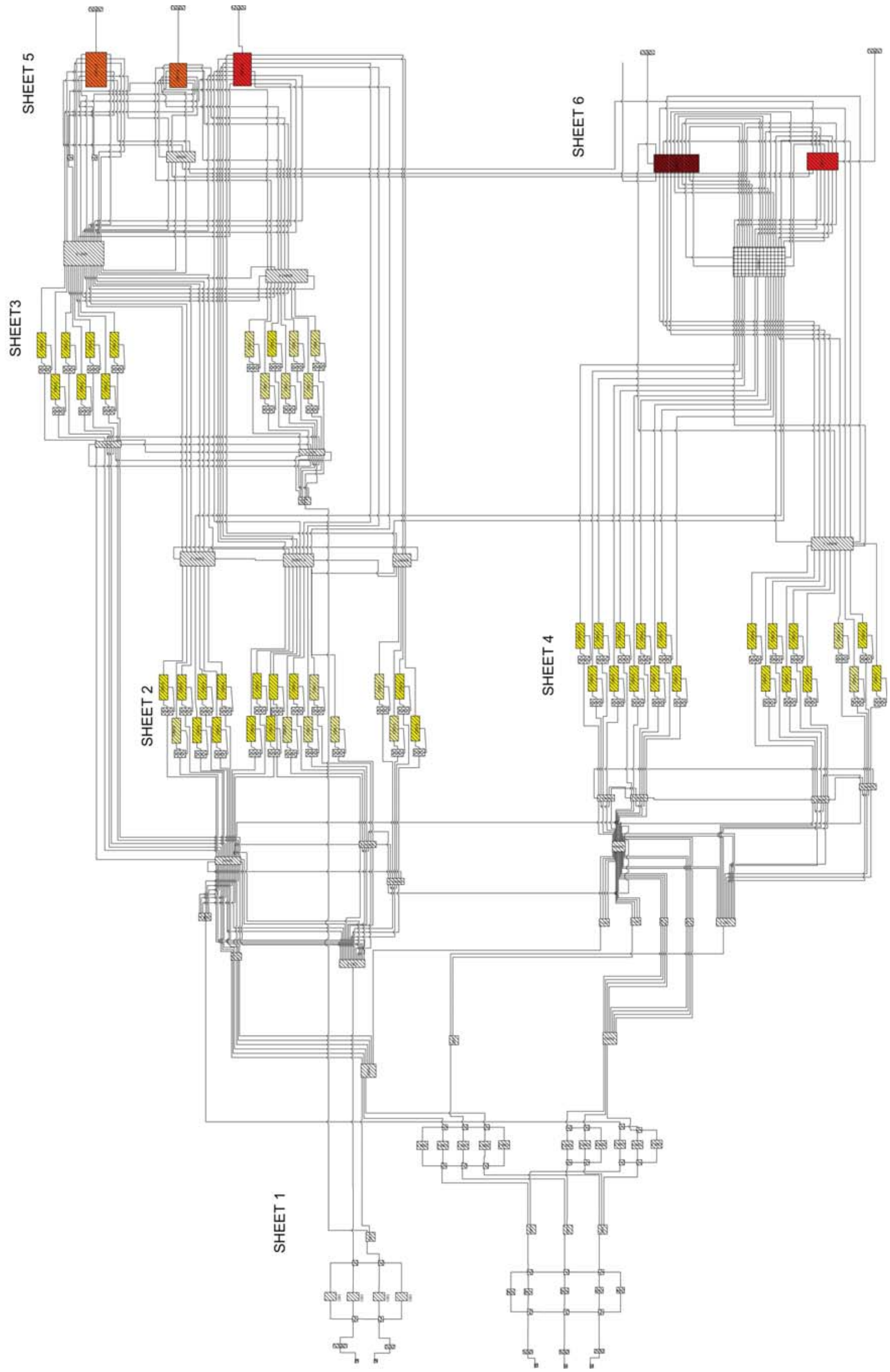
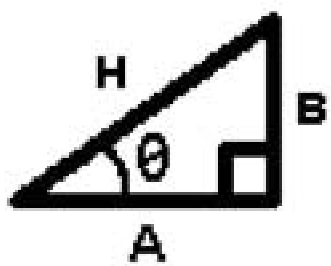


Figure 57 *First iteration diagram created from the original six.*

The information that is displayed on the diagram is:

- Rectangles with the real base dimensions of the boxes.
- Lines representing each of the wires that connect a box.
- The name of the boxes.
- The mass of the boxes labelled by different crosshatch densities.
- Heat dissipation of each box during their operational phase labelled with different colours.
- Real size of the panels.

To determine the distance between a box and the panels edge in order to avoid boxes merging (virtually) with the structure or with nearby boxes when closing the panels, Pythagorean trigonometric identities were used. These identities were only used with boxes that would be put near the edges of the panels or were very high.



$$B = A \cot \theta$$

Figure 58 *Pythagorean trigonometric identity.*

“B” is the height of the box, “A” the distance between the box and the edge of the panel, and “θ” is the inside angle between the external panel and the internal one and is equal to 60°.

The first iteration of the wiring and box diagram shown in Figure 57 gives a better idea of the amount of boxes and wires that the panels would hold. It is also very easy to distinguish how to split the boxes in four semi-homogeneous sets. Some of the boxes had a lot of connections between them and it was a clear decision to put them in the same group. Most of the hot boxes had to be aligned along the panel so that the heat pipes could be fixed beneath them. The goal was to have an equal number of heat pipes on each panel that were placed in the same position. Four panels were drawn to actual dimensions and the boxes were arranged on them as shown in Figure 59.

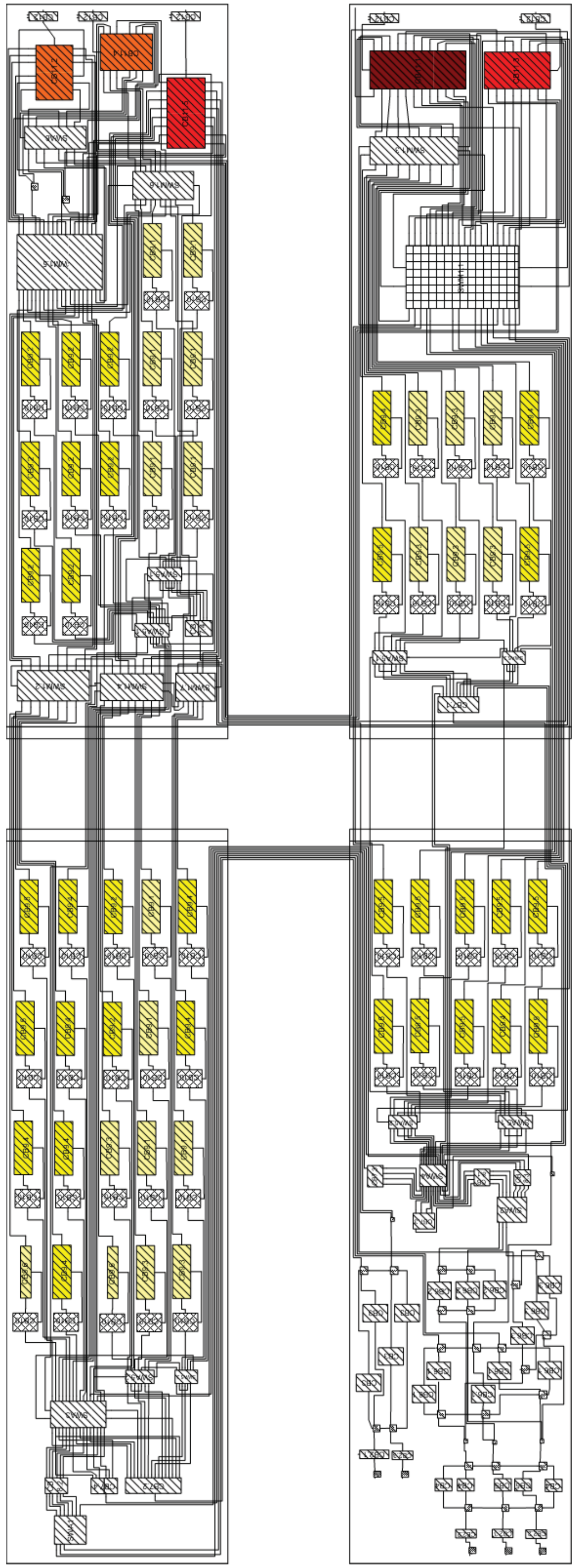


Figure 59 *Second iteration of wiring diagram, boxes arranged into panels.*

The considerations for arranging the boxes into the panels are:

- The dimension and orientation of the base of the boxes.
- The complexity of the interconnection between boxes.
- The given number and type of similar boxes.
- The heat dissipation of each box during its operational phase.
- The proximity of the contiguous panel.
- The position of each box according to the adjacent elements.
- The number of cables connected to each box.
- The height of the boxes that would be put nearby the edges of the panel.

Some of the considerations that were not included are:

- Box and wire magnetic fields.
- Wiring types and diameters.
- Operational phase times.
- Bus box wiring diagrams.
- The wire connections of some payloads like antennas and batteries.

As was said before, it is important to know if a contiguous panel is near to the panel that is being arranged, so some extra considerations were taken. The intention was to put the more interconnected sets onto the panels that where closer to each other, so that only two small wire bundles would cross the hexagon from side to side, as is shown below in the Figure 60.

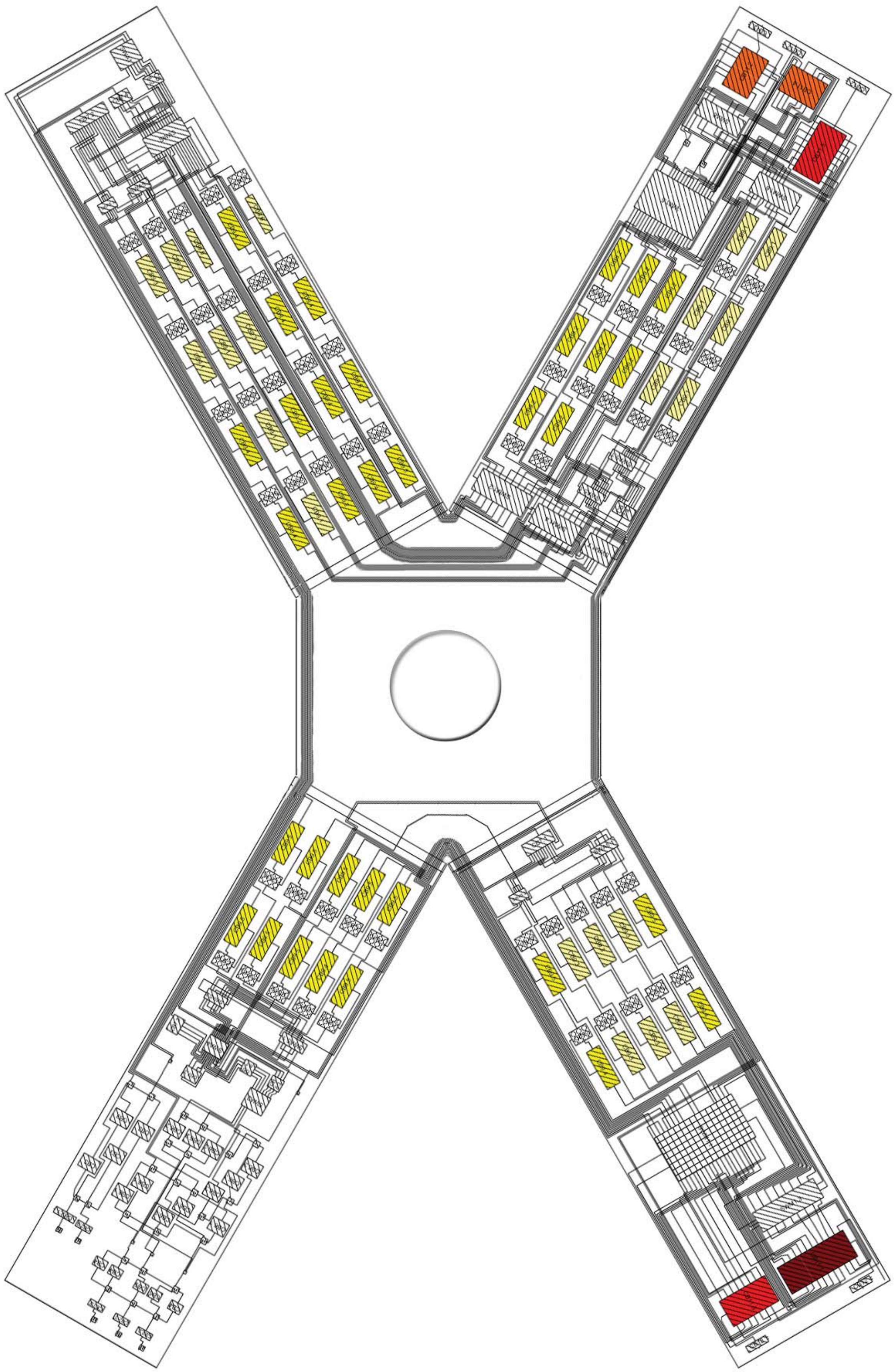


Figure 60 *Third iteration of wiring diagram, boxes arranged into panels.*

The heat pipes cross along the panels and are embedded in them, as it is shown in Figure 61. The team decided to put six heat pipes in each panel that would be in contact with hot boxes to extract and transfer heat from one side of the satellite to the other. The idea was to arrange the heat pipes in the same configuration for all panels.

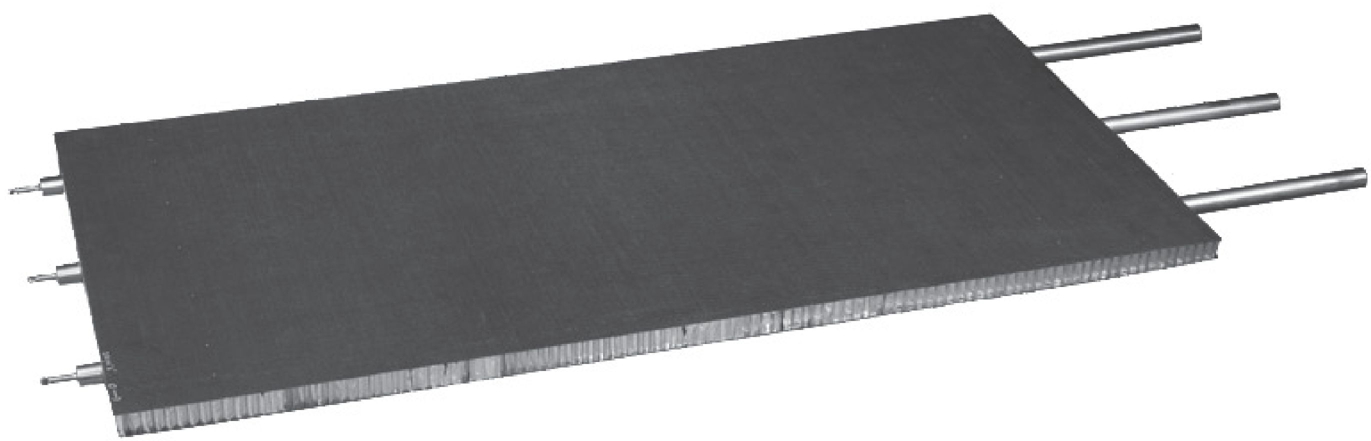


Figure 61 *Embedded heat pipes crossing along the panels.*

5. Design Description

Since the team could not build a full-scale, high resolution prototype of a full communication satellite, a 1:3 scale low-resolution prototype of the entire satellite and a full-scale high-resolution prototype of the satellite joint were constructed. The sections below outline the specifications for the two prototypes that were built and propose some specifications for a full scale satellite utilizing the Open Space design.

5.1 Cutout Joint Model

This final cutout joint model is made as if it were cut out from the actual Open Space satellite structure. The base panel is a 18"-tall trapezoid with a 80.78" base and a 60" top dimension to model the cutout of the Open Space hexagon base structure. The foldable panel is a rectangle that is 60" wide and 18" tall (Figure 62). The panels are made out of 1-inch thick honeycomb with 3/4" cell size and 0.025"-thick aluminum face sheets (Figure 63).

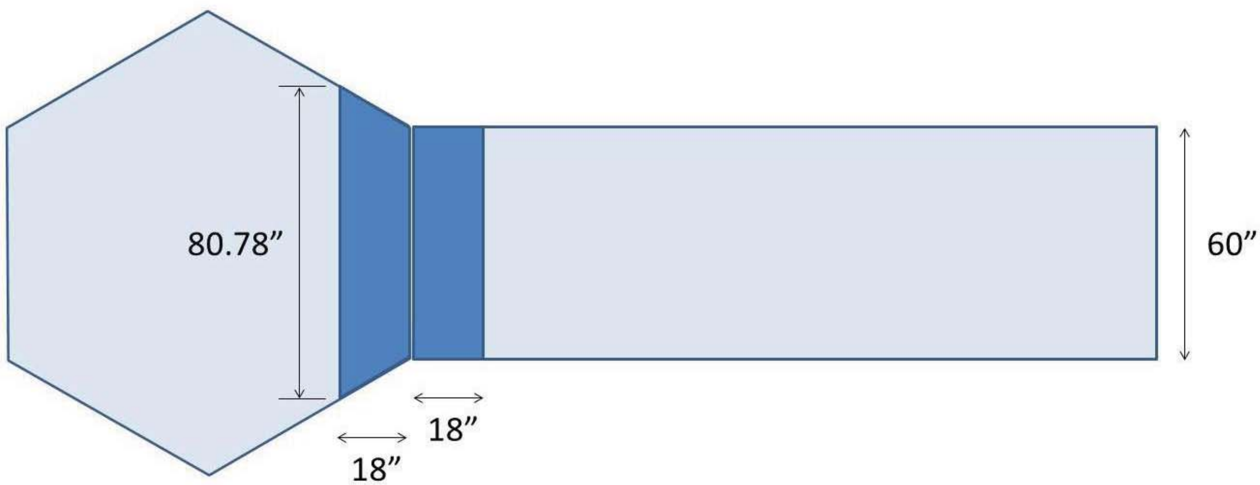


Figure 62 *The light blue shows the top view of the Open Space structure with one panel folded down. The dark blue shows the panel shapes that were used to represent the full-scale panel joint for the final prototype.*

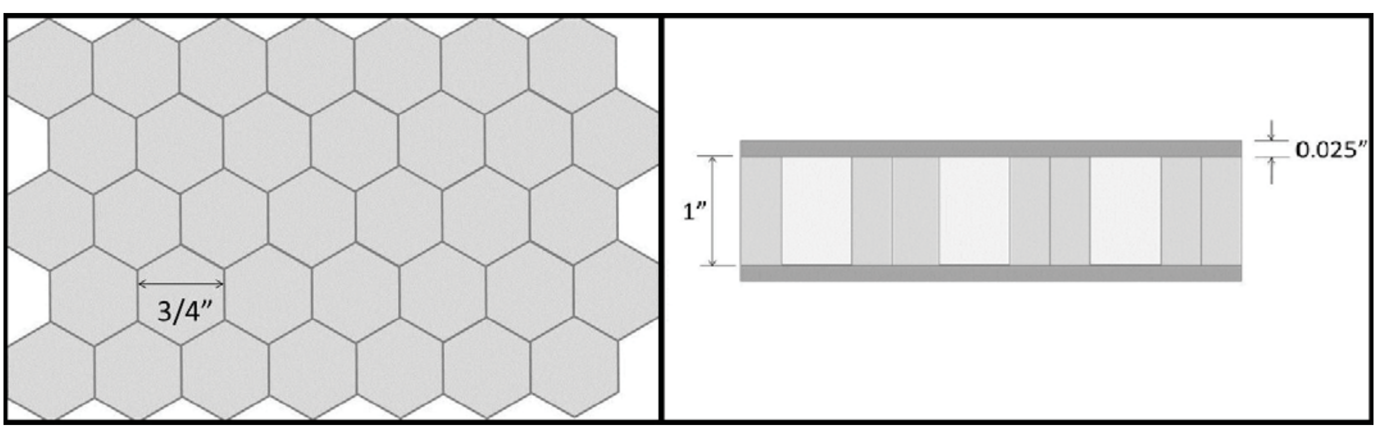


Figure 63 *The aluminum honeycomb cell size is ¾" as shown in the top view (left). The core is 1" thick while the aluminum face sheets are 0.025" thick as shown in the side view (right).*

The strongback was made out of 1-inch aluminum T-slotted extrusions, as shown in Figure 42. Each bar was connected with single two-hole 90° brackets, as shown in Figure 64.

Figure 64 *The 1-inch aluminum T-slotted extrusions that were used to model the ground support strongback was connected using single two-hole 90° brackets.*

The actual model is shown in Figure 65. The sides of the panel that would be an actual edge in the actual model were taped closed with aluminum tape as is done in industry. On the other hand, the honeycomb on the remaining edges were left exposed to represent cut edges. Various electronic components were used to model the boxes on an actual satellite panel. The specific dimensions of the wires bending and heat pipe configurations are described in Sections 5.1.1 and 5.1.2.

Figure 65 *The final cutout prototype is shown in its open configuration (left) and its closed configuration (right).*

5.1.1. Joint Heat Pipe Description

The heat pipes connection at the joint is described below:

- Material: Aluminum
- Heat pipe: Section side length: 0.5 inches;
- Radius: 2.5 inches;
- Bending angle: 90 degrees
- Flange: Size: 1.5 × 1.2 ×0.2 inches;
- Bolts: 4 per heat pipe connection

Heat pipes run through panels parallel to the long side of panels, positioned at the places where hot boxes concentrate, according to boxes arrangement. The ideal design is to standardize the distribution of heat pipes in panels, which would standardize the manufacturing of panels, reducing the cost and time. The position and amount of heat pipes built in the panels needs further research to be decided.

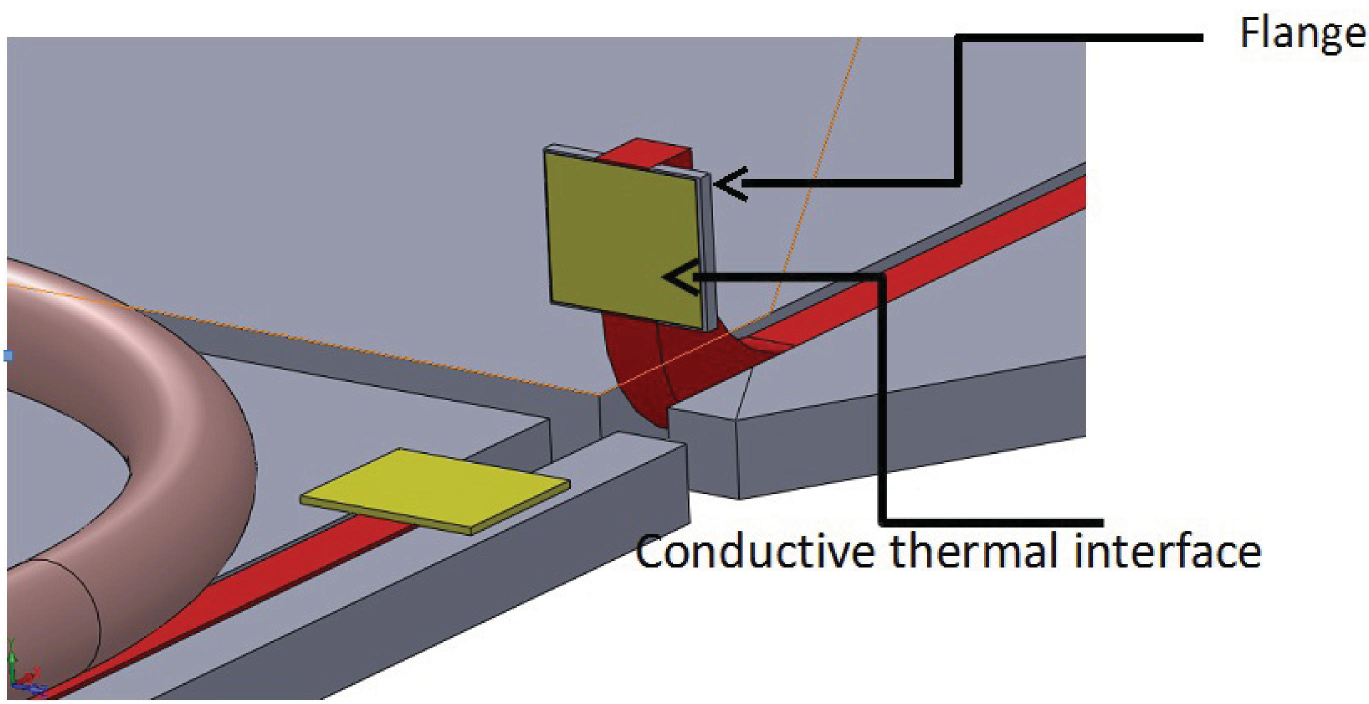


Figure 66 *Solidworks model of heat pipe connection*

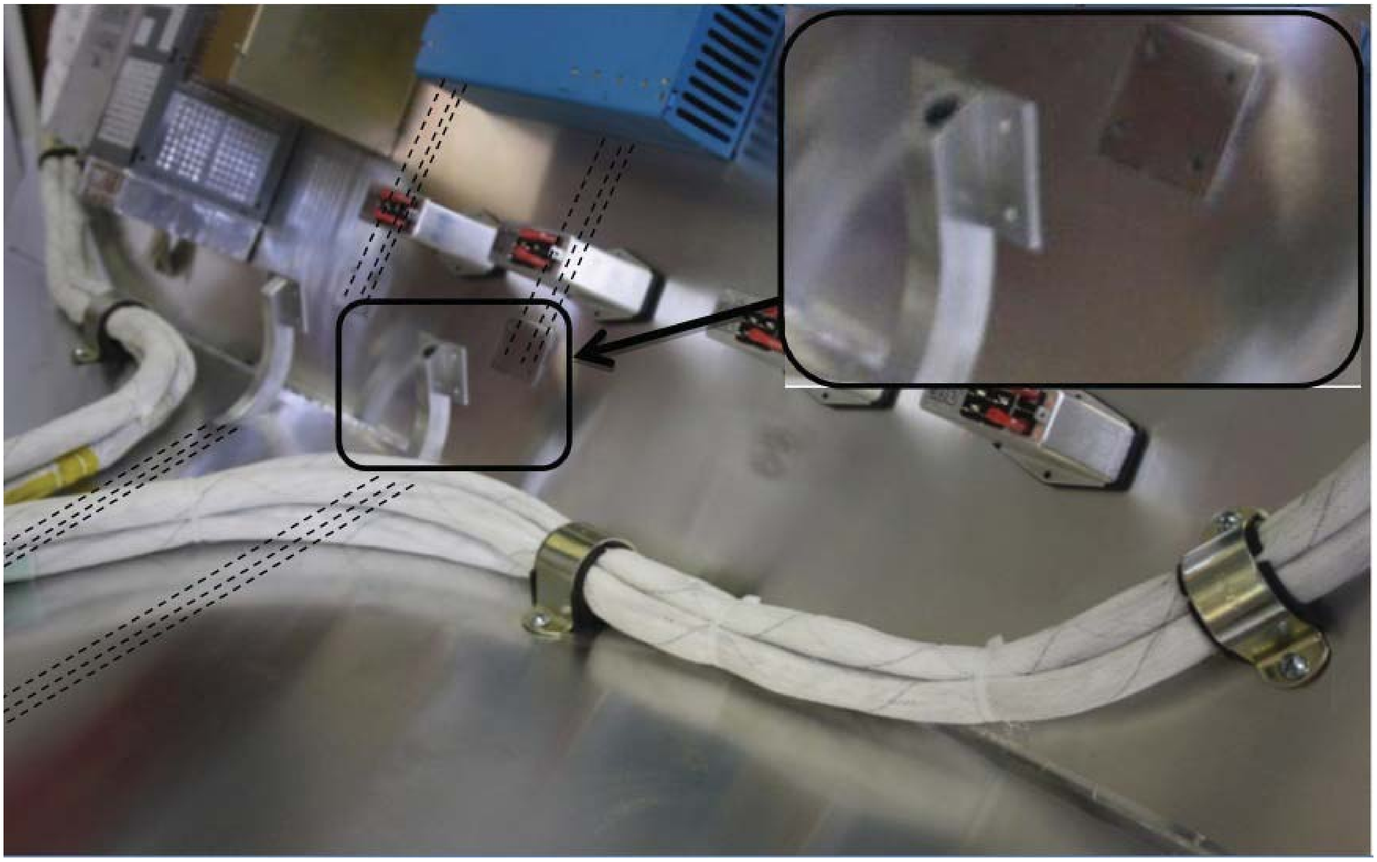


Figure 67 *Heat pipe connection: Dashed lines show how heat pipes run through the panel*

5.1.2. Joint Wiring Description

The wiring crossing the joint was arranged according to the dimensions shown below in Figure 68. The figure shows a cutout of the satellite at the joint. The diagonal lines in the top view designate where the diagonal panels in the core structure are. The curved lines are the wiring bundles, which have a 1.5" OD and a 9" radius of curvature when the panel is in the stowed position.

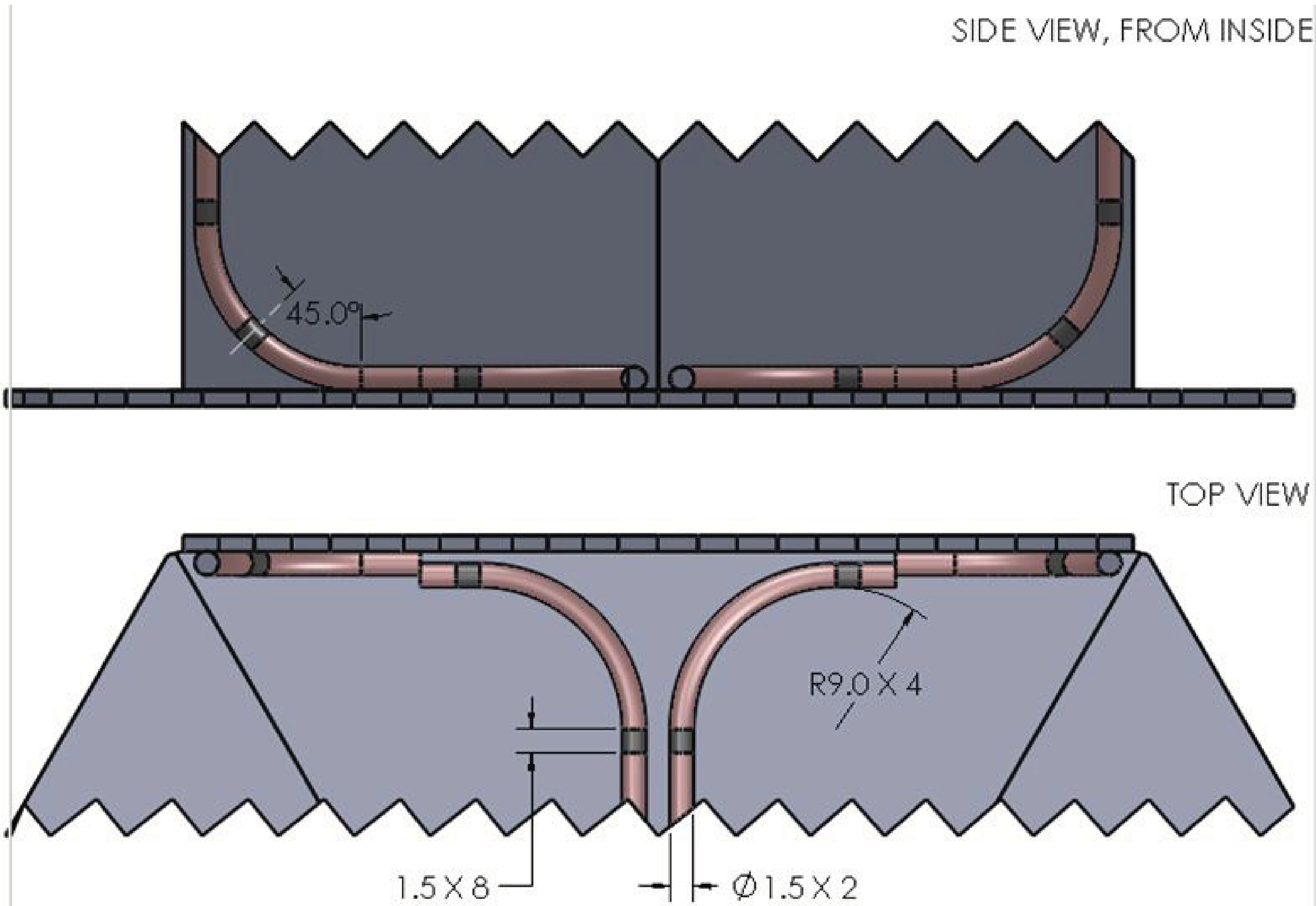


Figure 68 *Specification for the wiring across the joint, dimensioned. Note: apparent break where the wire bundles meet does not reflect the actual situation; wires actually angle slightly here, but this is not reflected in the CAD model.*

The wires in the prototype were clamped using 1.5” diameter vibration damped wire clamps purchased from McMaster Carr, and the wires were obtained as samples from a Lockheed Martin liaison and bundled together to an approximate 1.5” diameter (see Figure 69). The clamps were placed at the transition from curvature to straight wire bundle as shown, except for two clamps on the panel which were placed at 45° angles from the vertical as shown to provide a longer section of twistable wire bundle. Finally, the wire bundles were spaced 0.75” from all edges to allow room for the clamp flanges. In the CAD model this makes the wire bundles appear to break in the middle; in reality they simply bend slightly at this point.

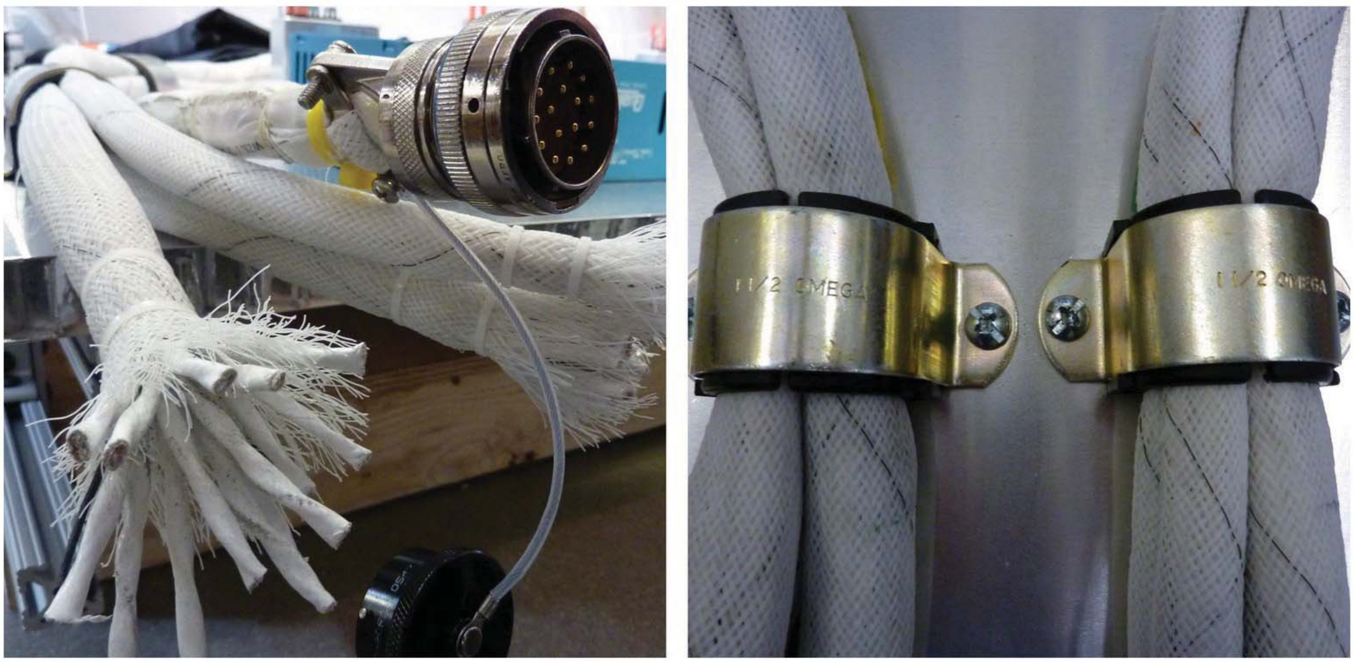


Figure 69 *Photographs of the wires used (left) and the wire clamps used (right).*

The specifications above are for the prototype that was built. If this concept were to be realized as a satellite, steel wire clamps would probably not be used (they are too heavy) and wire bundles might vary slightly in size depending on which boxes were placed on the panel. However, these specifications give enough information for someone to replicate the wire bundling built for this prototype.

5.2 1/3 scale model description

The 1/3 scale model was built from PVC foam. Although this material can be cut easily, the team used a water jet machine to cut the pieces for better precision and easier assembly. The dimensionsof the model are shown in Figure 70. The dimensions of the pieces are shown in Figures 72 - 75.

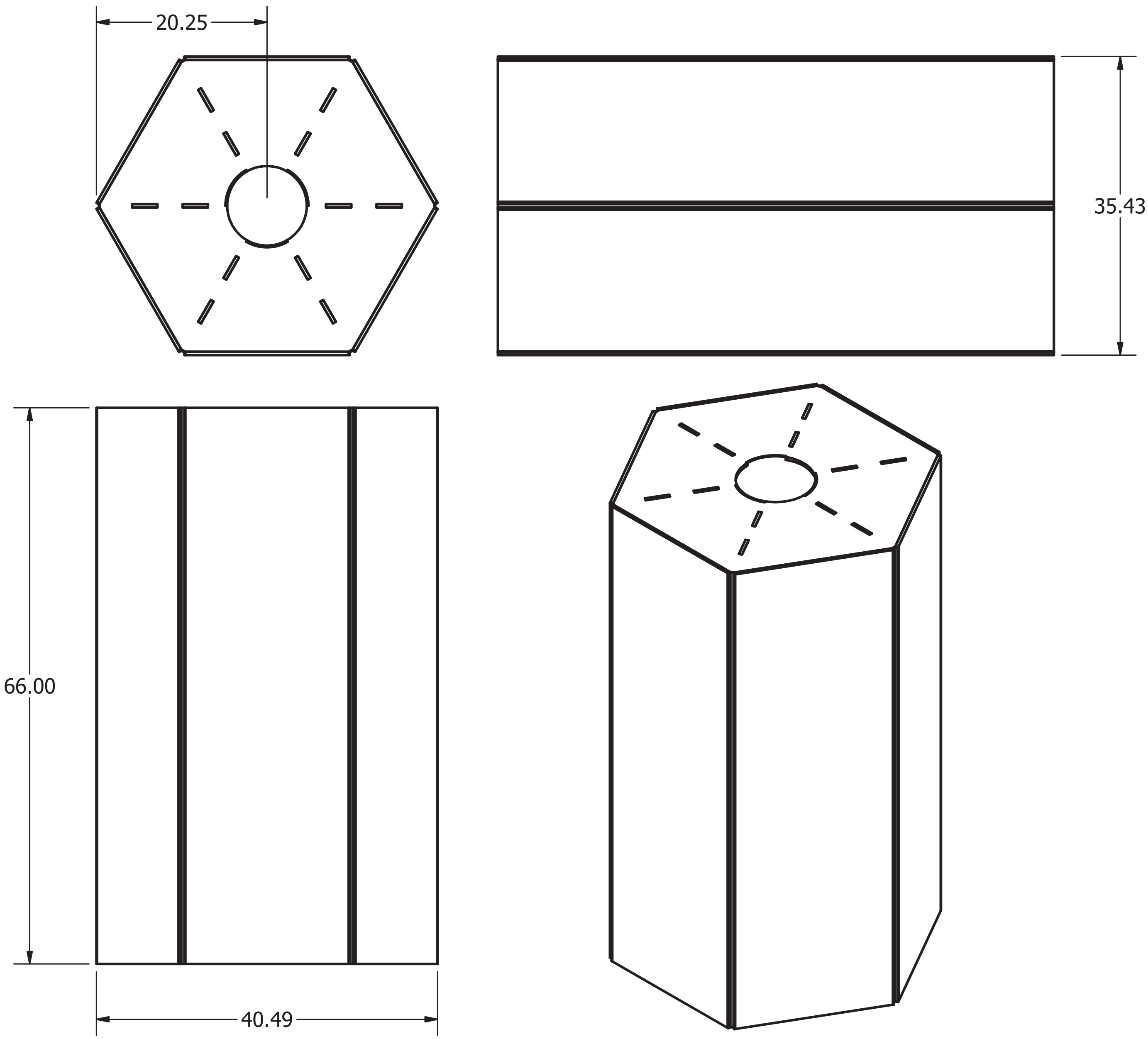


Figure 70 *General Dimensions of the 1/3 Scale Model*

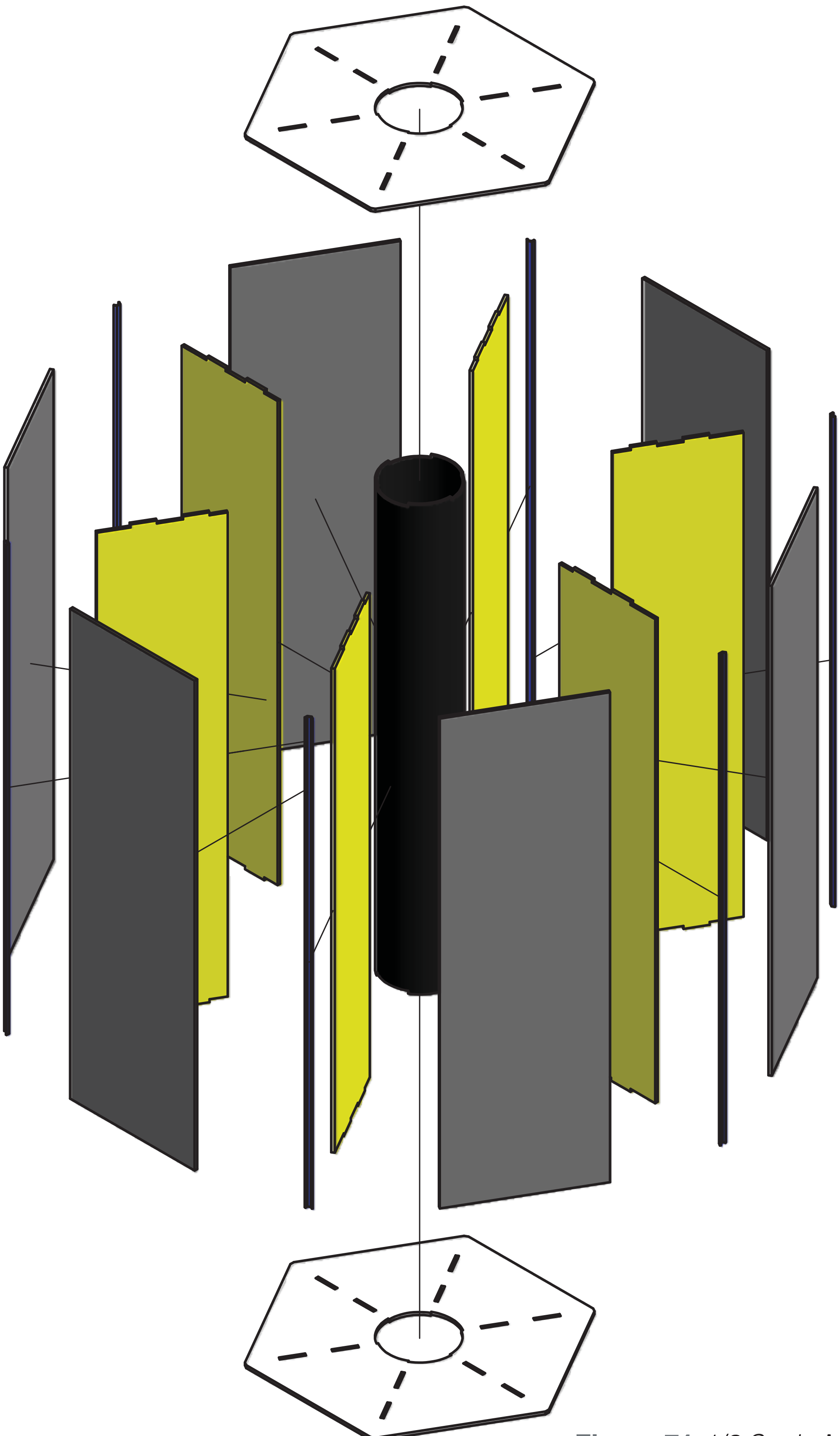


Figure 71 *1/3 Scale Model Exploded View.*

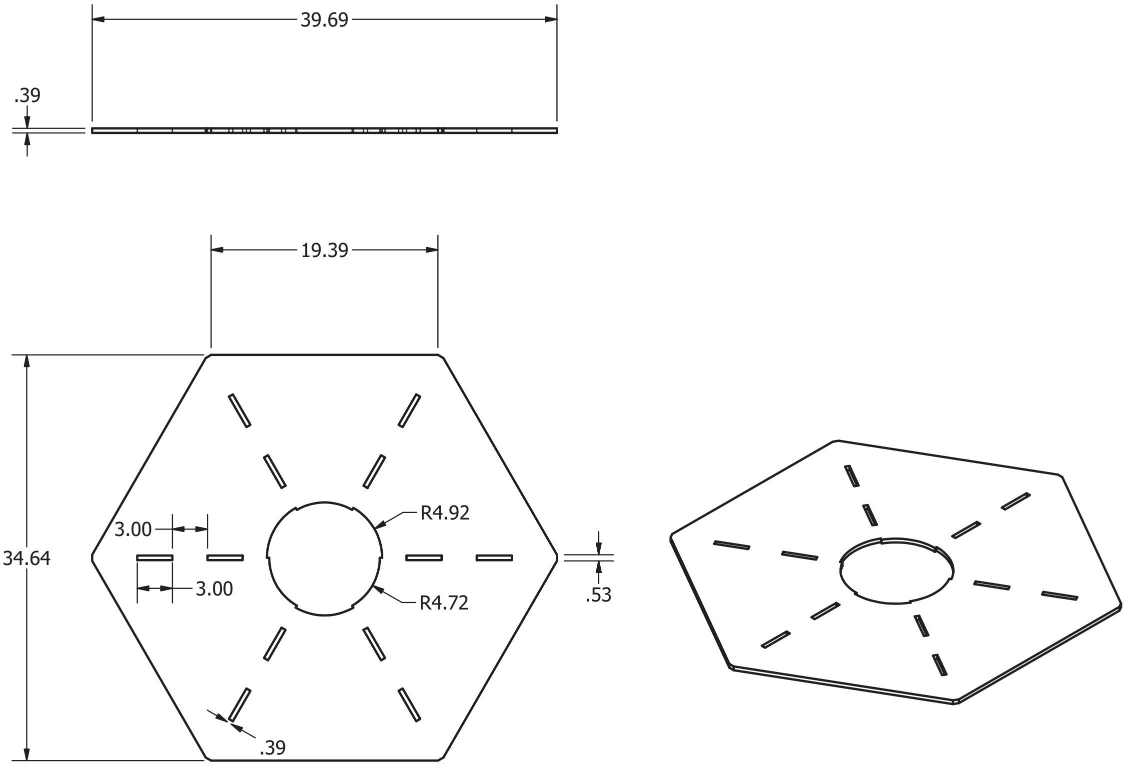


Figure 72 *Hexagonal Cap Dimensions*

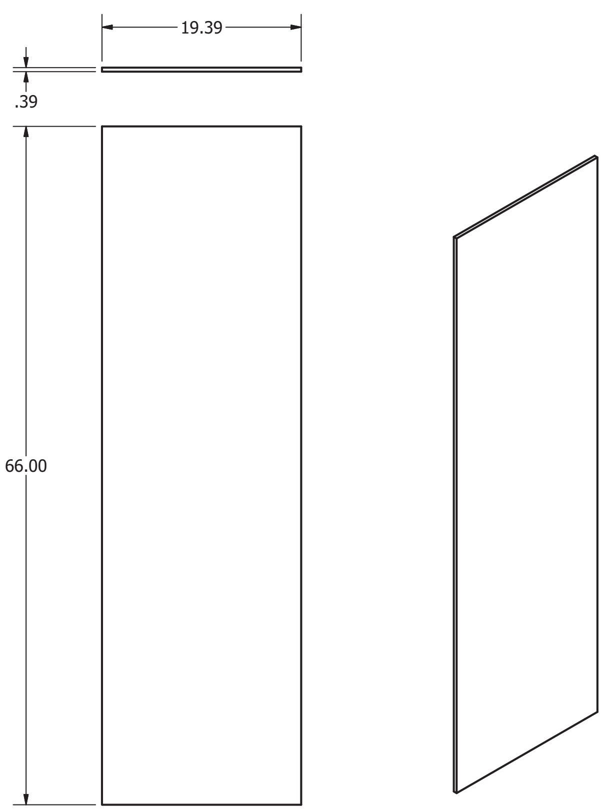


Figure 73 *External Panel Dimensions*

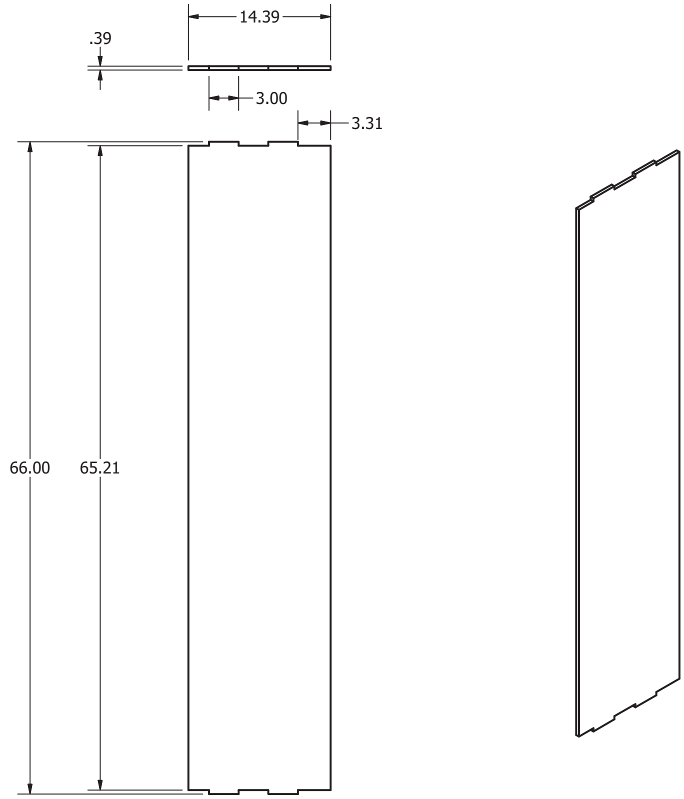


Figure 74 *Internal Panel Dimensions*

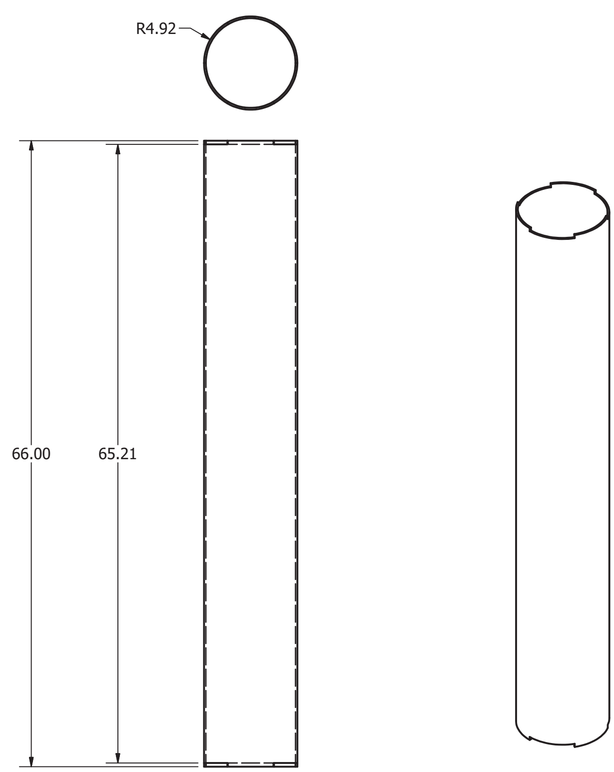


Figure 75 *Core Cylinder Dimensions*

As shown, the internal panels were built with two flanges that match corresponding grooves on the top and bottom hexagons to make the assembly easier and more precise. Three grooves were also cut in the circular hole in the hexagonal panels to match three flanges on each end of the PVC tube to be used for the core structure. These grooves were cut in the core cylinder using a moto-tool since the PVC tube could not be cut in the water jet machine.

Figure 76 *The control screen for making water jet cuts in the PVC foam.*

Figure 77 *: Using a moto-tool to cut flanges in the end of the PVC central cylinder.*

The external joint extrusions for this prototype were made from aluminum with a cross section of 1/16 X 1.25. This aluminum was bent to get the U shape desired and were bent in two sections to fit within the bending machine. Three holes were placed in each section for screws to attach the section to its corresponding panel.

The internal joint extrusions were commercial aluminum pieces with cross sections of 1/16 X ½ and an L shape. Since these joints came bent to the configuration needed, they only needed to be cut to the correct length.

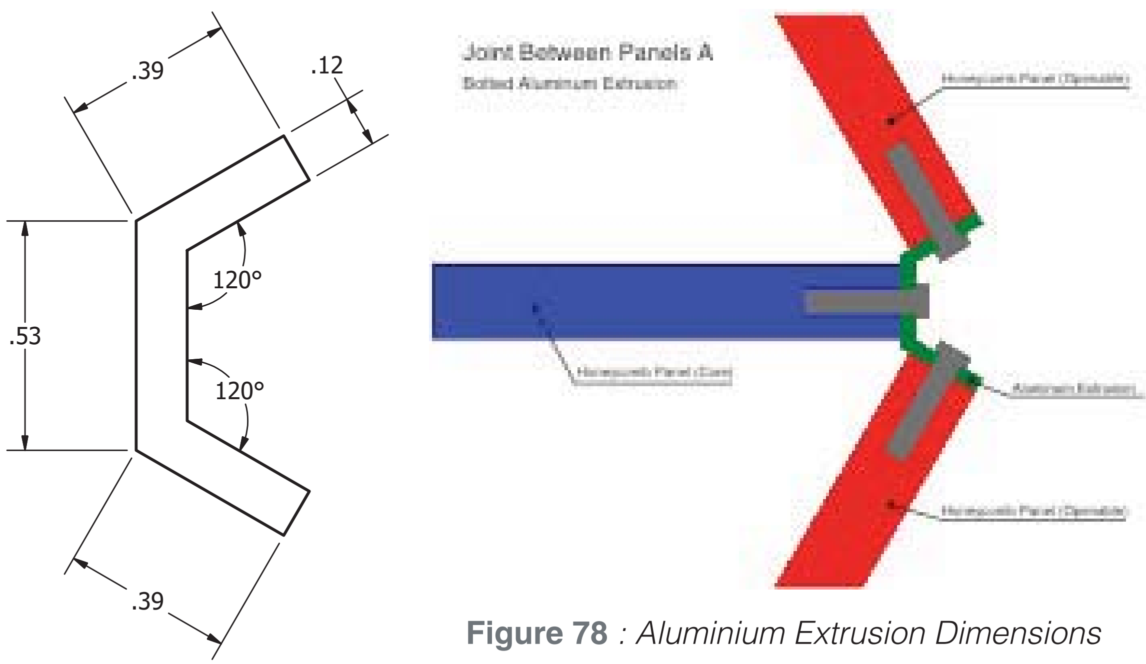


Figure 78 *: Aluminium Extrusion Dimensions*

For each external joint the team used 12 Allen screws of 1/8 X ½, which were placed according to the previous drawings. For the internal joints only 8 screws were used for each union.

The boxes for the open panel were made with a translucent acrilyc sheet of 3mm of thickness at 1/3 of the dimensions given for the boxes on that panel (see Appendix 8.1).

Finally, the lighting for each box was made with a comercial phenolic PCB and 6 or 10 yellow or red LEDs according to the heat dessipation of each box (see Appendix 8.1).

Figure 79 *The 1/3 Scale Model finished*

5.3 Structure Final 3d Model.

The design of the final structure was made in the SolidWorks CAD. This model has the real dimensions of the final structure and was drawn with the dimensions of the real honeycomb that the team bought. The aluminum honeycomb panel is: GPP-1-M3425, which means it is 1" thick core, M = "mil", 34 = 3/4" cell size, 25 = 0.025" Al face sheet, no finish, so total thickness, with face sheets, is 1+0.025*2 = 1.050 inches.

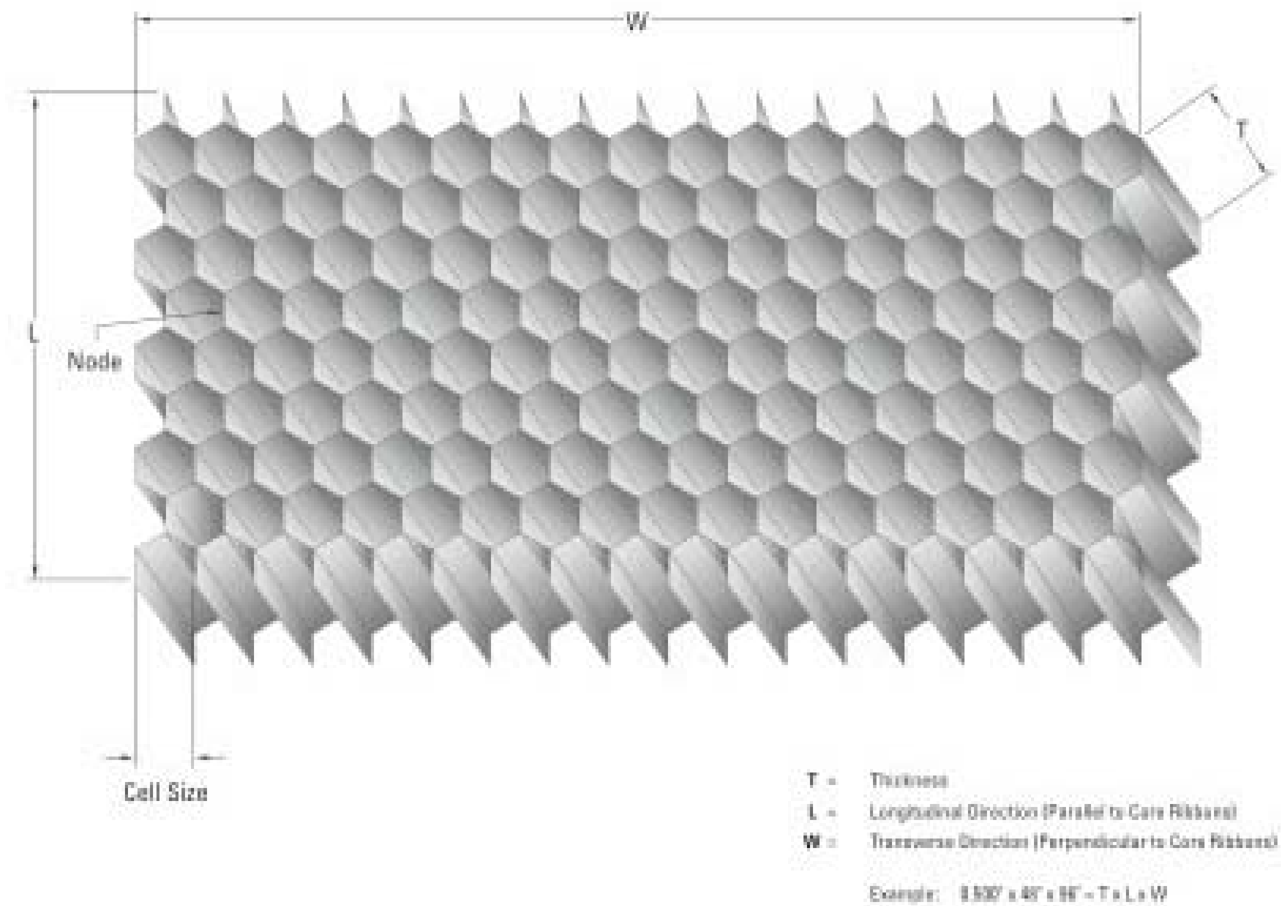


Figure 80 *Honeycomb Terminology*

The honeycomb panels and all the other elements were modeled with their mass properties to make an estimate of the final total mass (neglecting wires, fuel, etc.) and the center of mass of the structure. All the boxes for each panel were modeled and placed carefully on the panels according to the heat dissipation required and cable arrangement. Extrusion joints like those used for the 1/3 scale model are proposed to allow the panels to attach easily and reliably.

In this model the team did not draw the fuel tank arrangement, the heat pipes, or the solar array. However, since the fuel would be placed in the satellite center and the heat pipes and solar arrays would be distributed evenly, studying the boxes gives a good indication of whether the center of mass was in the center of the satellite (whether the mass was evenly distributed). The model showed that this was in fact the case. More analysis would be necessary, however, to determine the vertical location of the center of mass to meet the requirement that the center of mass be within a certain distance of the satellite bottom. Further along in the design, when more detailed wire masses, heat pipe masses, fuel placements, etc. are decided, this important factor should be taken into consideration.

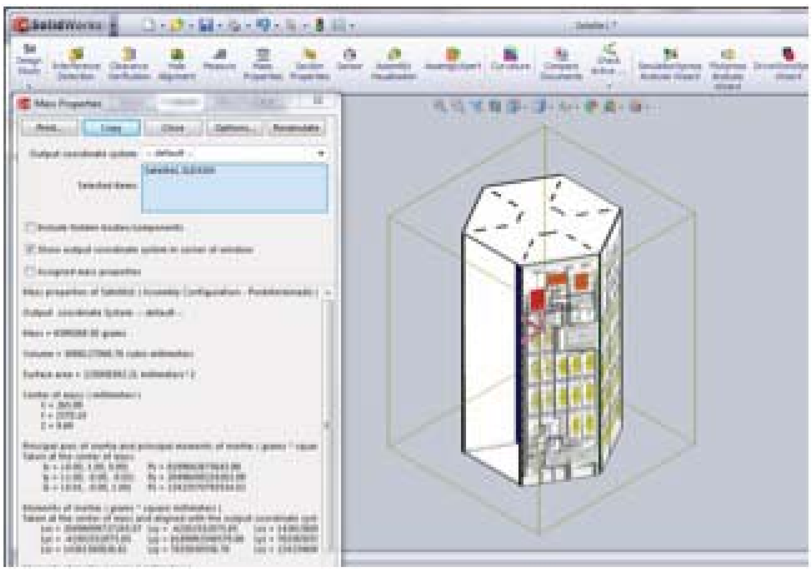


Figure 81 *Solidworks model showing the center of mass near the centerline of the satellite.*

Another important thing the team learned from this model was that all the boxes could be put inside the satellite without the boxes interfering with the radial structural panels when stowed in the vertical position. This is something CAD is very useful, allowing a quick verification that all components are packaged with clearances.

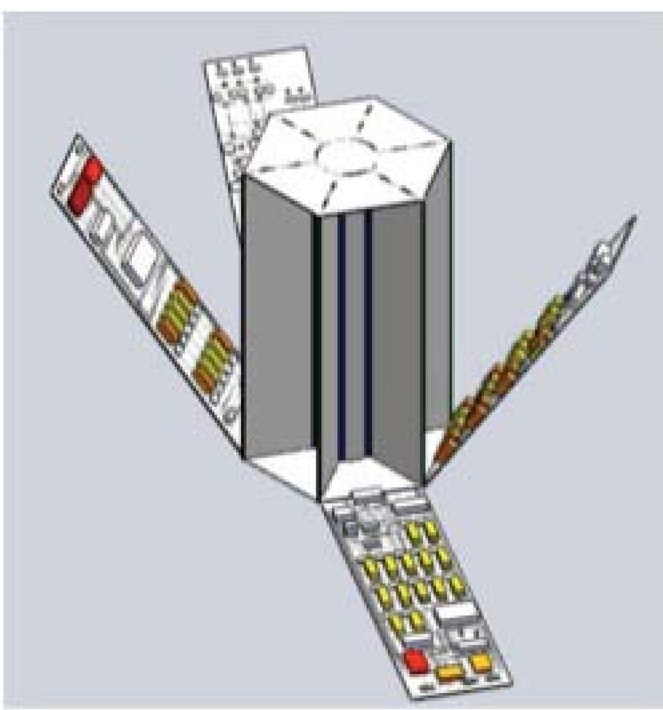


Figure 82 *The final Solidworks model.*

5.4 Boxes, wiring, heat pipes and fuel tanks arrangements

Based on the wiring diagrams provided by the liaisons, the virtual boxes were placed on the four panels of the Open Space satellite model, as was described in Section 4.9. One wiring diagram was created to consolidate information from the original six. This diagram shows important aspects of each box so that it is easy to visually distinguish them and make fast decisions. The diagram shows the size of each box, the thermal dissipation represented with six different colors, the mass represented with a different shading pattern (denser mesh means heavier box), and the wiring connections represented with solid lines.

The information related to the names, types, codes, masses, power consumptions, thermal dissipations, quantities, and sizes of each box is listed in appendix 8.1. Also, Table 12 below clarifies the color used for each box with some example information.

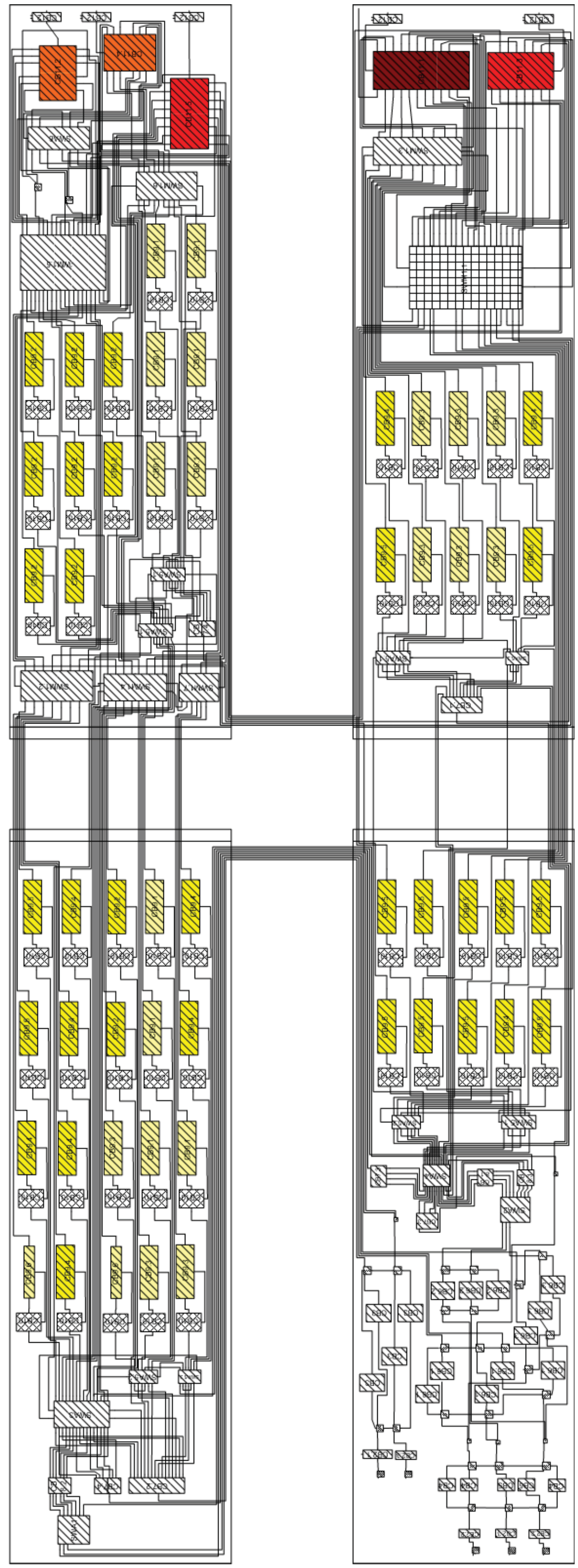


Figure 83 *Wiring diagram.*

	Operational Phase			Total			Dimensions		
Code	Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)	Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)	Length (in)	Width (in)	Height (in)
CB9.1	0.23	232.1	72.5	2.30	2321.00	725.16	14.57	4.92	5.51
CB9.2	0.23	353.5	110.4	2.30	3535.00	1104.46	14.57	4.92	5.51
CB9.3	0.14	232.1	72.5	1.26	2088.90	652.65	14.57	4.92	5.51
CB9.4	0.19	353.5	110.4	1.90	3535.00	1104.46	14.57	4.92	5.51
CB9.5	0.11	353.5	110.4	1.43	4595.50	1435.80	14.57	4.92	5.51
CB9.6	0.20	152.8	47.7	0.40	305.60	95.48	14.09	2.89	2.53
CB10	0.52	-	-	28.08	-	-	6.69	4.94	1.64
CB11.1	3.57	0.0	489.0	3.57	0.00	489.00	26.05	10.31	3.15
CB11.2	3.93	0.0	216.0	3.93	0.00	216.00	14.86	9.99	3.15
CB11.3	6.68	0.0	339.0	6.68	0.00	339.00	17.88	9.93	3.15
CB11.4	5.10	0.0	224.0	5.10	0.00	224.00	14.05	9.93	3.15
CB11.5	4.83	0.0	377.0	4.83	0.00	377.00	19.07	10.32	3.15

Table 12 *Color code for the heat dissipation of the boxes.*

On the Table 12, it is easy to distinguish that red boxes dissipate more heat than yellow ones. White boxes do not dissipate heat at all.

The size of the wiring diagram used for the 1/3-scale model, described in Section 5.2, is shown in the Figure 64.

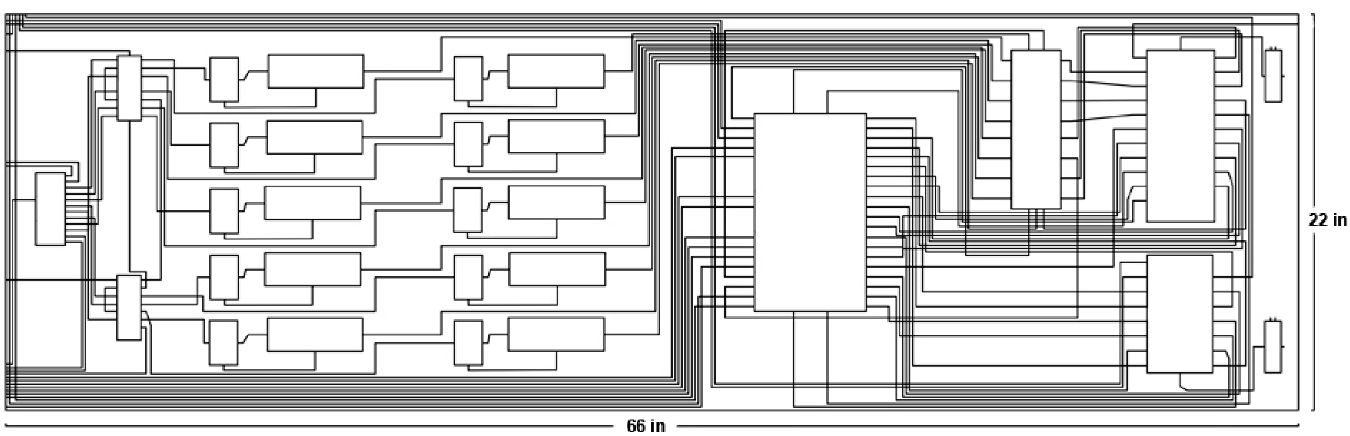


Figure 84 *Size of wiring diagram.*

Communication satellites use three tanks for the propulsion system: a fuel tank, an oxidizer tank and a pressurant tank.

- Fuel tank: 35.25” ID x 69.2” long, 70 lbm, 57215 in3 capacity.
- Oxidizer tank: 21.25” ID x 34.69” long, 20 lbm, 9712 in3 capacity.
- Pressurant tank: 16.7” OD x 29” long, 25.8 lbm, 4,967 in3 capacity.

Figure 85 *Oxidizer tank (left) and pressurant tank example (right).*

So the total capacity needed for the three tanks is 71,894 in3 (1,178 liters). In the proposed design, the internal part of the structure has a cylinder in which the team decided to put the three tanks and the propulsion system. The total capacity of the central cylinder is 195,432 in3 (3,203 liters), which means that the three tanks fit within it.

6. Project Planning and Management.

6.1 Deliverables and Milestones

The main deliverables from Fall Quarter to Spring Quarter are presented in Table 6.1. Bolded events are especially significant for the development of the project.

Date	Event	Remark
Fall Quarter		
Oct 17	Project Assigned	Team LM was assigned to the project sponsored by Lockheed Martin; Stanford division first met with UNAM division
Oct 19 – Oct 21	Global Workshop	Team LM got to know each other better and developed first ideas for persona, set up with need-finding
Oct 22 – Oct 25	Team website/ Launch your Venture	Team LM built a fancy website, decided on a weekly video meeting time and started to share ideas through email
Oct 26	Need-finding and Benchmarking started	Stanford division started with a brief communication with Cubesat student in Space and Systems Development Lab, got to know about satellite industry
Oct 26 – Nov 2	**Persona Development**	Team LM talked to design engineers at Stanford, test engineers from Boeing and scheduled a tour to Space Systems Loral. Meanwhile, Team LM brainstormed about benchmarking, explored IKEA and Home Depot for inspiration
Nov 2 – Nov 4	Benchmarking	Team LM took apart desktop computer, explored customer experience using customized online shopping, Travis and Jessica toured Space System Loral
Nov 4	Function and Experience Benchmarking Reviews	Modularity and collapsibility were highlighted to be further developed based on the need-finding and benchmarking
Nov 9 – Nov 11	Launch CFP/CEP	Team LM brainstormed with X-mind about what kind of questions to answer for CFP/CEP
Nov 11	**CFP/CEP Design Review**	Team LM met with liaisons from Lockheed and got a lot of useful information, scheduled with liaison to have phone meeting every Tuesday

Date	Event	Remark
Nov 11 – Nov 18	CFP/CEP building	Two rotating-panel prototypes were built; Team LM learned that some questions could only be solved through building and testing physical prototypes
Nov 29 – Dec 2	Fight for final presentation	Modularity and Accessibility were two main focuses for Fall Quarter; Through presentation preparation, Team LM also brainstormed about future plans of Dark Horse
Winter Quarter		
Jan 3 – Jan 13	P.Bot Design	Team LM scheduled weekly meeting with liaisons (10:00am every Wednesday); the two-week paper robot design practice warmed up the teamwork; Team LM also had lots of discussions about Darkhorse
Jan 17	First Skype meeting within team	Team LM made small prototypes individually of ideas for Darkhorse
Jan 17 – Jan 20	Brainstorming of Darkhorse; Project goal summarized and clarified	Team LM decided to focus on combining giant PCB idea and imbedded conductors to solve wiring issues, while improving the structure with an umbrella bus structure
Jan 20 – Jan 27	Darkhorse building	Team LM benchmarked breadboards and decided on details for the Darkhorse prototype and user testing
Jan 27	**Dark Horse Demonstration** **FunKtional Prototype Began**	Around this time, Team LM felt lost because of the complexity of the satellite industry and the realization that wiring issues were much more complicated than the team had thought. Team LM refocused the goal on satellite structural design after lots of discussion.
Feb 7	Composite Workshop	Team LM learned how composite material could be made for light/strong structures.
Feb 10	FunKtional Prototype Demonstration	Team LM raised a new idea which was to design a satellite kit for design engineers

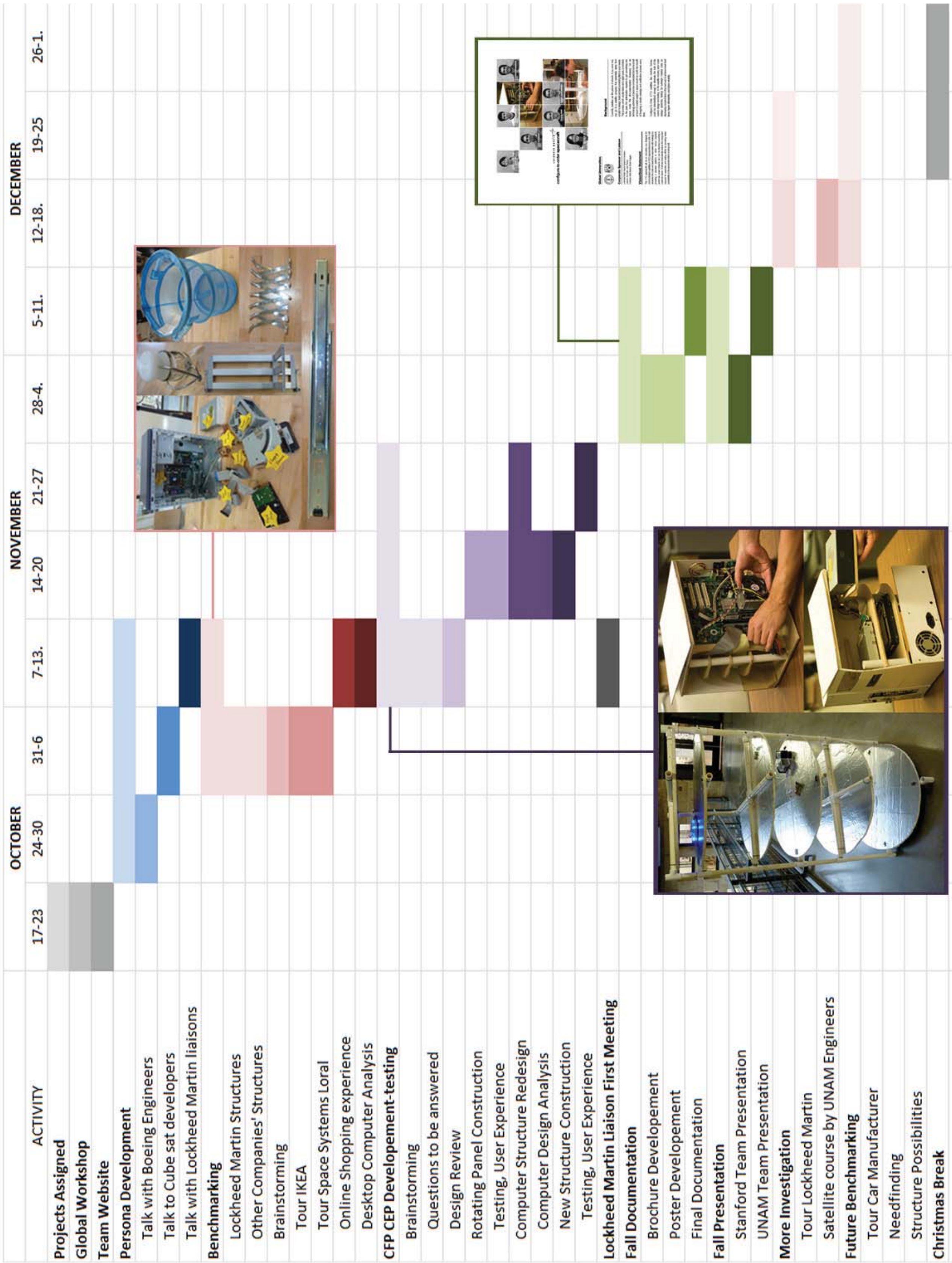
<table>
<tr><th colspan="2">Date</th><th>Event</th><th>Remark</th></tr>
<tr><td rowspan="5">Feb 12 – Feb 20</td><td>Feb 14</td><td>Team LM brainstorming for Turning Point presentation and project orientation</td><td rowspan="5">Stanford division on travel to Mexico City to meet UNAM division, a project vision was decided, which was to combine the two FunKtional Prototypes together and explore further.</td></tr>
<tr><td>Feb 15</td><td>Further Discussion on project orientation: whether to make a design kit or bus structure</td></tr>
<tr><td>Feb 16</td><td>Phone Meeting with Liaisons: decided to continue with bus structure design</td></tr>
<tr><td>Feb 17</td><td>Turning Point Presentation</td></tr>
<tr><td>Feb 18</td><td>Tour of AeroMexico’s aircraft Hangar</td></tr>
<tr><td colspan="2">Feb 22</td><td>Tour of Lockheed Martin in Sunnyvale</td><td>Jessica and Travis went on the tour and learned about Lockheed Martin’s current satellite production procedures.</td></tr>
<tr><td colspan="2">Feb 24</td><td>Functional Prototype Began</td><td>Team LM divided work so that Stanford division focused on structure and UNAM division focused on hinges.</td></tr>
<tr><td colspan="2">March 3</td><td>Functional System Prototype Testing</td><td>The Team LM made a more realistic satellite structure.</td></tr>
<tr><td colspan="2">March 10</td><td>Project Design Review</td><td>The liaisons attended Stanford division’s presentation, approved Team LM’s work and provided useful suggestions.</td></tr>
<tr><td colspan="2">March 11 – 17</td><td>Winter Documentation</td><td></td></tr>
<tr><td colspan="4">Spring Quarter</td></tr>
<tr><td colspan="2">March 29</td><td>First SGM in Spring Quarter</td><td>Team LM arranged meetings with liaisons and within team members (4:00pm every Thursday), and started discussion about the “X is finished” assignment.</td></tr>
</table>

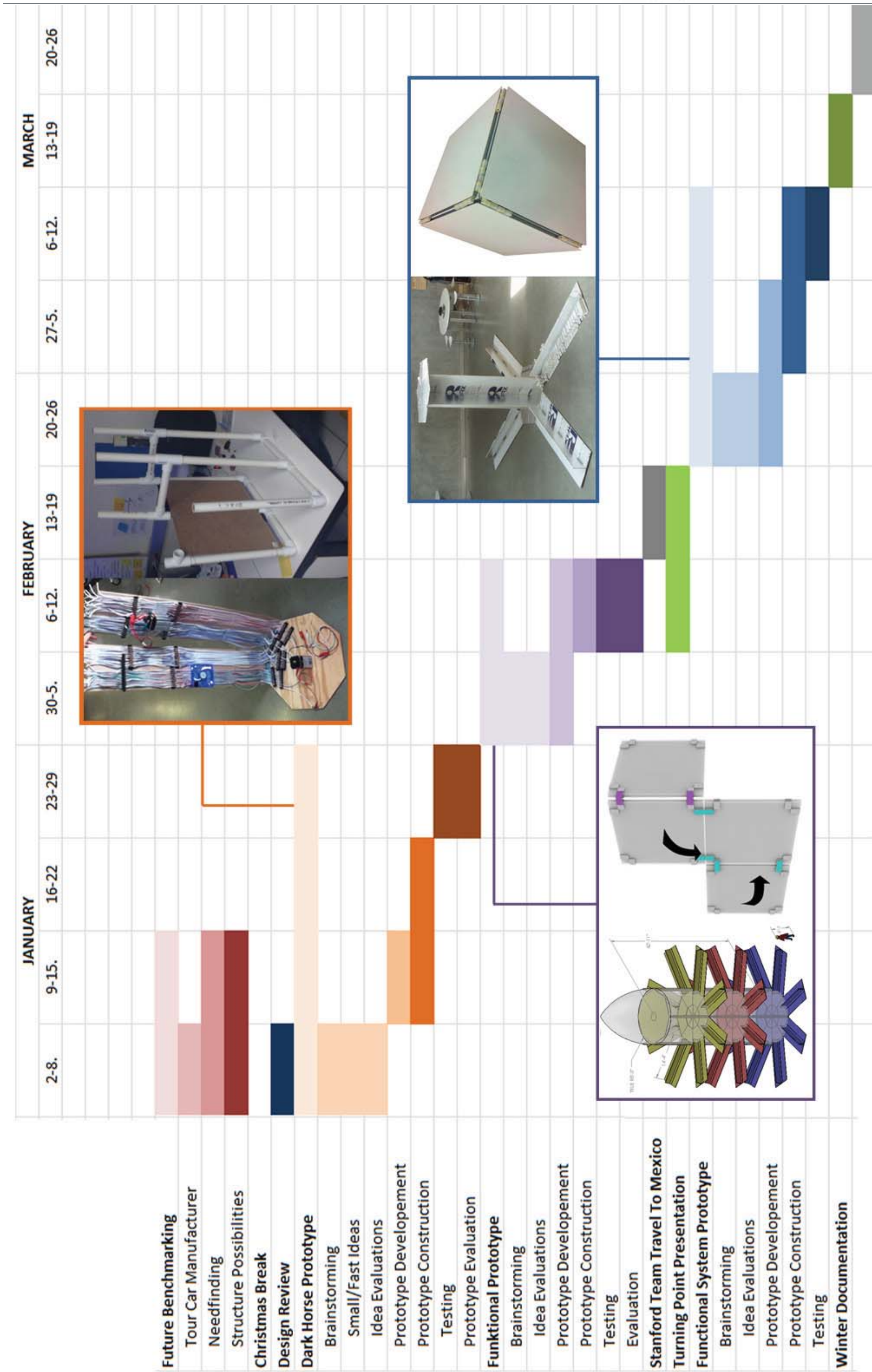
Date	Event	Remark
March 30 – April 6	**Jumping out of a Dilemma**	Team LM was diverged to two directions: to refine the bow-tie structure or to design a modular structure with small panels connected by hinges. With the feedback of TTeam and liaisons, Team LM decided to dive into the first choice.
April 7	“X” is decided	Team LM decided “X” should be a cutout full-scale joint to show the folding/unfolding of panels. Work distribution: Stanford division built the “X” and UNAM division worked on box arrangement according to the wiring diagram and core structure design.
April 7 – April 19	Design and Decision about details of bow-tie structure	Team LM did preliminary frequency analysis of the structure in Solidworks, based on which the core structure needed redesign; brainstorming and researches about: mechanisms of ground support: strong back attached to panels with crane lifting; hinge design: hinges on strong back instead of on the panel; heat pipe design: flexible heat pipes; ways to attach bolts in honeycomb panels; wiring solution at the joint: wire bundle loop Core structure redesign
April 14	Learning about honeycomb	Stanford division met with a sales manager of Plascore, Inc. to learn about honeycomb material
April 19	X is finished: A cutout full-scale joint	Feedback from TTeam drove Team LM to refine the presentation of “X”: make the strong back, wire bundles, heat pipes realistic; think about option B of “X”: create a video of how the joint works; reason about radius of wire bundle loop, heat pipe connection
April 25	Frequency analysis combined with ME309 FEA project	To perform a better frequency analysis, Team LM invited Abhishek Shiwalkar (ME310 student) who was taking a course in Finite Element Analysis to work together on the analysis

Date	Event	Remark
May 4	**Design Iterations**	Preliminary design of core structure was done
May 6		Wiring bundle redesign was decided: twisting instead of bending
May 9		UNAM division started building 1/3 scale model
May 6/10		Meeting with FEA alumnus on deciding how to do CAD analysis
May 10		Discussion about what kind of heat pipe to be used and how to realize heat pipe connection
May 13 – May 17	Building cutout full-scale joint	Stanford division rebuilt cutout joint and strong back, designed heat pipe connection and tank arrangement; wire bundle position was based on calculated loop bending radius; Box and wiring arrangements on panels were finished
May 17	Penultimate Design Review	Team LM got affirmative feedback from the TTeam! Project calendar was updated
May 20	UNAM division arrived at Stanford	
May 23 – May 25	EXPE preparation	1/3 scaled boxes for one panel were made; Heat Pipes were mounted on the cutout full-scale joint
May 26		Final Brochure was finished
May 28		Name & Motto was decided
May 30		Poster was finished
May 31	Practice presentation	Team LM finalized video, presentation, T-shirt, postcards, decoration for EXPE booth, and enjoyed the EXPE fair!
June 1	Executive Briefing	
June 2	**EXPE Design Fair**	
June 3	Frequency test of honeycomb panel	Travis and Jessica went to Lockheed to do a frequency test of honeycomb panel for basis of FEA analysis
June 3 – June 7	Spring Documentation	

Table 13 *Project Development of Team LM*

6.2 Project Time Line




JANUARY
FEBRUARY
MARCH
2-8.
9-15.
16-22
23-29
30-5.
6-12.
13-19
20-26
27-5.
6-12.
13-19
20-26
Future Benchmarking
Tour Car Manufacturer
Needfinding
Structure Possibilities
Christmas Break
Design Review
Dark Horse Prototype
Brainstorming
Small/Fast Ideas
Idea Evaluations
Prototype Developement
Prototype Construction
Testing
Prototype Evaluation
Funktional Prototype
Brainstorming
Idea Evaluations
Prototype Developement
Prototype Construction
Testing
Evaluation
Stanford Team Travel To Mexico
Turning Point Presentation
Functional System Prototype
Brainstorming
Idea Evaluations
Prototype Developement
Prototype Construction
Testing
Winter Documentation

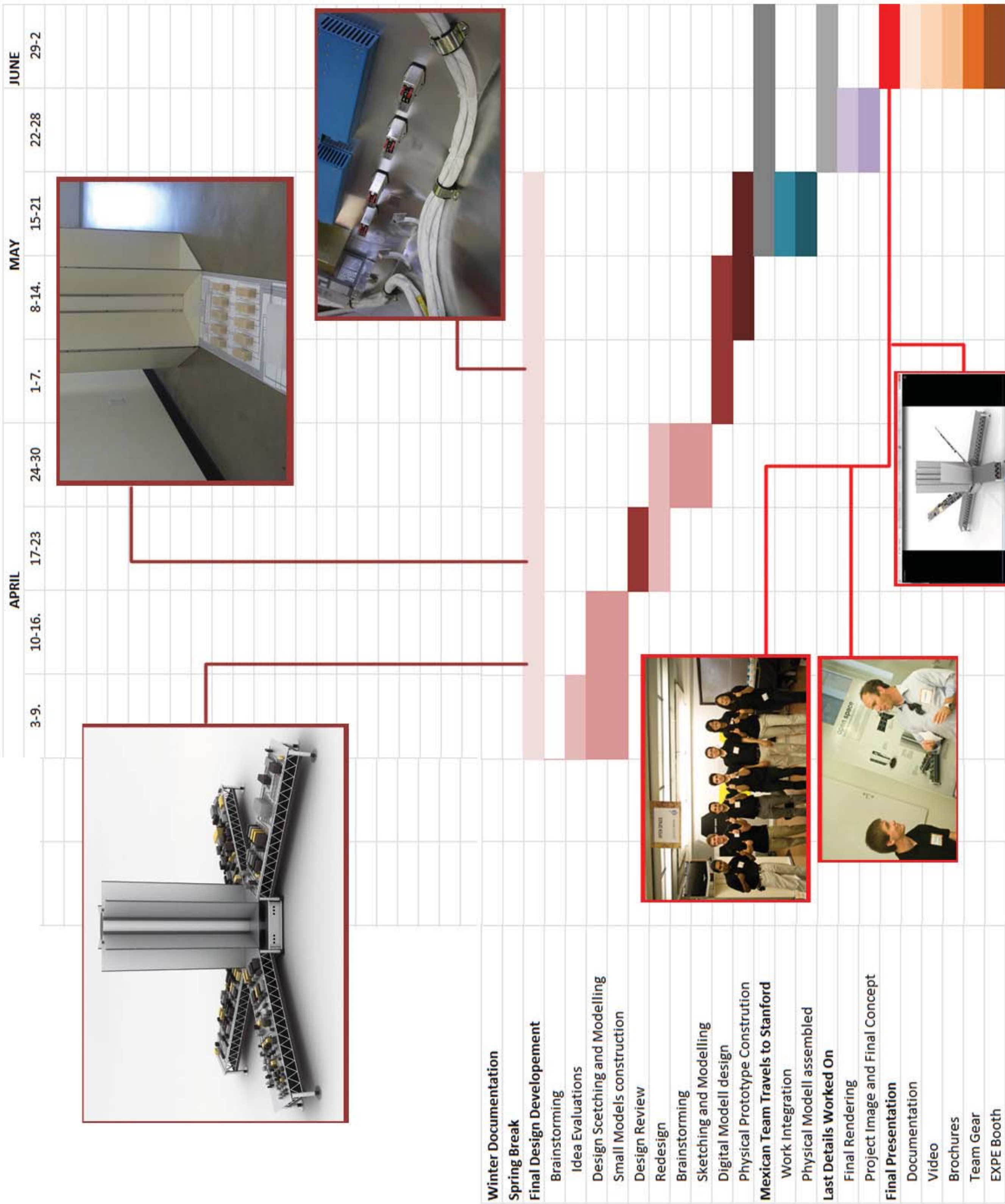


Figure 86 *Project Timeline*

6.3 Distributed Team Management

6.3.1. Communication, organization and planning

By the spring term, the team had already learned what types of communication systems did and didn't accommodate the group's way of working together, so the use of software and applications remained the same as in the past terms, using the resources that proved useful to the team. Programs such as Skype and Polycom allowed the team to be in constant communication throughout the term and stay in touch while developing prototypes.

Team meetings were arranged to be held at least once a week, varying in day and time depending on needs. Having a much more difficult agenda this term, it was harder to determine a schedule in which the team could agree, since most of the time at least one of the members had classes to attend. As the deadline grew nearer and nearer, the team had to increase the number of meetings so that both divisions could be aware of what was being done on the other end.

Even though schedules were a problem, meetings were usually set during the interval between UNAM's and Stanford's ME310 class (the first took place several hours before the latter).

This term the meetings were focused on topics previously mentioned on emails sent between team members regarding ideas for further prototypes, new information found or given, and how the project was unfolding. Having addressed these subjects beforehand helped the team to focus on specific ideas and concerns, which were constant problems faced the past terms.

Adversity was encountered in the beginning of the term when the team found that they had been planning on two different ways to further develop the project. Since there wasn´t much time left to discuss possible solutions, communication between team members was key in finding a way to merge both ideas so that the whole team agreed with the final decision.

Meetings with the liaisons were more frequent this term, since more information from the liaisons was needed, and were scheduled to be held at 4:00 pm on Thursdays so the whole team could discuss the contents that were covered during the session, since the UNAM team wasn't able to be present on each one. Before these meetings, both the Stanford and UNAM divisions would prepare a small document of topics and questions that had arisen during the week to be addressed to the liaisons.

After each meeting, the Stanford team, (which usually had a better understanding of the conversation because of communication problems using Skype and the Polycom) prepared a summary of the various topics that were discussed for further reference, also including documents that were handed by the liaisons directly to the Stanford team.

These meetings were a key part of the design process in this term and proved to be a successful way of organizing activities and having idea explorations between all the team members. Although the team never fully developed the desired communication system for SGMs and Meetings with liaisons, this last term was very successful in terms of having the whole team on the same page and aware of the decisions made and the information that was discussed.

6.3.2. Work administration

During the various stages of the project, the team decided to divide the work into two groups, transforming the disadvantage of having the team separated into the advantage of having groups focusing on different topics. This proved to be useful when creating prototypes since the development of various designs gave the whole team a bigger set of things learned at the end of each phase.

Focusing on separate subjects, more ideas were given in brainstorming sessions and the project grew from different points of view, preventing the team from sticking with one single idea.

The final stages of the design process saw the biggest separation of the team, since the background of each member allowed them to focus on a different task that would be easier for them. Analysis like the center of mass and other technical parts were developed by the mechanical and mechatronic engineers; rendering, modeling and the presentation parts were done by the designers. Although the group divided into teams for these sections there were still some parts that were done by the whole team, or groups of designers and engineers together.

Final stage at Stanford

The last two weeks of the design process, the Mexican team traveled to Stanford to finish up the project with the other part of the team. This stage was very important for the overall presentation, since in this time the team had to come up with the final image, ideas and presentation of the whole project.

Handouts and Feedback

Writing the handouts at the end of each design stage gave the team a good perspective on what had been done and what needed to be done in the future. They were very important to keeping the team on track and providing a record of where the project came from and how it should continue to unfold. This allowed the whole team to know what needed to be done, and each member to have an idea of the big picture. This is helpful because sometimes teammates can go through phases in which they are not sure where the project is going, and it is important to keep the whole team on the same page.

Information problems

One of the biggest issues confronted during the design process was the lack of information that the team has on the subject. Some ideas were delayed due to uncertainty in terms of the prototype being innovative or useful to the project. Some prototypes had to be discarded after the design was finished because information was found on related topics shwoing that the idea wasn't as good as the team thought, or was not possible to apply to the structure of a satellite.

6.3.3. Design stages

X is finished

For this prototype, the main goal was to finish some part of the final prototype, so the team could make sure that work would be divided through the last few weeks of the project instead of working on everything at the last minute.

Since two different prototypes were planned to be shown on EXPE, each part of the team worked on a separate model. One of them would show a cutout of the connection between the base panel and the opening panel, with a representation of what the strongback would look like and how it would actually work. The second prototype would be a 1/3 scale model showing what the whole structure would look like. Also, one of the panels would be open, showing what the box arrangement would be and how hot the different boxes are.

The group working on the first prototype started working on a wood prototype without boxes and real wires, which proved to be a poor representation of what the actual satellite would look like. The team had to plan a way of showing the same idea, but with better and more accurate materials and aesthetics. A new prototype was built using heat pipes, wires and real material, so this was a really big step from one stage to the other.

The second group started working on two steps at a time. The first part was to create a wiring diagram with the boxes that were given by the liaisons. The second part was to come up with a way of building the 1/3 scale model so that it could be taken apart and sent to Stanford and built afterwards. Different materials were tried, but since the team wanted to have a clean and simple model, some plans failed to represent what was wanted.

Final Global Meeting

The team met up at Stanford to finish up the final details of the whole project. This time the team did not divide into groups depending on nationality, but rather based on the tasks that had to be done and the time that each would take to be finished. Some members worked on the image for the final presentation, making sure that everything looked like the same project, so that the whole project would have brand identity. The rest of the team worked on finishing both prototypes, doing analysis and writing information for the final document and presentation.

This stage was the most important one, since the team came to one conclusion and could agree easily on what to do and how to do it.

Final presentation

The final presentation was a mixture of graphic design, videos, information, and a set of team gear (i.e. team shirts, postcards, and other things). The team had to work really hard to finish the different tasks that had been set to have everything presented for EXPE. A booth was designed using the same colors and shapes that were used in the whole presentation, and in only one day the stand was mounted and ready to go.

Figure 87 *The design team and its booth at EXPE*

Figure 88 *Visitors viewing the prototipes in the Open Space booth*

6.4 Project Budget

During the design process, there were a series of purchases made by both sides of the team for experimentation and investigation purposes as well as for the various prototypes that were made. These expenditures are presented in two separate tables showing the funds spent by each half of the team throughout the whole design process.

Expenditures

The Lockheed Martin team´s term allocation was set to $1000 dollars for the fall term, $3000 for the winter term, and finally $4000 for the spring term, which were divided into 3 different sections for organization purposes. The first part was used for functional and experience prototypes, the second one was used for tools and other materials, and the third would be for general purposes such as teamology and research.

Fall

During the fall term the team didn’t spend much money on supplies since the team had supplies available for working. The biggest expenditure involved materials used for critical prototypes which were developed with more specific components that had to be bought.

Winter

Having worked on several prototypes on the winter term, expenditures increased more than double since more materials and components had to be bought. Having more detailed prototypes forced the team to spend more money on better components and more realistic materials.

Spring

During the final term the team added one more section to the budget (final presentation material). So, apart from having the usual prototype, tools and general sections, the team made a new part for posters, brochures, and materials for the EXPE. Since the team met at the end of the project the budget was divided more evenly than the other terms.

ME310 Budget Spreadsheet - Fall Quarter 2010								
Team Name:	Lockheed Martin		Budget Monitor: Jessica Ji					
Reference*	Date	Vendor Name	Description of expense	Pre-tax Amount	Shipping & Handling (if any)	Amount Incl Sales Tax	Purchased by	Receipt Turned in to Manny on
	10/30/2010	IKEA	bottle, napkin holder, laundry hamper, d	$23.95		$26.17	Travis	11/17/2010
	10/30/2010	Home Depot	drawer slide	$11.48		$12.54	Jessica	11/17/2010
	11/1/2010	William Mason (craigslist)	HP desktop w/ keyboard & mouse	$40.00		$40.00	Travis	11/17/2010
	11/13/2010	Home Depot	PVC pipes/tees/crosses, foam matts	$93.19		$101.81	Jessica	11/17/2010
	11/15/2010	Home Depot	PVC pipes/tees, glue, zip-ties	$28.42		$31.05	Travis	11/17/2010
	11/15/2010	Fry's Electronics	Battery, Switches, Wires, Eletronics	$53.42		$58.36	P-card (Jessica)	11/16/2010
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
				$0.00		$0.00		
			Total			$269.93		
			Fall Allocation	-->		$1,000.00		
			Available Balance	-->		$730.07		

Table 14 *Stanford Division Fall Expenditures*

ME310 Budget Spreadsheet - Winter Quarter 2011

Team Name: Lockheed Martin **Budget Monitor:** Jessica Ji

Reference*	Date	Vendor Name	Description of expense	Pre-tax Amount	Shipping & Handling (if any)	Amount Incl Sales Tax	Purchased by	Receipt Turned in to Manny on
	1/4/2011	Teaching Assistants	dual-heat soldering iron	$25.00			TAs (Travis)	N/A
	1/4/2011	RadioShack	Mini buzzer & Photoresistors for PBot	$6.48			Jessica	2/7/2011
	1/5/2011	Fry's Electronics	Servos for PBot	$19.98			P-card (Travis)	1/7/2011
	1/5/2011	Phil's Treasure Pot	Chinese & Hawaiian food for SUDS	$240.49			P-card (Jessica)	1/6/2011
	1/18/2011	Stanford PRL	2-quarter PRL license for Jessica	$230.00		$230.00	Direct Transfer	N/A
	1/18/2011	Stanford PRL	2-quarter PRL license for Travis	$230.00		$230.00	Direct Transfer	N/A
	1/18/2011	Stanford PRL	2-quarter PRL license for Xiao	$230.00		$230.00	Direct Transfer	N/A
	1/18/2011	Walmart	Plastic drawers, pipecleaners, hot glue sticks, other prototyping material	$38.45			Jessica	2/7/2011
	1/21/2011	Home Depot	wood, wires, string, tape, staple-gun, hinges, screws	$84.71			P-card (Travis)	1/21/2011
	1/24/2011	Jameco	electronics for Dark Horse	$62.46			Jessica	2/7/2011
	2/2/2011	Stanford PRL	1/4" duron sheet	$8.00		$8.00	Jessica	2/7/2011
	2/3/2011	Teaching Staff	business cards	$79.30		$79.30	Direct Transfer	N/A
	2/7/2011	Stanford PRL	1/4" duron sheet	$8.00		$8.00	Jessica	2/7/2011
	2/7/2011	Stanford PRL	1/4" duron sheet	$8.00		$8.00	Jessica	
	2/26/2011	Home Depot	Foam boards, metal brackets, bolts, nuts, washers for Functional	$196.51			Jessica	
	3/2/2011	Orchard Supply Hardware	Hinges, latches	$26.48			Travis	
			Total					
			Winter Alocation	-------------------->		$3,000.00		
			Available Balance	-------------------->				

Table 15 *Stanford Division Winter Expenditures*

Team Name:	Lockheed Martin		Budget Monitor: Jessica Ji					
Reference*	Date	Vendor Name	Description of expense	Pre-tax Amount	Shipping & Handling (if any)	Amount Incl Sales Tax	Purchased by	Receipt Turned in to Manny on
	1/5/2011	Phil's Treasure Pot	Chinese & Hawaiian food for SUDS		25		P-card (Jessica)	3/31/2011
	4/11/2011	U-Haul	Trailer to move large panels	$18.95	$8.00		P-card (Travis)	4/13/2011 (by email)
	4/11/2011	Home Depot	Panels, epoxy, rivets for building a satellite structure	$172.23			P-card (Jessica)	4/11/2011
	4/11/2011	Skype	Skype credit to call global teammates	$10.00		$10.00	P-card (Travis)	4/11/2011
	4/29/2011	McMaster Carr	T-slotted framing & hardware for joint	$703.30	$121.23		P-card (Travis)	5/4/2011 (by email)
	5/3/2011	Halted Specialties Co	Line filters, AC plugs	$18.58			Jessica	5/18/2011
	5/3/2011	Weird Stuff	Power supply, video/audio equipment	$14.00			Jessica	5/18/2011
	5/9/2011	Pacific Panels	Aluminum honeycomb, cut to size/shape	$456.00		$500.46	P-card (Jessica)	5/17/2011
	5/11/2011	Home Depot	Epoxy, tape, cable ties, screw driver, wire connectors, bolts	$88.70			Jessica	5/18/2011
	5/12/2011	Halted Specialties Co	Power supplies	$80.00			P-card (Jessica)	5/12/2011
	5/13/2011	Home Depot	Epoxy	$195.12			P-Card (Travis)	5/13/2011
	5/21/2011	Tap Plastics	Acrylic, 60% light weight, 2'x4' sheet	$52.00			Jessica	
	5/29/2011	FedEx Office	Poster	$103.99			Travis	
	5/30/2011	FedEx Office	Panel wiring image	$5.39			Jessica	
	5/31/2011	Walmart	Wrapping paper, tape, scissors, Xacto knife, safety pins, cloth, T-shirts, transfer sheet, fabric, tulle	$109.05			P-Card (Jessica)	5/31/2011
	5/31/2011	Target	Polo shirts	$79.92			P-Card (Jessica)	5/31/2011
	5/31/2011	Diddams	Cellophane wrap	$11.97			P-Card (Jessica)	5/31/2011
	6/1/2011	PRL Room 36	Heat transfer vinyl	$23.00		$23.00	Travis	
				$0.00				
				$0.00				
				$0.00				
			Total					
	Fall Excess		Spring Allocation	------------------------------------>		$4,000.00		
	Winter Excess		Available Spring Balance	------------------------------------>				
			Excess from Fall & Winter	------------------------------------>				
			Available Balance	------------------------------------>				

Table 16 *Stanford Division Spring Expenditures*

Fecha	No. Comprobante	Concepto	Partida	Ingreso ($)	Egreso ($)	Saldo ($)	
						0.00	
#########	4108	Impresión Plotter			144.00	-144.00	-144.00
#########	18959	3 Servo HS 322HD			0.00	-144.00	-580.50
#########	FS 1187	Artículos diversos (electrónica)			0.00	-144.00	-797.86
#########	FS 1341	Artículos diversos (electrónica)			0.00	-144.00	-95.02
#########	APQF04254	Artículos diversos (papelería)			43.00	-187.00	-43.00
#########	16	Corte láser			174.00	-361.00	-174.00
#########	N/A	Artículos diversos (papelería)			0.00	-361.00	-21.50
13/1/11	120075	Materiales diversos (construcción)			0.00	-361.00	-78.00
'otal (al corte)						-361.00	-1933.88
						0.00	
20/01/11	HGDFE254617	Materiales diversos (construcción)			335.00	-335.00	-335.00
21/01/11	802704	Materiales diversos (construcción)			189.70	-524.70	-189.70
21/01/11	120500	Materiales diversos (construcción)			76.00	-600.70	-76.00
24/01/11	1097	Corte láser			319.00	-919.70	-319.00
24/01/11	N/A	Artículos diversos (papelería)			0.00	-919.70	-21.00
24/01/11	120587	Materiales diversos (construcción)			86.00	-1005.70	-86.00
26/01/11	APQF04343	Artículos diversos (papelería)			35.90	-1041.60	-35.90
31/01/11	1101	Corte láser			348.00	-1389.60	-348
'otal (al corte)						-1389.60	-1410.60
						0.00	
#########	B 8143	Pemex Magna 32011			210.03	-210.03	-89.53
#########	BFASF52705	Artículos diversos (papelería)			149.00	-359.03	-149.00
#########	B 132685	Materiales diversos (construcción)			250.56	-609.59	-250.56
#########	'VINSURGEN001690	Artículos diversos (papelería)			258.00	-867.59	-258.00
#########	AJOF242517	Artículos diversos (papelería)			26.90	-894.49	-26.90
'otal (al corte)						-894.49	-773.99
						0.00	
#########	2778	Herramientas			120.00	-120.00	-120.00
#########	818100	Materiales diversos (construcción)			186.00	-306.00	-186.00
#########	23080	Materiales diversos (construcción)			97.94	-403.94	-97.94
#########	43831	Materiales diversos (construcción)			123.67	-527.61	-123.67
18/3/11	AJOF258337	Artículos diversos (papelería)			93.44	-621.05	-93.44
'otal (al corte)						-621.05	-621.05
						0.00	
#########	TA6387	Pemex Magna 32011			280.13	-280.13	-150.00
#########	57967	Materiales diversos (construcción)			580.00	-860.13	-106.62
#########	CN78033	Pemex Magna 32011			470.05	-1330.18	-470.05
#########	)-1C48-A0EB-CAFFI	Materiales diversos (construcción)			5445.93	-6776.11	-5445.93
17/5/11	823518	Materiales diversos (construcción)			402.25	-7178.36	-402.25
18/5/11	28356	Materiales diversos (construcción)			420.00	-7598.36	-420
19/5/11	5446	Pintura y Complementos			649.99	-8248.35	-649.99
19/5/11	FS9001	Artículos diversos (electrónica)			847.33	-9095.68	-847.33
19/5/11	425	Materiales diversos (construcción)			3480.00	-12575.68	-3480.00
23/5/11		Envío de prototipo			9000.00	-21575.68	-9000.00
						-21575.68	-20972.17
Total(Todo)						**-24841.82**	**-25711.69**
				Boletos	17535.00		
				Devuelto	1576.60		
				Falta	14265.22		
				x Justificai	1000.00		
					34246.69	-25841.82	
				En dolares		**-2210.59196**	

Table 17 *UNAM Division Expenditures*

6.5 Reflections

Individual team members' thoughts and reflections are recorded here.

Travis

This quarter started out with the stress and confusion of last quarter culminating in an argument over what we were going to do. After several weeks of arguing on Skype, talking to the liaisons, consulting the teach team, and beating our heads against the wall, we finally came together and settled on a goal. When this happened, the whole project suddenly became more worthwhile, real things started getting built and improved, and by the time EXPE rolled around I was finally proud of our project. I'm really happy with the result and glad that we were able to come together and finish strong.

Jessica

Satellites are very complicated. There are so many issues to consider. It seemed as if the more we learned about constraints, the more we deviated away from crazy ideas and towards existing designs. However, it was important to learn the reason behind those designs. Basically, we had to remember to ask WHY things are the way they are. And not only learn it, but share it as well; communication among the global teammates is essential! Often, it is easy for half the team to learn something and store it in the back of our minds. But we must remember to let the other half of the team know about it, too. I expected communication to be a lot easier when everyone was at the same location again, but the short time left until EXPE increased stress levels. Remembering to update every member of the team was difficult since half the team still had other classes and finals to prepare for at the same time. Overall, though, ME310 was a great experience—in addition to learning so much about satellites, heat pipes, and other technical analyses, I also gained understanding about teamwork, global communication, managing a budget, and so much more. Our final product was innovative and realistic, and I'm excited that our liaisons are planning to look into it more!

Xiao

Looking back, I see clearly how ME310 has redesigned my life. When I first heard about benchmarking from Larry in Fall Quarter, I didn't even know what it meant. I spoke out little about my ideas, shamed of how bad I was able to clearly express my thoughts. However, the SGMs, presentations and day-and-night teamwork have pushed me forward and opened my mind. I have learned, in addition, how to "design" through the journey, from defining the product to presenting the product. In this quarter, we haven't brought in any brand-new ideas and even compromised to some traditional designs. However, we have had to deal with a lot of details and constraints that were masked under a shiny concept design. I have also learned how to present a product and how important it is -- people would judge our product by attending the EXPE through a 15-min presentation, nodding at lifeless pieces of words and pictures, which alerted me that millions of products are also born through a similar way—its success or failure is decided by only 15 minutes. At last, I think what I have learned is not just some techniques to design, but also techniques to learn to design. And, communication is always the main source of inspirations.

Isaac

This project was a big challenge. We started with a blurry idea regarding satellites and spacecraft. Now we have developed a creative solution which may start innovation sparks in the manufacture process of the communication satellites in the near future. I have learned that, as designers, we do not need to be experts in every topic; instead, we just need to use the right design process and be aware of all of its phases' discoveries.

The ME310 design process and its tools are the tip of the "knowledge iceberg" I have got during this year. Below there are lots of experiences, as the challenge of sharing the responsibility of finishing a project with a team or to overcome the distance between the teammates, not just the physical distance between two countries but the distance between different professions.

Being part of this team reminds me of the power of collaboration. During the last weeks of the process, I experienced a family crisis which made it impossible for me to attend the last work sessions. My teammates supported me and were concerned about my situation. Now I express to them my appreciation and infinite thanks.

Rafael

The overall project was an amazing experience. Having a subject that I had never thought of or researched before was a really huge challenge and it was very difficult to approach as an industrial designer. The first part of the project was mostly slow, and I think none of us actually thought that we would come to a solution as complete as we did. The design process was truly interesting, and the way the project shifted from one idea to the other was what made the project interesting all the time.

The part that I regret the most was not being able to meet the liaisons until the end of the project, because I think that it would have given us a better idea of what the project's final goals were.

Another thing that I would have liked would have been to attend to the tour at Lockheed Martin's facilities since that would have given the whole team a different perspective and more idea of what the working conditions, spaces and flow were like.

In the end it was a really rewarding project, made me work really hard for a long period of time on a single subject, which I had never done before, and the last weeks made me work on a lot of graphics in a short amount of time.

Meeting so many different people from different countries also made this experience very unique, and I hope I get to do something like this in the near future.

Claudio

The spring quarter was pretty amazing, designing the prototypes and building them was a fascinating process. Before we got to Stanford, we had already been in a hurry, ending the prototype we build in Mexico and planning everything; we almost didn't finish. When we arrived, as the days went by, the pressure began to grow and although we had much to do, the plans were released one by one until the end. I can't still believe we could finish everything we had planned. I think that the most difficult part was to explain our design in a very simple way, so that everybody understood them in the presentation. I regret not having personally met our liaisons till the end of the process. I think that it also would have been much better if all the teammates had had the opportunity to see the Lockheed Martin facilities and understand the problem through their own eyes. These last two weeks have been amazing and I loved working with and getting to know so many people from other countries with such different languages and ideas. My goal for the future is to keep on working, finding design opportunities and designing new things with multidisciplinary groups.

Luis

At the end of all this process, I have realized that I learned more than I thought. I have learned many things related to Engineering and satellites but also many things about other topics, like the teamwork. This final quarter was very complicated because we had to work very hard, but at the same time this last quarter was very exciting because I had the opportunity to meet new people and live new experiences.

I am very proud of our final prototypes because all the members of the team made his/her best effort, and the prototypes show all the work that we did during the entire course, and during EXPE, the people said good things about our prototypes and about our work in general.

6.6 Review and Conclusion

6.6.1. Fall Quarter Review

The Fall Quarter features three parts: need-finding, benchmarking and a Critical Function Prototype. Team LM learned about satellite industry, clarified the goal of the project, specified preliminary requirements, and related unrelated ideas inspired from daily life. Through developing a user persona and visiting SSL, problem areas were revealed in satellite industry, including wiring, subsystem integration, heat management and the cost of testing and assembly. The benchmarking experiences of disassembling a computer and researching configure-to-order websites led the team to understanding the problems of customizability, heat management, space distribution, and user experience improvement. To solve these problems, Team LM came up with the CFP, which enabled easy access by rotating panels, modularity by adjustable panels, and simple wiring by central wiring, but also introduced problems such as stability and wiring difficulty.

On reflection of the progress in Fall Quarter, Team LM envisioned improving the work conditions of assembler and testing engineers by redesigning the satellite bus, which would be more accessible, easier wiring, and more modular, addressing more issues like heat management, fuel storage, and payload attachment. Ideas for simplifying wiring included:

1. Using wire harnesses as a structural component for satellite bus

The complicated wiring has been a constant issue for satellite assembly and testing. This idea points out that the wire harnesses have potential to become part of the support structure (or not necessarily supporting subsystems) built as part of the satellite bus.

2. Making a large breadboard as satellite bus

Breadboards are typically used for electric circuit conduction in experimental tests. What if electric connections were built inside the bus with multiple inputs and outputs for attachment of subsystems? This idea extends the prospect of using breadboards to the satellite field, promising potential applications.

6.6.2. Winter Quarter Review

In Winter Quarter, Team LM continued with a neat meeting schedule to update project researches within team members and with TTeam and liaisons. The Winter Quarter was a critical period during which the project orientation was clarified. Team LM learned about realistic conditions and restrictions of satellite industry, which led to a convergence of the design.

With the Dark Horse Prototype, Team LM validated the idea of integrating wires into satellite structure with a modular connection, but also found out the cons of this idea, which include difficult manufacturing, extra wire-weight, and lack of stiffness of long panels. To avoid these problems with the Funktional Prototype, Team LM designed an octagonal stackable satellite structure with foldable panels and a modular structure made of small standardized panels. The Mexico trip was a turning point for the design journey, during which Team LM decided to focus on designing the structure with a combination of modularity, which led to Functional Prototype. The Stanford Division made a 1/2 scaled bow-tie structure with proportional boxes attached to panels to show how the structure functioned. On the other hand, UNAM division designed an innovative hinge connection for honeycomb panels. By the end of Winter Quarter the main goal for Team LM had become clear: improve the bow-tie structure by improving it structurally and incorporating more modularity without lowering structure stiffness or involving additional issues of redesigning interacting systems. Meanwhile, Team LM also had to solve detailed problems for the structure, such as wiring design, heat pipes design, and boxes arrangement. CAD analysis should also be performed to verify the satellite structure designed.

6.6.3. Spring Quarter Review

The Functional System Prototype introduced a bow-tie satellite structure, named the Open Space structure, which became the first version of the final solution. In the Fall Quarter, for X is finished, Team LM designed wire bundle loops across the joint to enable folding/unfolding of the panels without impairing the wires. To improve the design, wire twisting instead of bending was introduced. Furthermore, wiring concept design was justified through calculation and prototyping. The idea to mount hinges on the strong back instead of the structure itself solved the problem of adding extra hinge weight to the whole structure. Research in heat pipe design led to a conventional while practical solution which is standard heat pipes connected with conductive interface at the joint. Fuel tank arrangement takes advantage of the design of core structure. The use of more realistic materials directed the team towards practical implementation considerations such as the use of cranes for lifting the large panels. In addition, boxes are arranged on four panels according to the wiring diagrams and heat dissipation of these boxes. The center of mass of the structure was also analyzed with all components mounted on the structure.

6.6.4. Conclusion

Team LM has arrived at a solid solution that demonstrates understanding of many aspects of satellite design and shows high potential for future development. To sum up, the design of Open Space addresses the problem of late box replacement by decreasing the required time from four months to just weeks, which will lead to a cost reduction of several million dollars. This dramatic improvement in efficiency is achieved by the folding panel design. The subsystem components are attached to the panels, which can be folded down. This feature allows access to satellite components with fewer necessary disconnections, and therefore fewer retests. The 5-foot wide panels are 35% narrower than current panels, allowing users to adopt more ergonomic positions during assembly and testing. Since the panels fold down, users will be able to sit and work on a horizontal surface instead of standing and working on a vertical plane. The panels can be folded down using ground support equipment that allows rotation without adding any launch weight. The structure is also composed of common panel shapes, which allow for easy manufacturing. The wires across the joint are in a loop configuration to decrease stresses. Boxes were placed according to heat output, and heat pipe solutions were also considered.

7. Resources

7.1 Bibliography

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[6] **Koelle, D.E.** Specific Transportation Costs to GEO--Past, Present and Future. Acta Astronautica. 2003, Vol. 53, 4-10, pp. 797-803.

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[12] **The Boeing Company.** Delta IV Payload Planner’s Guide. 1999.

[13] **Wikipedia.** (2009, Nov). Gas Spring. Retrieved Dec 8,2010 from http://en.wikipedia.org/wiki/Lockable_gas_spring

7.2 Interviews

- **Laura Bow,** Test Engineer from Boeing Company. October 30, 2010
- **Casey Thomas,** Test Engineer from Boeing Company. October 30, 2010
- **Ryan Salisbury,** Test Engineer from Boeing Company. October 30, 2010
- **Todd Lukkason,** Test Engineer from Boeing Company, October 30, 2010
- **Prof. Andrew Kalman**, professor in aeronautics. October 28, 2010

  aek@stanford.com I 415.336.4684
- **Rodrigo Alva Gallegos,** student involved in a CubeSat project. October 29, 2010

  roro_send@hotmail.com
- **Dr. José Alberto Ramírez,** researcher from CAT (Center for High Technology of UNAM), satellite expert., November 29, 2010
- **Dr. Carlos Romo Fuentes**, researcher from CAT (Center for High Technology of UNAM), satellite extpert. January 28, 2011

7.3 Visits

- **Loral Space Systems.** November 9, 2010.

  3825 Fabian Way

  Palo Alto, CA 94303

  650-852-4000
- **Aeromexico´s Maintenance Hangar.** February 18, 2011.

  Avenida Fuerza Aérea Mexicana 416

  Col. Federal

  México, D.F.
- **Lockheed Martin's Sunnyvale Facility.** February 22, 2011.

  1111 Lockheed Martin Way

  Sunnyvale, CA 94089
- **Lockheed Martin's Palo Alto Facility.** June 3, 2011.

  3251 Hanover St.

  Palo Alto, CA 94304

7.4 Vendors

- **IKEA**

  1700 E. Bayshore Rd.East
  Palo Alto, CA 94303
  650-323-4532

- **Home Depot**

  1781 E Bayshore Rd
  Palo Alto, CA 94303
  (650) 462-6800

  JameCo Electronics

  1355 Shoreway Road
  Belmont, CA 94002
  (800) 831-4242

- **Fry's Electronics**

  340 Portage Ave
  Palo Alto, CA
  (650) 496-6000

- **Tap Plastics Inc**

  312 Castro Street
  Mountain View, CA 94041-1206
  (650) 962-8430

- **Steren Electrónica**

  Av. Revolucion 1639
  Col. San Angel
  México, D.F.

- **Plastimundo**

  Av. Division del Norte 2951
  Col. El Rosedal
  Mexico, D.F.

- **La Paloma**

  Av. Revolucion 461
  Col. San Pedro de los Pinos
  México, D.F.

8. Appendix

8.1 Box Sizes, Masses, and Power Dissipations

Code	System Title	Operational Phase			Qnt.	Dimensions		
		Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)		Length(in)	Width (in)	Height(in)
Bus Components								
BB1	Bus Box 1	1.92	1.1	1.2	2	4.70	3.58	2.10
BB2	Bus Box 2	4.35	7.6	7.6	1	157.00	126.00	149.00
BB3	Bus Box 3	9.14	11.0	15.0	4	14.46	14.46	6.30
BB4	Bus Box 4	7.48	31.0	31.0	1	9.65	7.20	5.92
BB5	Bus Box 5	769.27	-	126.0	1	85.54	21.44	11.90
BB6	Bus Box 6	67.49	102.1	475.0	1	33.60	19.71	8.82
BB7	Bus Box 7	15.62	0.6	2.4	1	10.84	5.27	7.18
BB8	Bus Box 8	7.12	1.0	1.0	2	6.63	6.63	16.38
BB9	Bus Box 9	2.92	-	12.0	2	13.71	8.73	4.91
BB10	Bus Box 10	2.54	12.0	15.0	2	11.24	3.89	8.00
BB11.1	Bus Box 11.1	7.60	7.3	10.0	1	10.48	8.30	9.28
BB11.2	Bus Box 11.2	7.06	5.3	10.0	1	10.48	8.30	9.28
BB12.1	Bus Box 12.1	7.89	6.7	10.0	1	10.48	8.30	9.28
BB12.2	Bus Box 12.2	7.90	7.1	10.0	1	10.48	8.30	9.28
BB12.3	Bus Box 12.3	7.19	6.0	10.0	1	10.48	8.30	9.28
BB13	Bus Box 13	4.25	11.0	15.0	1	8.99	5.85	11.79
BB14	Bus Box 14	1.91	10.1	20.0	2	6.30	5.35	2.80
BB15	Bus Box 15	1.35	14.8	15.0	4	9.02	2.13	6.87
BB16	Bus Box 16	1.30	12.0	10.0	4	6.19	5.10	2.80
BB17	Bus Box 17	2.84	-	-	2	10.53	7.14	4.40
H	Harness	-	-	50.0	2	-	-	-

		Operational Phase				Dimensions		
Code	System Title	Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)	Qnt.	Length(in)	Width (in)	Height(in)
Communications Components								
CB1	Comm Box 1	0.05	-	-	5	1.85	1.61	1.57
CB2.1	Comm Box 2.1	0.30	-	-	1	7.94	2.31	1.77
CB2.2	Comm Box 2.2	0.20	-	-	2	5.62	2.31	1.97
CB2.3	Comm Box 2.3	0.20	-	-	2	5.64	2.31	1.97
CB3	Comm Box 3	0.67	23.0	-	4	6.73	4.72	2.24
CB4	Comm Box 4	0.86	6.4	-	2	4.57	3.35	1.91
CB5	Comm Box 5	0.38	1.6	-	1	4.57	3.35	1.91
CB6.1	Comm Box 6.1	0.56	22.5	-	5	6.34	4.72	2.01
CB6.2	Comm Box 6.2	0.56	15.0	-	3	6.34	4.72	2.01
CB6.3	Comm Box 6.3	0.56	15.0	-	3	6.34	4.72	2.01
CB7.1	Comm Box 7.1	2.10	-	-	1	11.06	4.25	7.17
CB7.2	Comm Box 7.2	2.70	-	-	1	15.07	4.25	7.17
CB7.3	Comm Box 7.3	0.80	-	-	2	5.79	4.25	7.16
CB7.4	Comm Box 7.4	1.20	-	-	2	7.11	4.25	7.17
CB8.1	Comm Box 8.1	0.60	-	-	1	4.49	4.25	5.51
CB8.2	Comm Box 8.2	0.90	-	-	1	6.10	4.25	5.51
CB8.3	Comm Box 8.3	0.60	-	-	1	4.49	4.25	5.51
CB9.1	Comm Box 9.1	0.23	232.1	72.5	10	14.57	4.92	5.51
CB9.2	Comm Box 9.2	0.23	353.5	110.4	10	14.57	4.92	5.51
CB9.3	Comm Box 9.3	0.14	232.1	72.5	9	14.57	4.92	5.51
CB9.4	Comm Box 9.4	0.19	353.5	110.4	10	14.57	4.92	5.51
CB9.5	Comm Box 9.5	0.11	353.5	110.4	13	14.57	4.92	5.51
CB9.6	Comm Box 9.6	0.20	152.8	47.7	2	14.09	2.89	2.53
CB10	Comm Box 10	0.52	-	-	54	6.69	4.94	1.64
CB11.1	Comm Box 11.1	3.57	0.0	489.0	1	26.05	10.31	3.15
CB11.2	Comm Box 11.2	3.93	0.0	216.0	1	14.86	9.99	3.15
CB11.3	Comm Box 11.3	6.68	0.0	339.0	1	17.88	9.93	3.15
CB11.4	Comm Box 11.4	5.10	0.0	224.0	1	14.05	9.93	3.15
CB11.5	Comm Box 11.5	4.83	0.0	377.0	1	19.07	10.32	3.15
CB12	Comm Box 12	0.24	-	-	5	7.81	2.44	1.61

		Operational Phase				Dimensions		
Code	System Title	Mass (kg)	Power Consumption (W)	Thermal Dissipation (W)	Qnt.	Length(in)	Width (in)	Height(in)
Switches								
SPT	Splitter	0.06	-	-	5	1.00	1.00	0.44
SW1	Switch 1	0.61	-	-	5	2.08	2.08	2.22
SW2	Switch 2	0.02	-	-	19	1.81	1.81	3.43
SW3	Switch 3	0.18	-	-	2	1.81	1.81	3.62
SWA1	Switch Assy 1	2.35	-	-	1	8.60	7.70	5.80
SWA2	Switch Assy 2	1.88	-	-	1	7.98	6.80	5.55
SWA3	Switch Assy 3	2.96	-	-	1	15.03	7.20	4.27
SWA4	Switch Assy 4	1.05	-	-	1	7.21	5.95	3.64
SWA5.1	Switch Assy 5.1	0.87	-	-	2	9.28	3.60	3.59
SWA5.2	Switch Assy 5.2	0.68	-	-	3	7.68	3.60	3.59
SWA5.3	Switch Assy 5.3	0.58	-	-	3	6.10	3.60	3.59
SWA6	Switch Assy 6	1.60	-	-	1	16.65	6.15	3.82
SWM1.1	Switch Matrix 1.1	12.62	-	-	1	32.22	17.04	4.80
SWM1.2	Switch Matrix 1.2	3.74	-	-	1	19.53	8.25	4.69
SWM1.3	Switch Matrix 1.3	4.90	-	-	1	24.39	7.26	4.69
SWM1.4	Switch Matrix 1.4	3.70	-	-	1	17.13	7.26	4.69
SWM1.5	Switch Matrix 1.5	9.58	-	-	1	23.12	14.97	4.80
SWM1.6	Switch Matrix 1.6	3.25	-	-	1	16.48	7.62	4.69
SWM1.7	Switch Matrix 1.7	2.16	-	-	1	10.75	7.62	4.69

8.2 Selected Pages from Delta IV Payload Planner's Guide

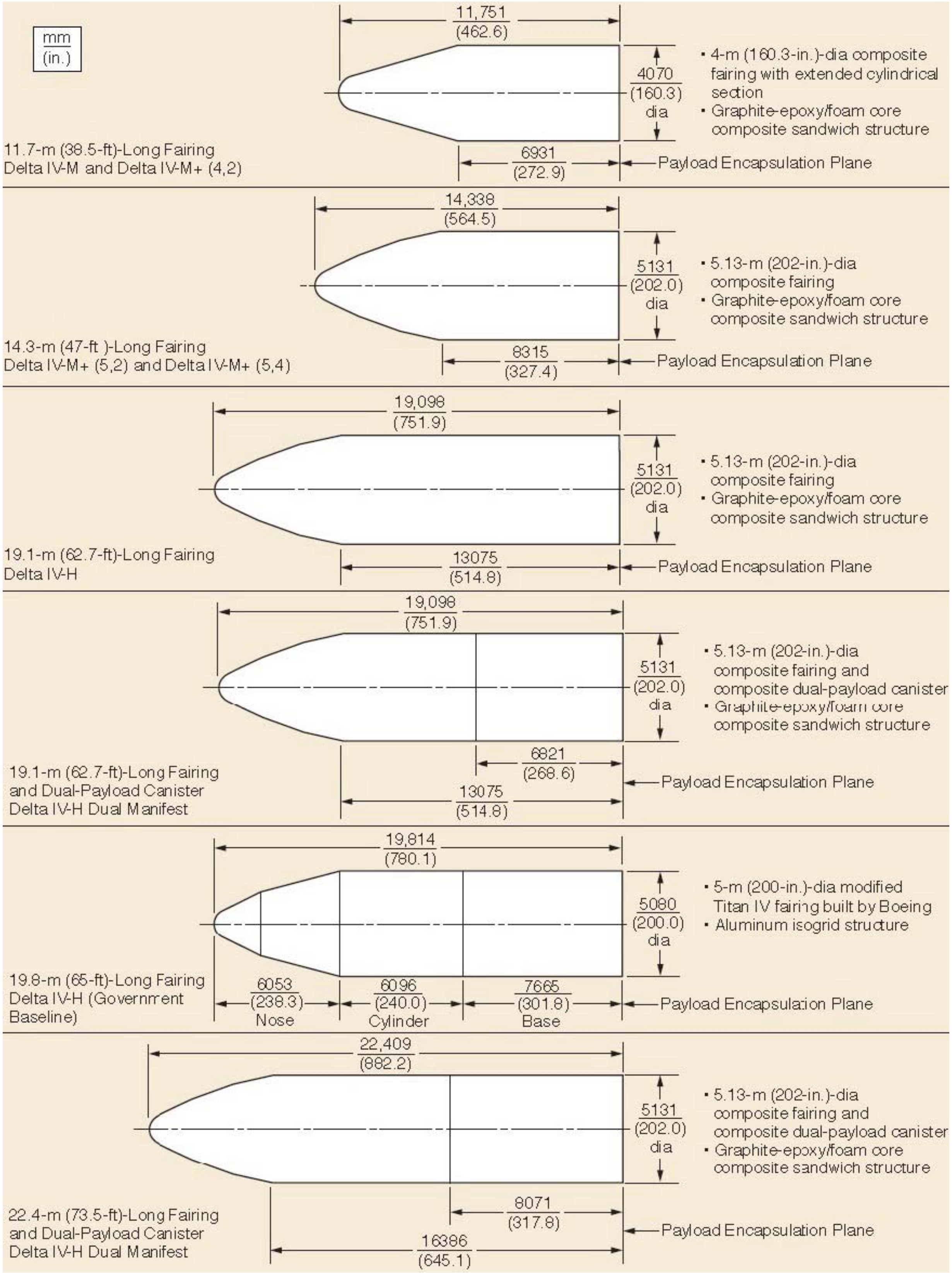
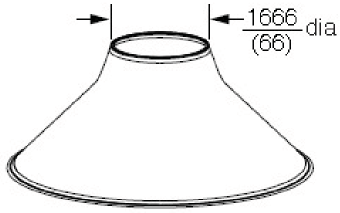
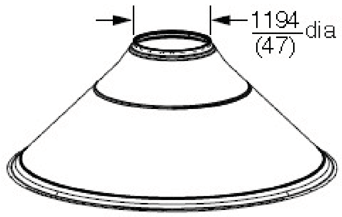
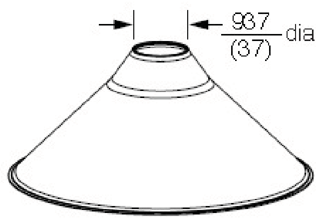
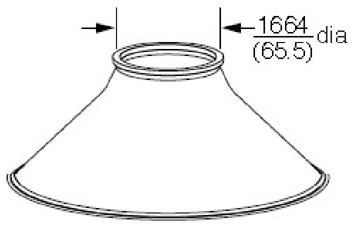
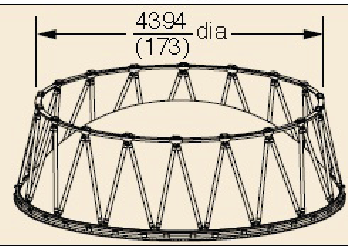


Figure 89 *Static fairing size envelopes from Delta IV Payload Planner's Guide*

Delta IV 1666-5 PAF		1666 dia (66) clampband	Two calibrated spacers to verify clampband preload. Four matched spring or differential spring actuators to provide different tip-off rate. Retention system prevents clampband recontact
Delta IV 1194-5 PAF		1194 dia (47) clampband	Two calibrated spacers to verify clampband preload. Four matched spring or differential spring actuators to provide different tip-off rate. Retention system prevents clampband recontact
Delta IV 937-5 PAF		937 dia (37) clampband	Two calibrated spacers to verify clampband preload. Four matched spring or differential spring actuators to provide different tip-off rate. Retention system prevents clampband recontact
Delta IV 1664-5 PAF		Four separation bolts 1664 dia (65.5) bolt circle	Four hard-point attachments, released by four redundantly initiated explosive nuts. Four differential springs to provide a tip-off rate
Delta IV 4394-5 PAF		72 bolts in a 4394 dia (173) bolt circle	4394 (173-in.) bolted interface. Standard only for 5-m metallic fairing

mm (in.)

EELV Standard Interface

Figure 90 *Standard Attach Fittings for 5m Diameter Fairing from Delta IV Payload Planner's Guide*

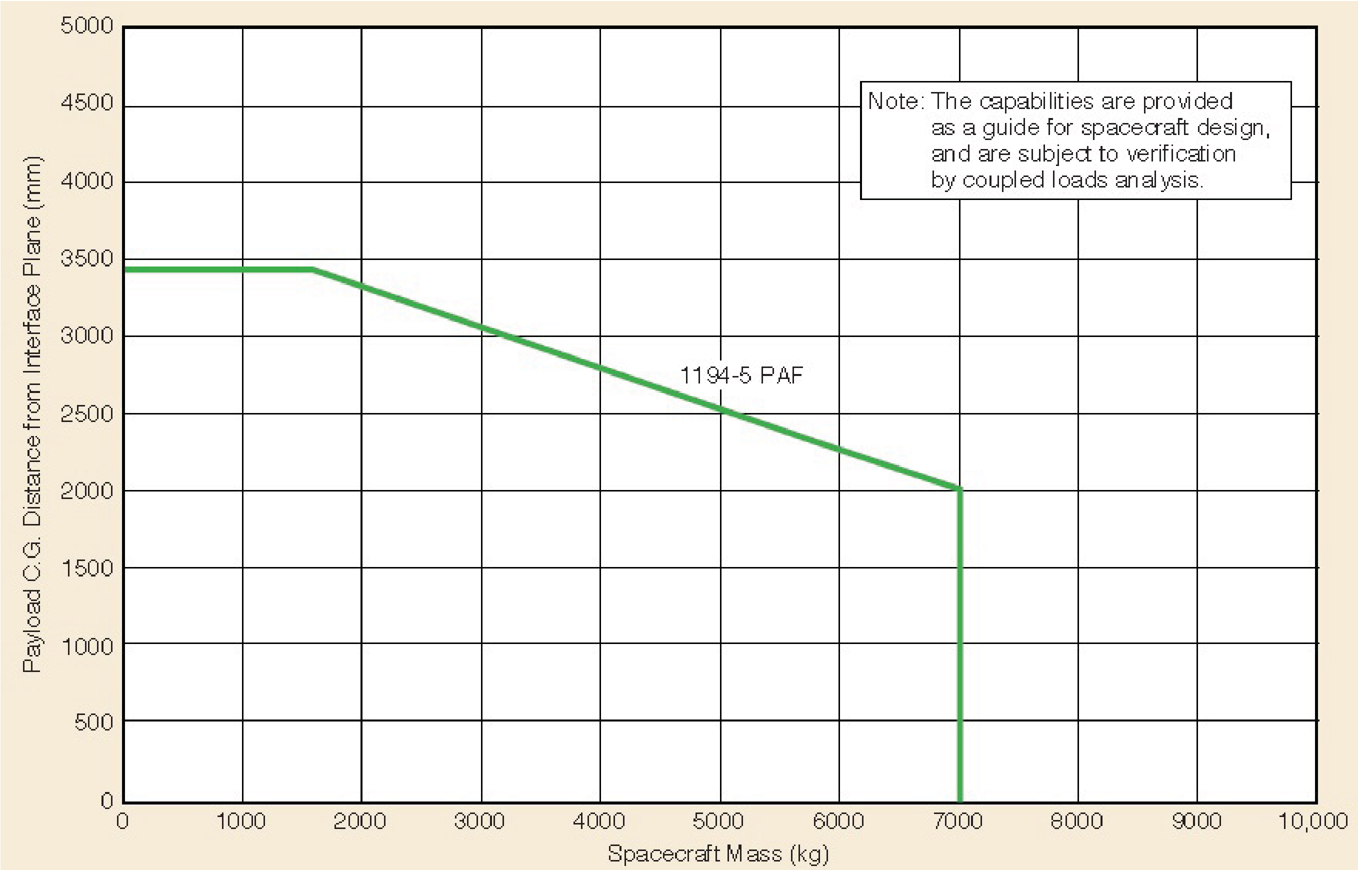


Figure 91 *Center of gravity maximum distance from interface as a function of satellite mass*

Table 4-5. Static Envelope Requirements

Static envelope requirements					Maximum lateral		Maximum axial	
LV type	Overall payload fairing length (m/ft)	Minimum axial frequency (Hz)	Minimum lateral frequency (Hz)	Static diameter (barrel section) (m/in.)	Maximum axial (g)	Maximum lateral (g)	Maximum axial (g)	Maximum lateral (g)
Delta IV Medium	11.7/38.5	27	10	3.75/147.6	+2.4/-0.2	±2.0	6.5*	±0.5
Delta IV Medium-Plus (4,2)	11.7/38.5	27	10	3.75/147.6	+2.5/-0.2	±2.0	6.5*	±0.5
Delta IV Medium-Plus (5,2)	14.3/47	27	10	4.57/180.0	+2.4/-0.2	±2.0	6.5*	±0.5
Delta IV Medium-Plus (5,4)	14.3/47	27	10	4.57/180.0	+2.5/-0.2	±2.0	6.5*	±0.5
Delta IV Heavy**	19.8/62.7	30	8	4.57/180.0	+2.3/-0.2	±2.5	6.0	±0.5
Delta IV Heavy Dual-Manifest	22.4/73.5	30	8	4.57/180.0	+2.3/-0.2	±2.5‡	6.0	±0.5

*Current projection; lower customer axial requirements may be accommodated through coordination with Delta Launch Services.
**Payloads greater than 12,250-kg (27,000 lb).
‡Current analysis indicates lateral acceleration levels approaching dedicated launch vehicle levels (2 g).

0000708.3

Figure 92 *Static envelope resonant frequency requirements from Delta IV Payload Planner's Guide*

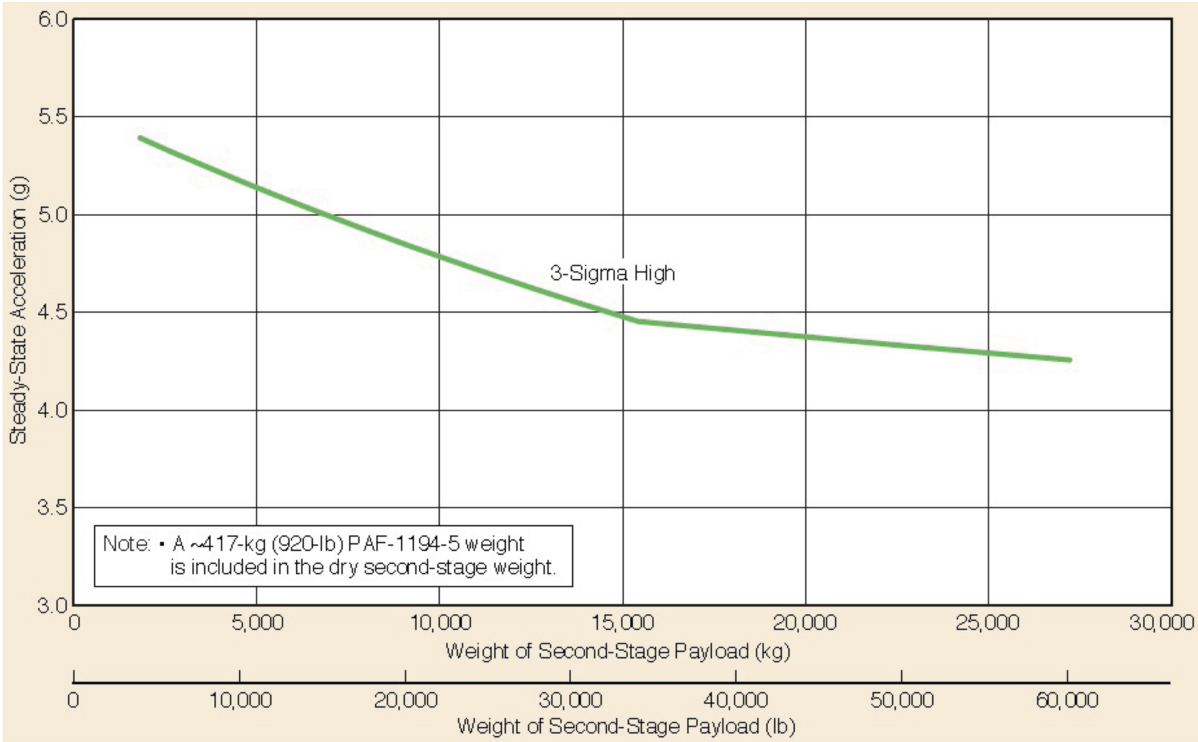


Figure 4-17. Delta IV Heavy Maximum Axial Steady-State Acceleration During First-Stage Burn vs Second-Stage Payload Weight

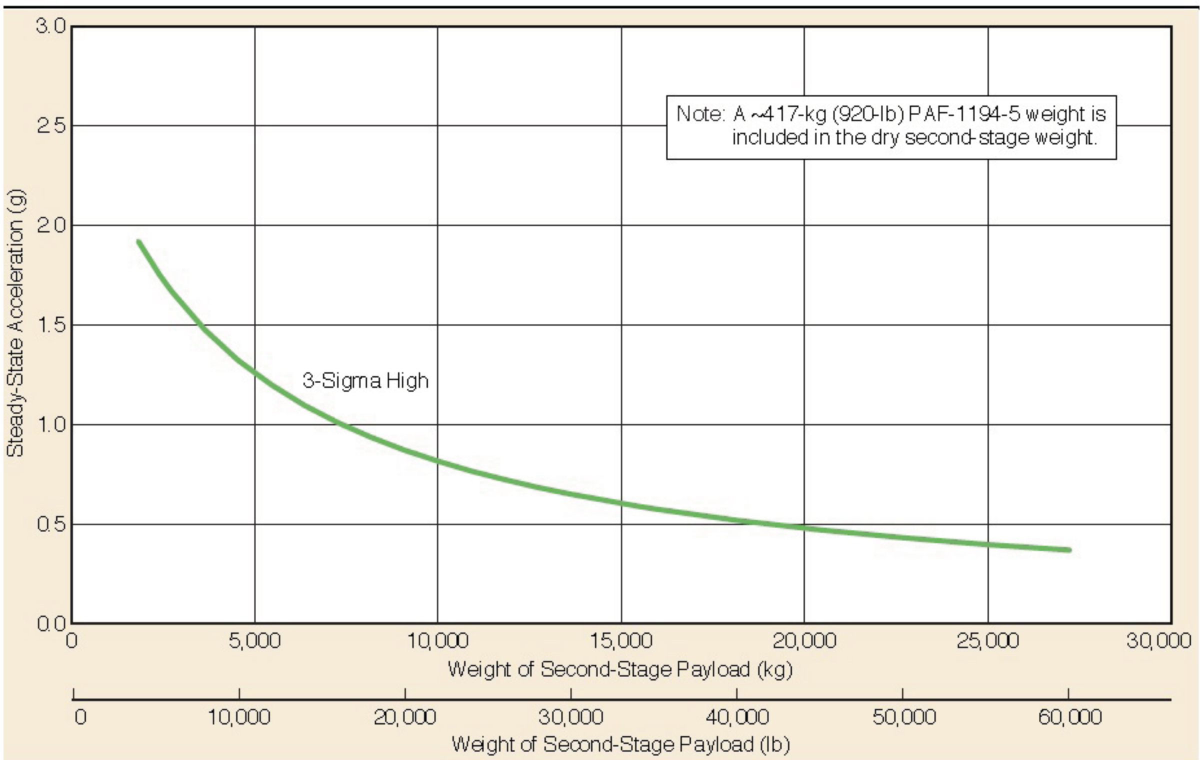


Figure 4-22. Delta IV Heavy Axial Steady-Stage Acceleration at Second-Stage Cutoff

Figure 93 *Launch loads as a function of payload mass for Delta IV H from Delta IV Payload Planner's Guide*

8.3 Notes from tour of Lockheed Martin's Sunnyvale Facility (2/22/11)

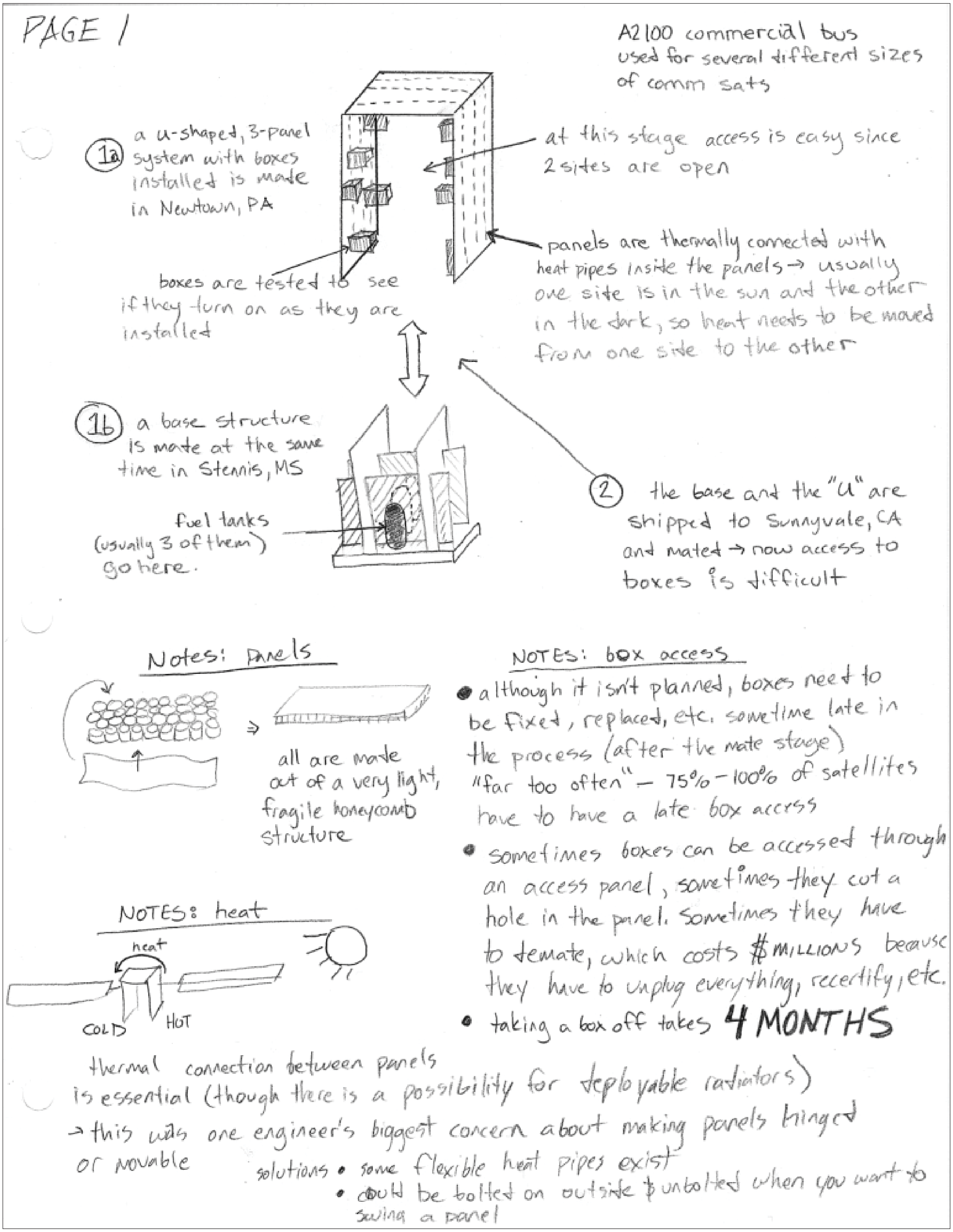
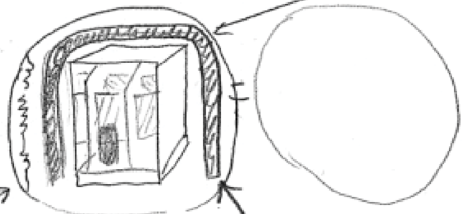


Figure 94 *Notes on general A2100 construction, late box removal, and heat management*

PAGE 2

(3) Thermal Vacuum test

→ under vacuum, cycles of heat & cold (like the sun)



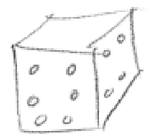
vacuum chamber

→ solar panels + payloads are not attached at this point

heater system

pipes filled with coolant

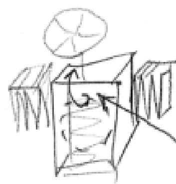
(4) ALignment



precise location of several marker dots is recorded

(5) solar panel attachment

solar panels and other payloads are attached.

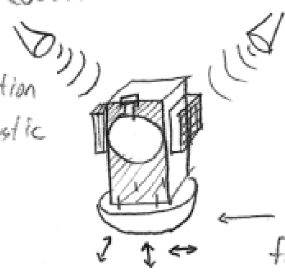


solar panels are attached to the sides of the "U"

payloads are generally attached to fold down into the open sides of the "U"

(6) VIBRATION AND ACOUSTIC

modes are checked with mechanical connection (vibrator) and with acoustic excitation (horns)

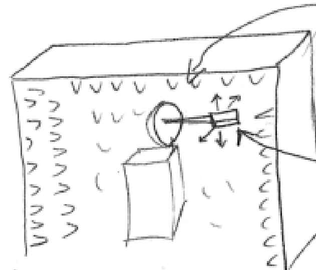


horns with sound > several hundred dB (rifle shot is 140 dB)

stand shakes in x, y, z directions anywhere from 1/4 Hz to inaudible frequencies

(7) RANGE

→ a scanner bounces RF signals off of the reflectors (antennas) to make sure their alignment and broadcast pattern for their intented target is correct.



foam cones dampen echoes in the room

scanner

• example

satellite broadcasting to Alaska had to be very careful not to hit Russia - Russia threatened to jam the signal otherwise

(8) Alignment → after all tests, dot locations are checked again to see if anything had shifted.

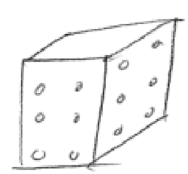
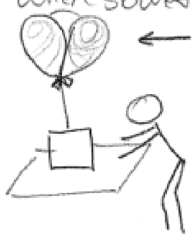


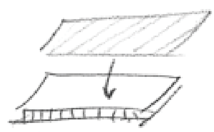
Figure 95 *Notes on full system tests performed on A2100*

PAGE 3 General notes

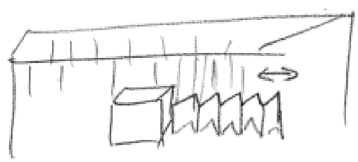
- glue (epoxy, HASMAT) is a major method of fastening, especially for composites. Even for bolted connections glue is often used to get a good thermal bond.
- special care has to be taken assembling in gravity since structures are not designed to deal with the force of gravity (except when stowed for launch)



← helium balloons are used to counteract gravity



metal sheeting supports honeycomb panels during installation



support structure is used for deploying solar panels partially

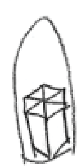
- LOCKHEED in general
  - → more willing to customize their satellite for customers than Boeing or SS/L
  - → A2100 bus doesn't change much for commercial satellites
    - → slots for different electronic cards
- iridium satellites

triangular small

100 were built

(best example of assembly-line type manufacture)

6 at a time were launched



- parts are usually kitted for assembly
- putting all boxes on the outside of the structure for better access has been tried → too much exposure in space, box specs have to be changed

Figure 96 *Other various notes*

8.4 Communication Block Diagrams Supplied by Liaisons

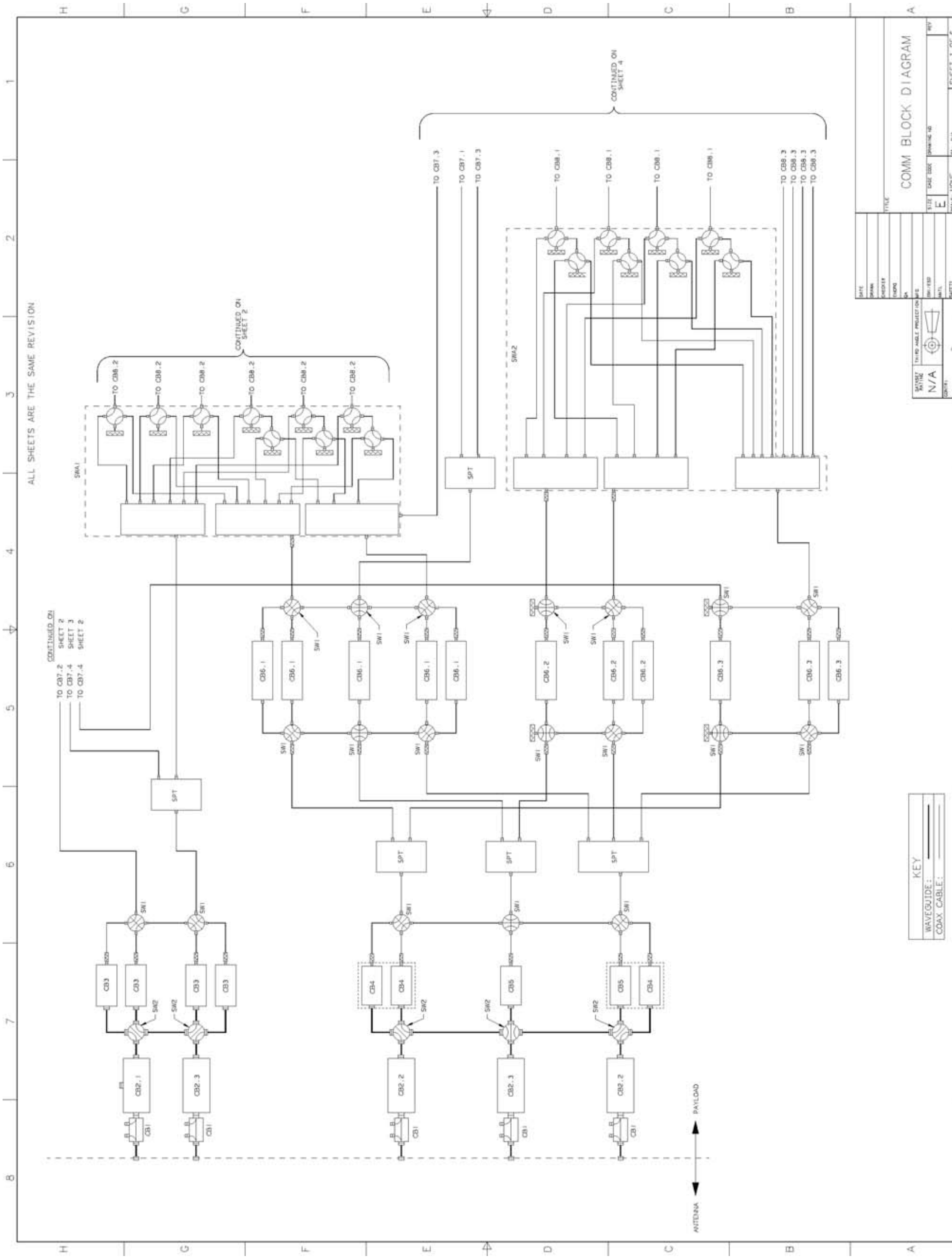


Figure 97 *Communication Block Diagram-Sheet 1*

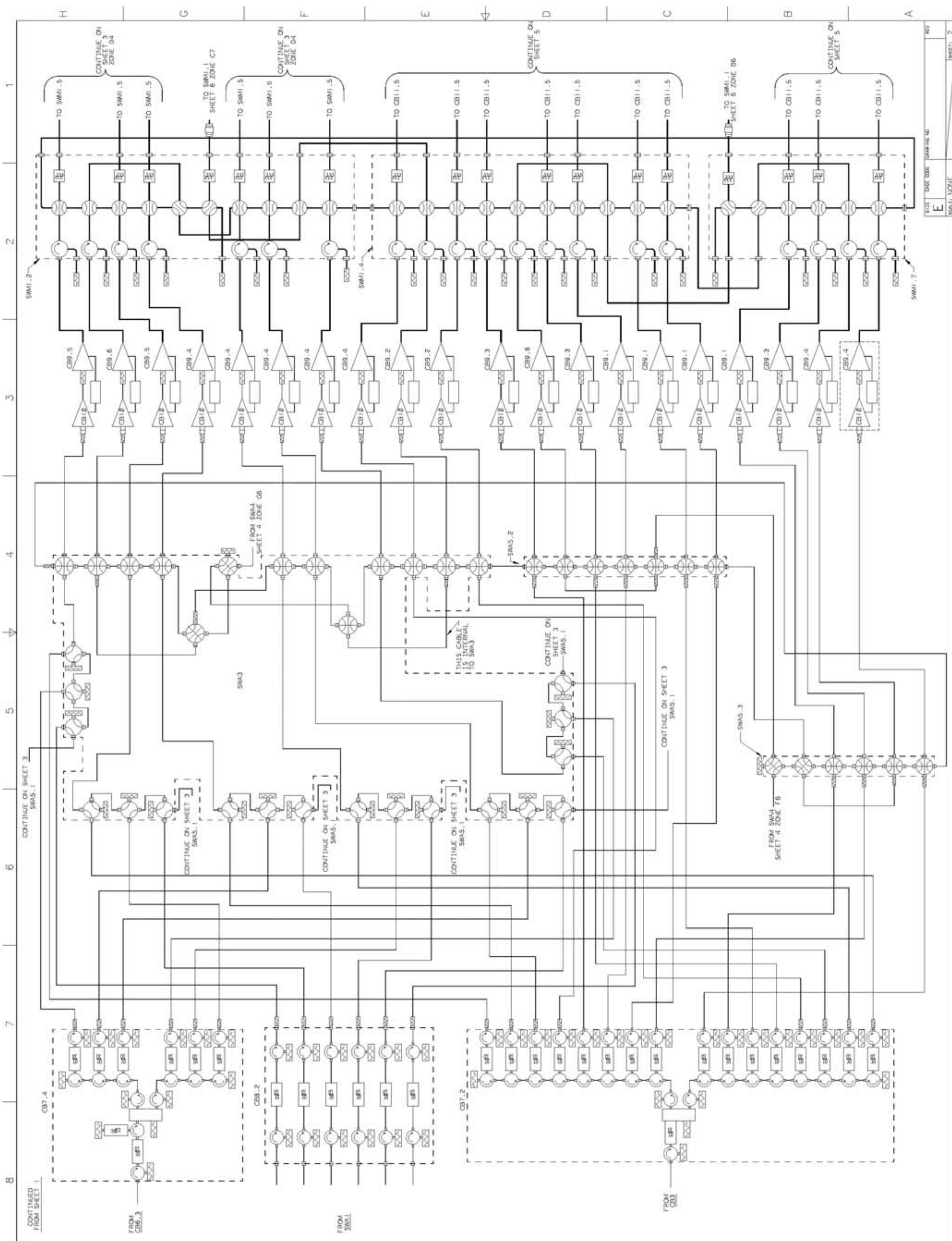


Figure 98 *Communication Block Diagram-Sheet 2*

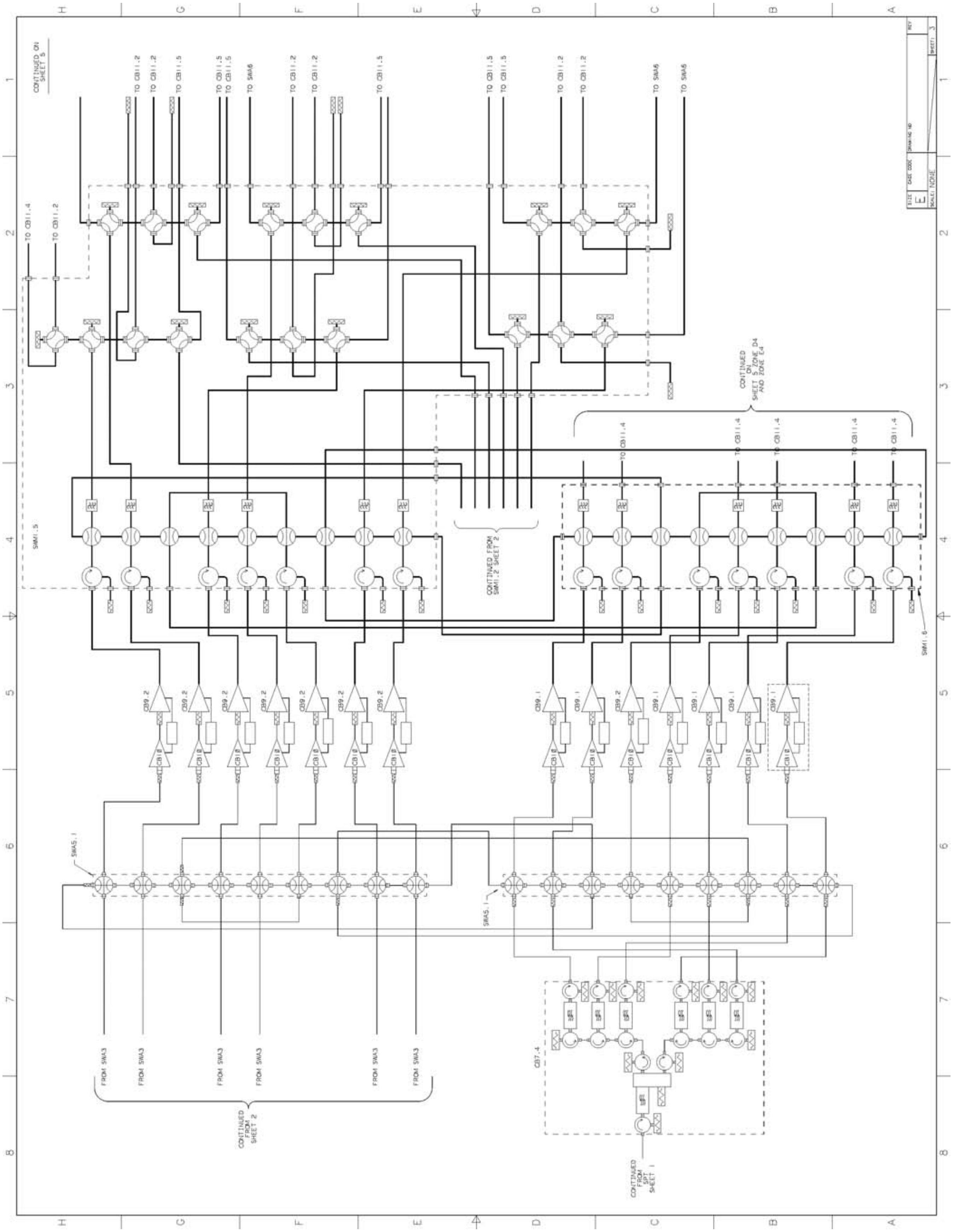


Figure 99 *Communication Block Diagram-Sheet 3*

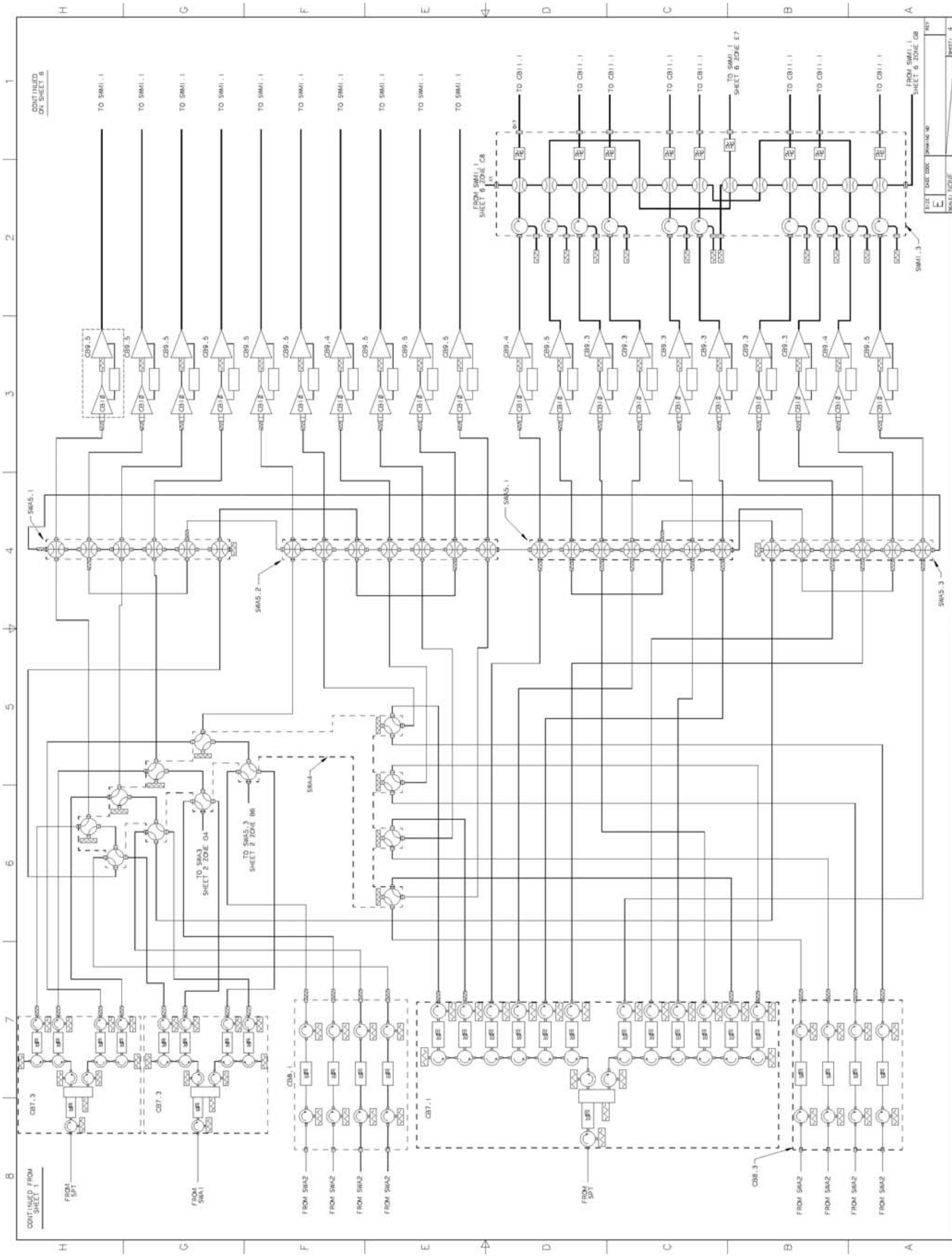


Figure 100 *Communication Block Diagram-Sheet 4*

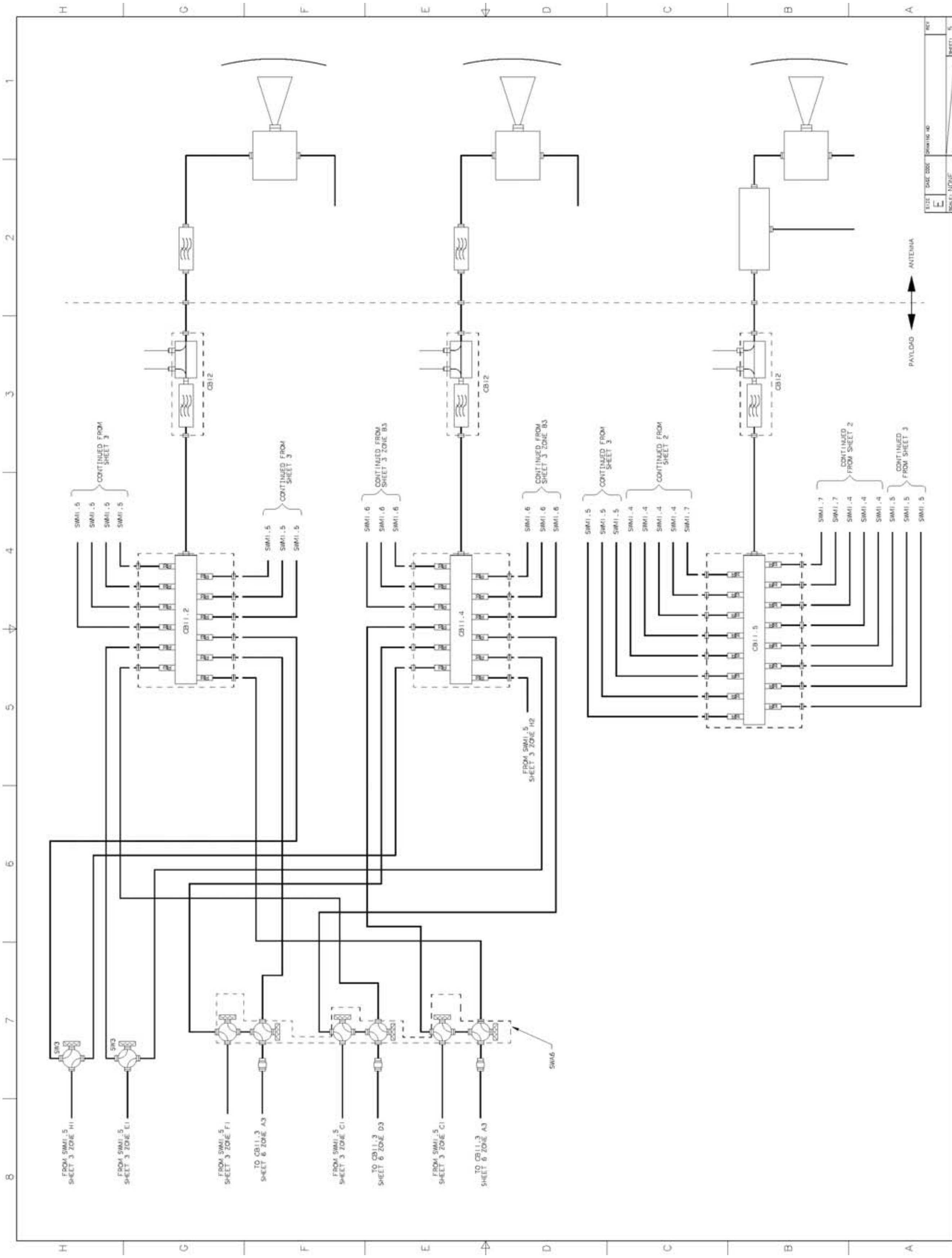


Figure 101 *Communication Block Diagram-Sheet 5*

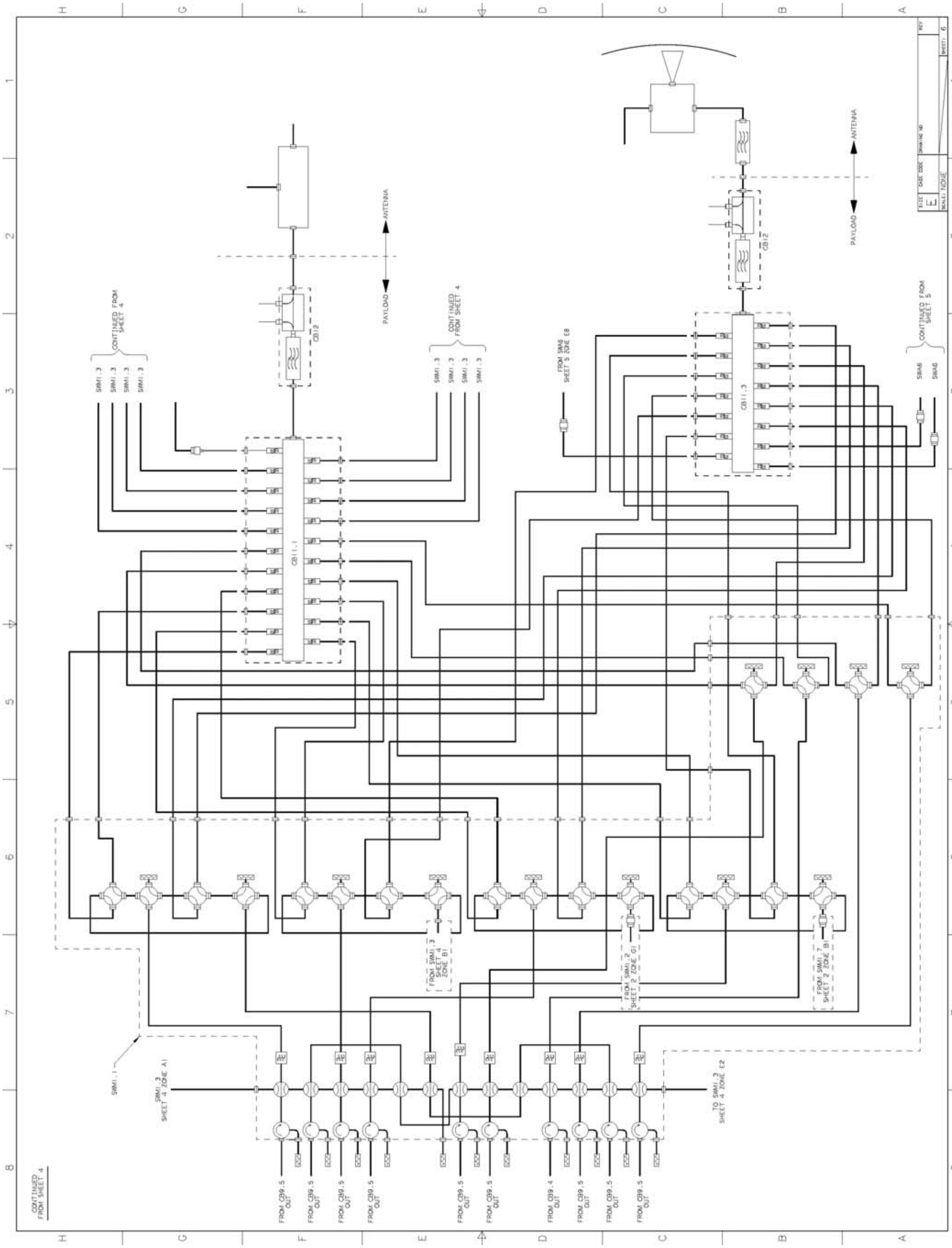


Figure 102 Communication Block Diagram-Sheet 6

8.5 Lockheed Martin´s original project proposal

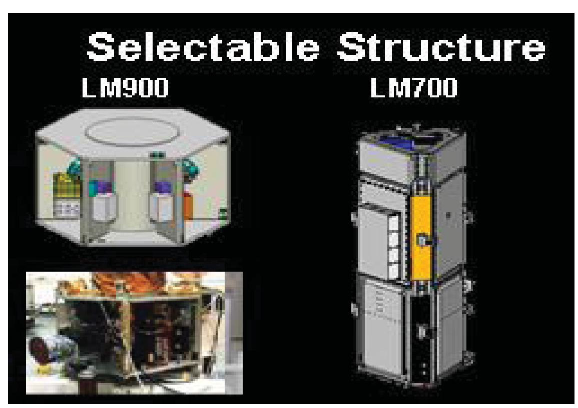
Configure-to-Order (CTO) Spacecraft

Currently, spacecraft are built as unique, custom platforms for each individual customer and even for follow-on missions. Amortization of extremely high launch costs drive hyper-optimization of spacecraft design to produce the highest value possible. Each unique design is driven by mass, volume, and power consumption, to the exclusion of design cost, operations cost, and total life-cycle system cost.

Modern sensing, processing, and power electronics, with mass and power consumption reduced by 99%, have changed the parametric cost relations. Advanced payloads can be assembled that fulfill the mission requirements, but that do not push mass and volume limits. It is now cost effective to avoid new design and qualification costs at the sacrifice of some small amount of excess weight or un-utilized volume. This opens up the possibility of having basic spacecraft platforms (buses) that are configurable to the particular mission at hand. In addition to lower design cost, the shorter time to produce and place the asset on orbit improves the capital cost.

The goal of this project is to define a configurable spacecraft platform architecture, especially the core structure. CTO Spacecraft would be assembled from a predefined set of subsystem components. The modularity could be maintained variously with a simple connector and bolt pattern, or within an encompassing box or tank. The structure would support attachment, cabling, launch loads, and thermal control, and must provide simple assembly, integration, and test (AI&T).

Issues to be defined include whether a single platform architecture can encompass the entire range of missions; whether electrical cabling and fluid interfaces should be integral with the structure; how to define the payload/bus interface; and especially the parametric range of cost and performance limits.



8.6 Open Space Brochure

open space

Satellite Manufacturing Inside Out

RIGHT NOW, making a satellite is an expensive, drawn-out process that can take years and hundreds of millions of dollars. A common production delay is LATE BOX REPLACEMENT, which occurs at least once on 75% of satellites. A single box replacement costs up to FOUR MONTHS and MILLIONS OF DOLLARS due to the extensive re-testing that becomes necessary when everything is disconnected. A DRASTIC REDESIGN IS NEEDED to improve the satellite production process.

The “OPEN SPACE” SATELLITE SOLUTION, as a concept, is simple: allow the satellite to fold open for easier access during manufacturing. This feature is expected to RADICALLY IMPROVE the process by allowing the wires to REMAIN CONNECTED. Furthermore, the hexagonal structure has narrower panels to allow EASIER REACH of internal components, and the horizontal surface provides a more ERGONOMIC work environment.

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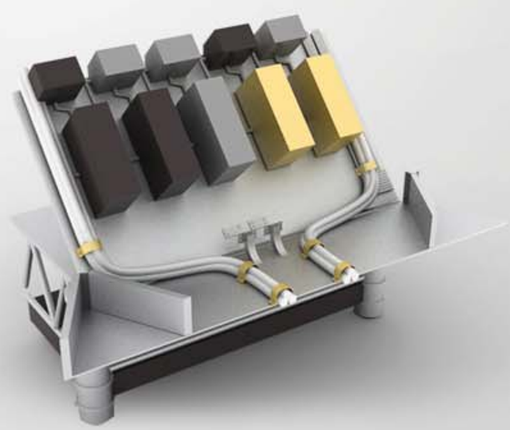
Claudio Hansberg
Luis Vazquez

LOCKHEED MARTIN

A HINGE MECHANISM
is part of the ground support and allows the panel to open during manufacturing, with the help of a crane.

THE PAYLOAD
of the satellite includes hundreds of electrical components. These “boxes” are arranged on the four panels of the OPEN SPACE satellite according to wiring, heat, and mass.

WIRE BUNDLES
are large, and two 1.5”-diameter bundles must cross the folding joint on each panel. Although bending the bundle can cause fatigue, the wires can be twisted to allow panel folding.



THE CORE STRUCTURE
can handle launch loads and vibration while holding over a thousand pounds of fuel. The central cylinder of the OPEN SPACE satellite provides structural support while the six panels increase the structural stiffness.

HEAT PIPES
are sealed tubes that carry heat from one side of the satellite to the other—an integral function to prevent boxes from overheating in space. These must also cross the foldable joint, so a conductive thermal interface is used.