CASTOR

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EXECUTIVE SUMMARY

The purpose of CASTOR (Cathode/Anode Satellite Thruster for Orbital Repositioning) satellite is to demonstrate in Low Earth Orbit (LEO) a nanosatellite that uses a Divergent Cusped Field Thruster (DCFT) to perform orbital maneuvers representative of an orbital transfer vehicle. Powered by semi-deployable solar arrays generating 165W of power, CASTOR will achieve nearly 1 km/s of velocity increment over one year. As a technology demonstration mission, success of CASTOR in LEO will pave the way for a low cost, high delta-V orbital transfer capability for small military and civilian payloads in support of Air Force and NASA missions. The educational objective is to engage graduate and undergraduate students in critical roles in the design, development, test, carrier integration and on-orbit operations of CASTOR as a supplement to their curricular activities. This program is laying the foundation for a long-term satellite construction program at MIT. The satellite is being designed as a part of AFRL's University Nanosatellite Program, which provides the funding and a framework in which student satellite teams compete for a launch to orbit. To this end, the satellite must fit within an envelope of 50cmx50cmx60cm, have a mass of less than 50kg, and meet stringent structural and other requirements. In this framework, the CASTOR team successfully completed PDR in August 2009 and CDR in April 2010 and will compete at FCR (Flight Competition Review) in January 2011. The complexity of the project requires implementation of many systems engineering techniques which allow for development of CASTOR from conception through FCR and encompass the full design, fabrication, and testing process.

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1 INTRODUCTION

MIT's Cathode/Anode Satellite Thruster for Orbital Repositioning (CASTOR) is an orbital maneuver and transfer bus with the technical objective of achieving one kilometer per second of delta-V over a one year mission in Low Earth Orbit (LEO). This is accomplished using a novel electric propulsion system described below. As a technology demonstration mission, the success of CASTOR in LEO will pave the way for a modular bus design, which would provide small payloads with a low cost, high delta-V orbital transfer capability in support of the NASA ESMD exploration and technology development missions. CASTOR will serve as a technology demonstration of this concept and of the DCFT (Diverging Cusped-Field Thruster) under AFRL's University Nanosatellite Program.

1.1 UNP/CAPSTONE CLASS

The UNP is a program jointly sponsored by the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/RV), the Air Force Office of Scientific Research (AFOSR), and the American Institute of Aeronautics and Astronautics (AIAA) to educate and train the future workforce through a national student satellite design and fabrication competition. This program is held biannually, currently undergoing its sixth iteration. A major focus area of UNP is developing student's communication abilities of technical topics. Each student's communications abilities are challenged before beginning the program, as entry into this program requires a detailed proposal about the student's design, motivation, and reason for participation which follows the UNP guidelines. MIT undergraduate capstone students, under the guidance of Space Systems Laboratory (SSL) faculty and graduate students, successfully gained its first entry into this program in the winter of 2009.

After being accepted, the team must begin iterating through design ideas. It is critical that the design and rational behind it are thoroughly documented as members are in flux and one cannot guarantee that the entire team will be able to remain with the design from conception to final product delivery (a 2 year period). Furthermore, this documentation is used on future satellite designs to ensure that mistakes are not repeated, granting the MIT Satellite Team continuity. Good documentation of the design goes beyond aiding the team, and is used as one of the primary methods of comparing competing university's designs and ensuring that predefined limitations are taken into consideration. Thus UNP ensures that students are not simply good at communicating ideas to others but also at processing others communications to them.

UNP grants students the opportunity to refine their communication abilities during a series of documentation submittals and design presentations. Each university undergoes five major design reviews: system concept review, preliminary design review, critical design review, proto-qualification review, and flight competition review. During these reviews, the team's documentation of the design (including design documentation, risk matrix, safety procedures, and requests for waivers), presentation about the design, and actual design itself are the primary aspects used to differentiate competing universities. Both the documentation and presentations are judged by a panel of experts. These experts provide feedback on the documentation and presentation to ensure that students develop their communications abilities. Thus the best design is not the guaranteed winner; the team that best communicates having a good design will win.

1.2 MISSION OBJECTIVE

The mission of CASTOR is to validate the performance and application of Diverging Cusped Field Thruster (DCFT) technology. This will be achieved by taking on-orbit state data to compare the degradation experienced by the DCFT to that of similar technologies. Mission objectives are:

- Minimum Success: Demonstrate that the DCFT will operate on-orbit
    - Objective: Operate the DCFT on orbit for 1500 hours, which is comparable to similar technologies
- Minimum Success: Use the DCFT to provide a measurable change in velocity
    - Objective: Measure the on-orbit performance, efficiency, and degradation of the DCFT during orbital maneuvers

The success criteria of these mission objectives are:

- DCFT Operation
    - Capture images of the DCFT as it thrusts. If the images show the plume is red, then the engine is not just venting Xenon
    - Show that the DCFT can transition from a standby heating mode to a full power operational mode
- DCFT Characterization
    - Measure a noticeable change in velocity to show performance
    - Measure the velocity over equal increments to determine if the degradation of the DCFT effects the performance of the vehicle
    - Compare input power of the engine to the output thrust to show the efficiency of the engine
    - Capture images of the plume, showing the change in flame color, which dictates the degradation of the DCFT

1.3 ESMD RELEVANCE

The availability of a low-cost Orbital Transfer Vehicle that can reach the Moon, Lagrange Points, and beyond will enhance NASA's capabilities for low-cost space exploration and scientific discovery. CASTOR serves as a key technology demonstration of this OTV capability in its demonstration of almost 1 km/s of delta-V in its one-year mission, a high delta-V for a satellite its size. This provides the following capabilities for NASA ESMD:

- A low-cost OTV with 2.0 km/sec of delta-V, or an upgraded CASTOR vehicle, would be able to depart GEO or GTO to carry small scientific payloads to lunar orbit (or impact) in support of lunar science. This would augment NASA's program to return to the Moon with a low-cost robotic exploration capability. Furthermore, it could provide a Scout-class lunar mission capability financially accessible to universities.
- Such an OTV could also depart GTO or GEO to travel to Lagrange Points where numerous astrophysical missions are envisioned to operate. One such mission is Stellar Imager (SI), a synthetic imaging mission that uses ultra-violet optics on multiple small, 65 kg spacecraft to image exo-solar stellar disks. The process of synthetic imaging requires that these individual spacecraft be frequently maneuvered to different relative locations to fill the Fourier coverage of the image being synthesized. A derivative of the CASTOR design could fulfill the needs of this mission. Other possible roles at ESL2 include inspection, repair, replenishment, and orbital maintenance of unstable Halo orbits of other astrophysical facilities.
- Autonomous rendezvous, close-proximity operations and capture/docking are essential enablers for telescope servicing, robotic assembly, inspection, and sample capture (Mars and Lunar Sample Return). These are enabled by efficient propulsion systems.

1.4 OVERVIEW OF SUBSYSTEMS

The current architecture of each sub-team is as follows:

- **Structures:** Four trusses mount around the propellant tank using three tank clamps. The ESPA (EELV Secondary Payload Adapter) ring mount attaches to the bottom of the trusses; two of the solar array panels are body-mounted directly to the trusses, and the other two solar panels mount to opposing trusses with a hinge. The solar arrays deploy using linear actuators that release pins in the panels. The structural configuration is shown in Figure 1.

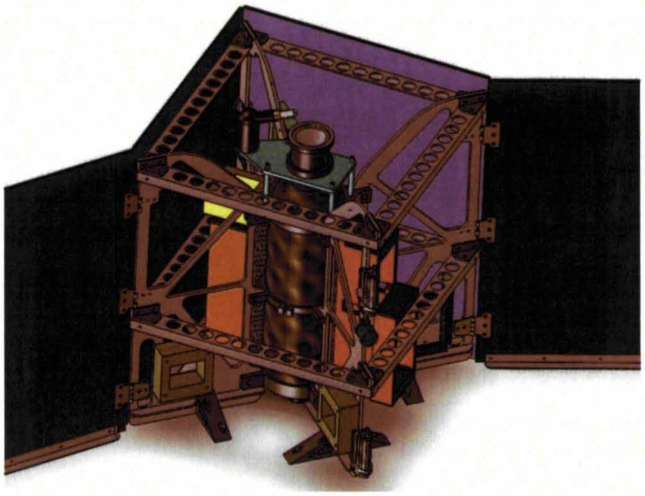


FIGURE 1: STRUCTURAL CONFIGURATION

- **Thermal:** The satellite is designed to sustain passive thermal control. Some components require surface treatments of Z93 in order to maintain operational temperatures. Temperature sensors will also be used to track the thermal state of the satellite to allow for active thermal control by increasing or decreasing power to certain units in response to unexpected temperatures.
- **Operations:** The HETE ground station at Cayenne will be used. Pre-launch and launch operations are compiled in the Concept of Operations Document (ConOps). The on-orbit operations will be performed as follows: detumble, solar panel deployment, commissioning, system verification (standard orbit operations), decommissioning, and finally end of life via an uncontrolled re-entry. Orbital maneuvers will be performed in LEO to demonstrate high delta-v capability via orbital altitude changes.
- **ADCS:** Attitude determination will be performed with 4 Sinclair sun sensors, 2 PNI Corporation 3-axis magnetometers, and a 3-axis gyro. Attitude control will be performed with 3 reaction wheel assemblies in each orthogonal thrust axis and 3 torque coils in each orthogonal axis. GPS navigation will be used for GNC using a space-rated SSTL GPS receiver. Furthermore, a NORAD TLE is provided for free on a daily basis for a cross check. Furthermore, a magnet will be placed opposite the engine to cancel the engine dipole.
- **Avionics:** The backbone of the avionics subsystem is 3 Microchip dsPIC33F 16-bit microcontrollers and a FLASH memory device. This is accompanied by all sensors and actuators while running FreeRTOS.
- **Communications:** Two Microhard S-band modems will support two patch antennas to provide 115 Kbps data rate capability.

- **Propulsion:** A modified Hall thruster built in-house will operate in either high power mode, providing about 4 mN of thrust, or in off mode, in which the cathode will remain heated. The propulsion system will also consist of the tank and various plumbing components. The thruster will be mounted on the opposite end from the ESPA ring mount. Plumbing will be provided largely by a NASA-provided flow controller called the Xenon Feed System.
- **Power:** Donated solar cells with an area of 1.1 m^2 will provide a maximum of 160 W to the Maximum Peak Power Tracker, which will provide power to the various components as needed and to Nickel-Cadmium batteries for storage during eclipse. Furthermore, the custom Power Processing Unit (PPU) and Power Distribution Unit (PDU) will provide power to propulsion and all other systems, respectively. The solar panel configuration is shown in Figure 1.
- **Science and Payload:** A camera pointed at the thruster plume will monitor the plume in order to measure engine health and thus efficiency throughout the mission.

1.5 DELIVERABLES

The CASTOR program has a series of deliverables, from hardware to documentation.

By the end of the nanosatellite design and protoflight build phase, the program will have constructed a protoflight (protoqualification) nanosatellite and have participated in PDR, CDR, and PQR. Protoflight implies that the Flight Competition nanosatellite deliverable is a flight unit with full hardware traceability (vs. a non-flight Engineering Design Unit, or EDU). Specifically, this requires:

- Protoflight Unit Nanosatellite: Experiment and support systems, including power to operate systems
- Mechanical and electrical interfaces with the Lightband, on the nanosatellite side of the interface
- Safety features/inhibits for nanosatellite-related hazards
- Ground handling and maintenance provisions for nanosats (mechanical and electrical)
- Ground support equipment and related procedures
- Operations (Ground, On-orbit)

A series of documents is used to represent the current state of the satellite and serves as the documentation that is necessary to present at reviews and to potential customers. Furthermore, it provides an incremental status of the design at different levels of maturity.

In order to maintain the documentation, it is necessary to implement a system of configuration control. Furthermore, this must be implemented in such a way that does not impose an excessive amount of documentation on the members of the CASTOR team. In general, configuration control systems require exorbitant amounts of paperwork to operate, so it is desired to find the bare minimum of paperwork that is necessary to implement configuration control. This implementation is two-fold: (1) by placing incremental documentation that represents the state of the system at key points in the design process under the team's fileshare and (2) by maintaining a system of Engineering Change Orders.

TABLE 1: DOCUMENTATION SUMMARY

Document/Model	Development Phases	Execution Phases	Status
Requirements Verification Matrix (RVM)	A-B	A-D	85%
Work Breakdown Structure (WBS)	A	B-E	80%
Program Schedule	A-C	A-E	90%
Budgets (MEL, Data, Power, Communications)	A-C	B-D	85%
CONOPS	A-C	D-E	90%
Risk Mitigation and Safety	A-C	D-E	50%
Integrated Systems Model	A-E	D-E	90%
Interface Control Documents	B-C	C-E	85%
CAD Models	B-C	C-E	90%
Systems Diagram	B-D	C-E	25%
Electrical Schematic Diagrams	B-D	D-E	25%
Manufacturing and Integration Plan	B-D	D-E	70%
Testing Plans and Reports	B-D	D-E	75%
Design Document	B-D	B-E	95%
On-Orbit Handbook	D-E	E	10%

The first column represents the document that is being referenced. The second represents the phases in which the document is created and the third likewise represents the phases in which that document is executed and/or referenced. The final column represents the approximate status of completion of the document for the CASTOR program. The phases are defined according to the standard NASA system maturation process as shown below:

- Phase A: Concept Development (completed with a System Requirements Review)
- Phase B: Preliminary Design (completed with a Preliminary Design Review)
- Phase C: Complete Design (completed with a Critical Design Review)
- Phase D: Build and Test (completed with a Flight Readiness Review)
- Phase E: Launch and Operations (Completed with end-of-mission)

1.6 OUTLINE

The remainder of this paper will:

1. Describe the system engineering process used in designing and testing CASTOR
2. How critical technologies are incorporated into the design
3. How the systems of the satellite are integrated together
4. How the satellite is fabricated and tested

Other tools that are used in order to best design the satellite.

2 SYSTEMS ENGINEERING PROCESS

2.1 CASTOR MILESTONES & RESOURCES

Throughout the CASTOR program there are multiple significant milestones which the systems team needs to prepare the entire team for. The following milestones give a sense of the type of work focused on during each phase of development as well as a general time reference for the CASTOR program.

Program Milestones

SCR – Systems Concept Review (March 2009 via Telecon)

- Focuses on challenging basic requirements and design concepts to determine if the satellite's mission is feasible.

SRR – Systems Requirement Review (April 2009 via Telecon)

- Reviews the underlying system requirements which will be driving all the major design decisions for the satellite.
- Makes sure that these top-level requirements will lead to the right design.

PDR – Preliminary Design Review (August 2009, Logan, UT)

- First thorough scrubbing of the design by UNP and NASA down to every subsystem level.
- Based on recommendations from UNP and NASA, significant design changes were made after PDR.

CDR – Critical Design Review (April 2010, MIT)

- CDR was the major milestone this semester.
- UNP review of a mature satellite design. CDR was more focused on assessing UNP confidence in our design as well as program management procedures.
- PQR – Proto-Qualification Review (August 2010, Logan, UT)
- Focus is to display operable hardware to strengthen confidence in satellite design and program management

FCR – Flight Competition Review (January 2011, Albuquerque, NM)

- At FCR, each university will have a 15 minute presentation and then a hardware station afterwards and groups of judges will evaluate the final design and choose the winner.

CASTOR Satellite

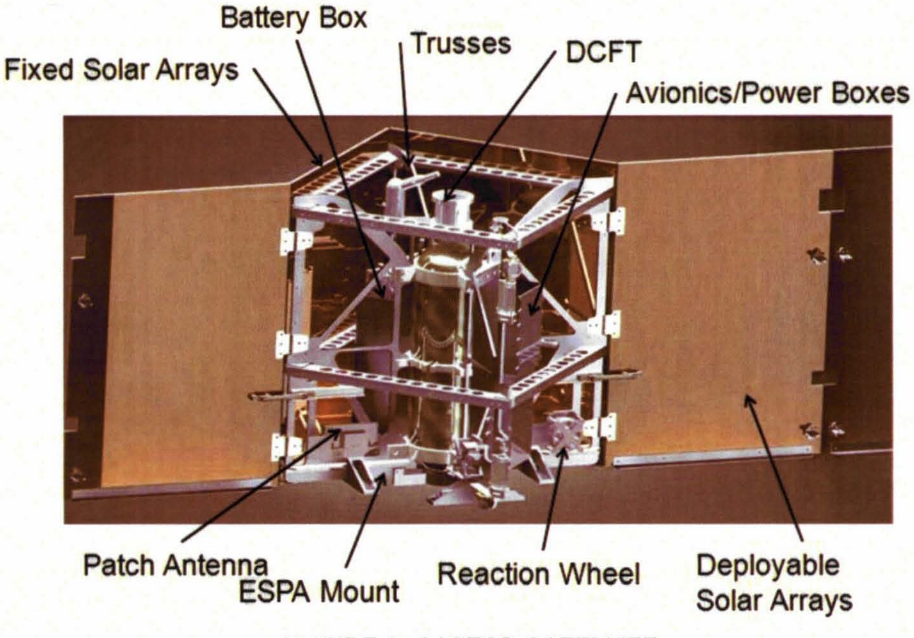


FIGURE 2: CASTOR SATELLITE

Significant design changes were made from PDR to CDR such as the deployable solar panels as well as the light band interface. This can be seen through the differences in this PDR layout vs. the CDR layout.

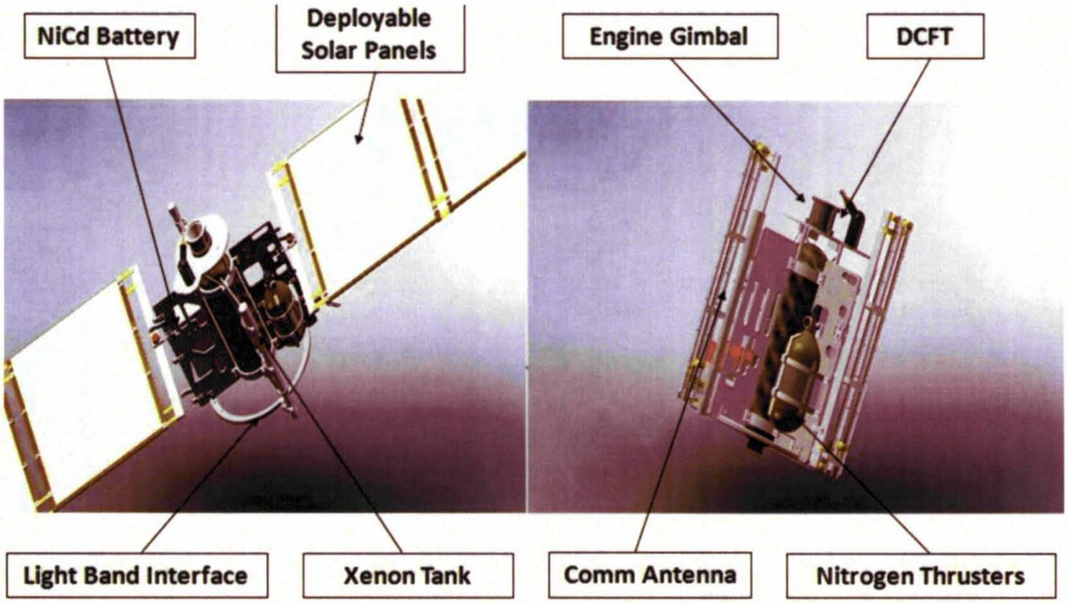


FIGURE 3: PAST DESIGN ITERATIONS

2.1.1 INPUTS & OUTPUTS

Identification of goals, in terms of inputs and outputs gives direction to the CASTOR project and helps to define the boundaries for achieving objectives. Primary inputs and outputs are outlined below:

Inputs:

- Personnel (undergraduate students, graduates, faculty mentors, and undergraduate researchers)
- Facilities
- Donors & Partners

Outputs:

- Proto-flight satellite (with supporting documentation and ground support) by January 2011 for Flight Competition Review

2 2 REQUIREMENTS ANALYSIS/VALIDATION

CASTOR's requirements stem from a couple of different sources such as flowdown, interfacing, and UNP guidelines Flowdown requirements come from the mission and system requirements meaning that these are needed in order to meet the mission statement Another source for requirements is interfacing, which is needed to ensure that everything interfaces correctly The CASTOR team also needs to make sure that they comply with the UNP guidelines

The mission requirements are stated as follows

- Measure the on-orbit performance, efficiency, and degradation of the DCFT during orbital maneuvers
- Operate the DCFT on orbit for 1500 hours

The system requirements are flowdown requirements from these and are stated as follows

- CASTOR shall have a DCFT as the primary propulsion system, which shall operate throughout the mission lifetime
- The CASTOR bus must be able to support on-orbit mission operations for the mission lifetime of at least 6 months
- CASTOR shall provide sufficient state data to measure the change of performance, efficiency, and degradation over the DCFT's operational lifetime

Each subsystem has requirements that flowdown from these system requirements

In addition to stating each of the requirements, the spreadsheet lists the document that shows how that requirement was met and the test that verified it was met For instance, the requirement "EPS must be able to generate 113 7W in a fully operational state" is met in the Design Documentation and tested in the solar panel test

The RVM has all of the requirements listed and each of these requirements is met through the design All of the requirements have a verification document listed, and if applicable the appropriate test is listed (Appendix 9 1)

2 2 1 RELIABILITY, SURVIVABILITY AND PRODUCTION

An overarching objective of the CASTOR program is to produce a reliable satellite that can survive launch and operate in orbit To this end, requirements flow down to the various subsystems to meet these mission objectives Survival goals generally correlate with UNP requirements which stem from well-margined launch requirements For compliance with these requirements, CASTOR must survive 20 G forces in all directions, and have a lowest natural frequency above 100Hz Ensuring that the CASTOR structure can meet these restrictions, and do so reliably, requires careful design and planning

Often the best way to see if a design works is to build it The structure alone has undergone at least some redesign after each time it was built Learning how to design parts that are easy to assemble and manufacture is key to creating a simple design By having students build what they design, students can identify what aspects need improvement For instance, using a standard set of screw sizes is important so as to reduce lead time on ordering parts and tools It also allows for interchangeability of wrenches and such which makes facilitates building

2 2 2 SAFETY

From a human factors and safety standpoint, the safety of personnel involved in all stages of design through operations is of paramount importance With safety in mind, conservative choices are made throughout the design process to lead to the generation of a product that is safe to operate Designs are required to meet certain safety guidelines outlined by UNP In the laboratory, various precautions are strictly followed Students are not allowed to work by themselves in certain laboratory environments, and are required to take a special safety class designed for engineering students in the department before accessing the laboratories Only students who have taken a four-hour machine-shop training session are allowed into the Gelb machine shop to manufacture parts on the mills, lathes and waterjet

2 2 3 TRANSPORTABILITY

Since ultimately CASTOR shall be launched from a location far from MIT, transportation and ground support equipment are under consideration Weighing concerns between transportation of a highly pressurized xenon tank with risk associated with having students assembling the satellite around a pressurized tank, the former was chosen Modifications were made to the design to allow insertion of the tank after the majority of assembly had taken place, thus allowing the separate transport of satellite and pressurized tank to the launch site Ground support equipment, including a carrying case for the 50kg satellite, is currently under design

2 3 FUNCTIONAL ANALYSIS AND ALLOCATION

The general approach to CASTOR is to break the system down into manageable subsystems An outline of the CASTOR system using Product Breakdown Structure (PBS) is shown in Figure 4

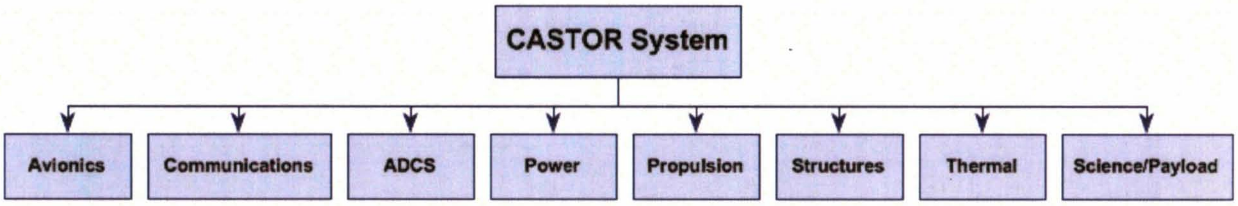


FIGURE 4: PBS FOR CASTOR PRIMARY SYSTEM

The primary responsibilities of these subsystems are described in Table 2.

TABLE 2: CHARACTERIZATION OF SUBSYSTEMS

Subsystem	Primary Responsibilities
Avionics	Provide computing control for CASTOR
Communications	Communicate data & telemetry back to ground station and upload commands to CASTOR
ADCS/GNC	Attitude and control for positioning CASTOR
Science & Payload	Camera for monitoring thruster performance
Structures	Structure to interface with all other subsystems and launch vehicle Solar Panel Deployment capability
Thermal	Provide thermal control for CASTOR including all components
Power	Provide power to CASTOR subsystems
Propulsion	Design and operation of thruster

Additional aspects of the CASTOR system include the concept of operations, including the ground station (both at MIT and through HETE-2 at Cayenne), and interfacing with the launch vehicle. Since the primary path to launch involves winning the UNP competition and thus being provided with a launch as well as an ESPA ring interface, focus on launch accommodations will be a much later stage in the program. As our primary payload is the propulsion system, with the camera as a monitoring device, the CASTOR vehicle is its own payload, and thus separation of craft and payload is unnecessary.

Since CASTOR requirements indicate that thruster degradation and performance must be measured, a long mission of approximately one year is envisioned. A useful analysis tool for developing this mission is to use a Functional Flow Block Diagram (FFBD) to describe the mission over time. The FFBD in Figure 5 shows the top level mission plan from a concept of operations perspective, and works down into more detailed levels of operation for the on-orbit deployment stage, the commissioning stage, and the normal operations stage.

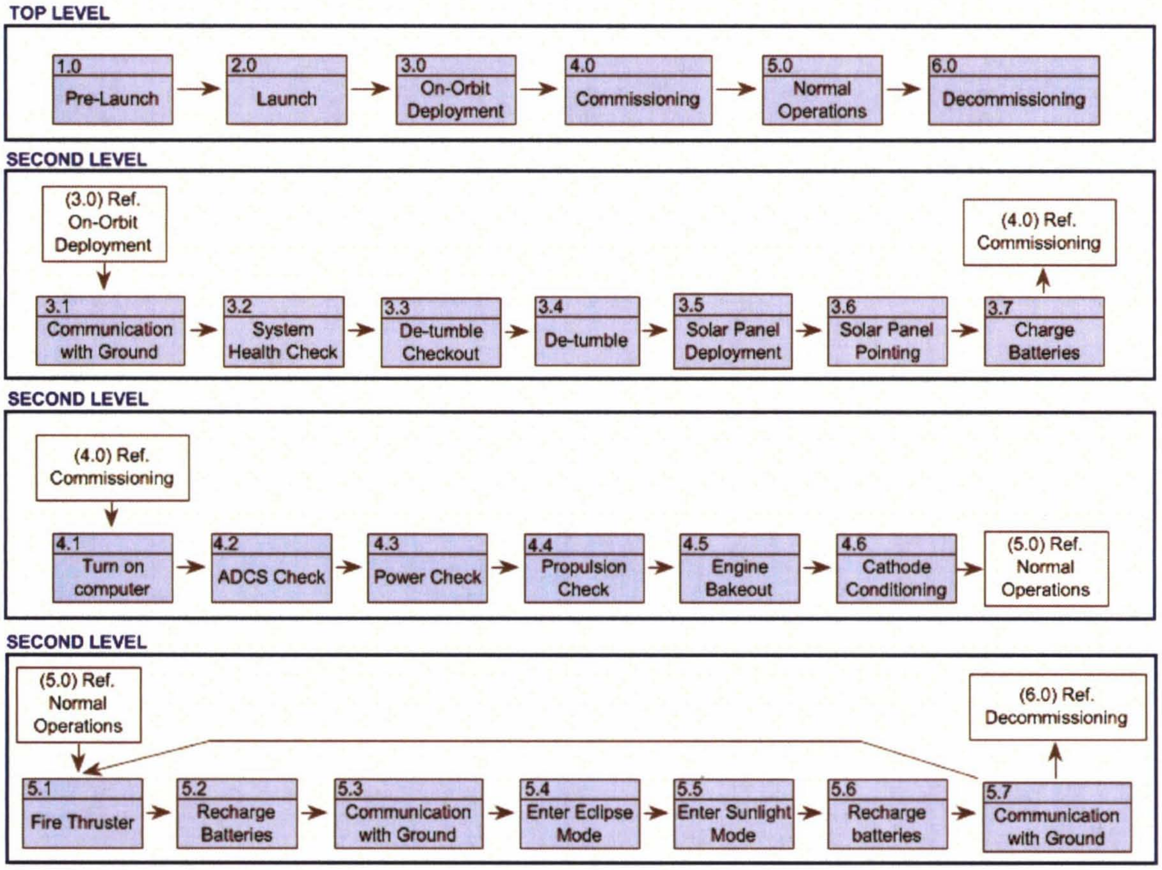


FIGURE 5: FFBD OF MISSION CONOPS

The normal operations stage shows iteration, in that the mission continues to cycle through sunlight and eclipse every 90 minutes, until the satellite ceases for function properly. Only at this point in time is the satellite decommissioned for destructive re-entry into the Earth's atmosphere.

2.4 SYNTHESIS

2.4.1 COTS VS. CUSTOM (DEVELOPMENT ITEMS)

Commercial Off-The-Shelf (COTS) items have become of increasing interest as space-qualified components reach the open market. These are defined as items which can be purchased as a unit, in quantity (inferring the availability of identical units), and are generally supported by a vendor and operated without requiring knowledge of the inner workings of the component. COTS components are common in CASTOR. Non-Developmental Items (NDI) are not used in CASTOR, due to the program's non-governmental nature. Developmental items (DI), or those items custom-designed for CASTOR, are found throughout the project.

Key design tradeoffs exist between COTS and custom items that must be balanced from the program level down to the component level. These decisions can drastically affect operations and integration down the road, and thus must be considered in detail. Tradeoffs between COTS and DI components are outlined in Table 3.

TABLE 3: COTS VS. DI TRADEOFFS

	COTS	Developmental Item
Pros	• Requires fewer student resources (less time) • On-demand spares and replacements • Need not re-invent wheel • Degree of quality	• Flexibility to design to specific needs • Compatible with system – easy to test and integrate • Often less expensive than purchasing space-qualified components
Cons	• Testing/reliability/compatibility issues • Black-box product (no control over product or little transparency) • Expensive (sometimes) • May not be space-qualified	• Ties up resources (student time) • Students may not have experience to achieve quality of equivalent COTS component • No space heritage

Time and money are two of the biggest factors which influence design choices to implement COTS or DI components. While DI components initially may seem cheaper, in reality student time is not free. The opportunity cost of that student's labor working on furthering the design of another system must be considered. Some COTS components are also more reliable, and some are also inexpensive.

A summary of key COTS and custom components is shown below in Table 4.

TABLE 4: COTS/DI COMPONENTS

Component	COTS/DI	Reasoning
Cathode/Anode Thruster	DI	Mission Requirement
Solar Panel Deployment Mechanism	COTS linear actuator DI release hinge	Reliability of deployment is essential, as well as non-deployment during launch, thus COTS linear actuator provides reliability, while DI release hinge provides interface to CASTOR system
Reaction Wheels	COTS	Perceived as more accurate & sturdy than student-built RW; Requires less student time, though expensive
Camera	COTS camera DI casing	Camera is inexpensive, however must extensively test to ensure space-qualification & survival in thrusting environment; Requires modification (DI casing) to reduce negative impact of thruster plume on lens
Sun sensors	COTS	Meets system requirements without increasing student workload or going over budget

2.4.2 REUSE

Reuse of previous designs, and applying lessons learned from them allows for the development of an improved system. Graduate students who participated in the FalconSat program as part of their undergraduate curriculum have been able to contribute lessons learned to members of CASTOR. Experienced team members who have contributed over the life of the project are also valuable to the CASTOR program.

Since the CASTOR mission involves destructive re-entry as a decommissioning procedure, reuse of the vehicle itself is not planned. However, CASTOR designs shall be well-documented in order that future satellite designers can utilize them. Heritage components, such as the GPS, sun sensors, magnetometer, linear actuators, and reaction wheels, have all been flown in space previously. Using heritage components gives more confidence in the reliability of the design.

Facilities

Members of CASTOR have access to a number of facilities. Outlined in Figure 6, the potential of each facility should be realized, and can be used for multiple purposes.

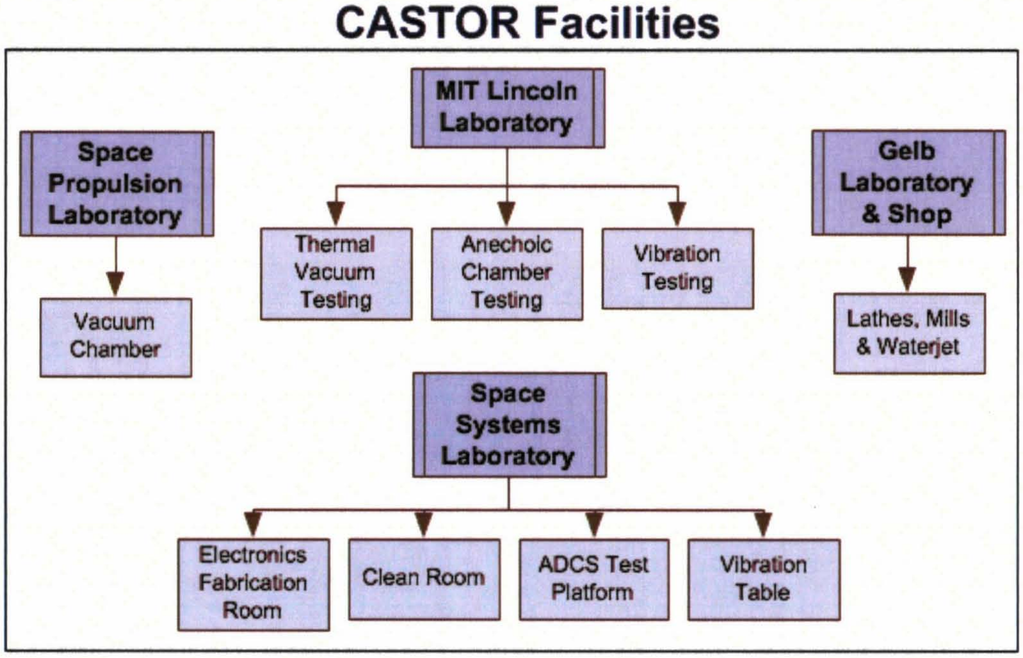


FIGURE 6: FACILITIES

2.5 SYSTEMS ANALYSIS AND CONTROL

2.5.1 TRADES

During the design process the sub-teams often have multiple options as far as components or methods to use when fulfilling the requirements. In order to determine which option is best, it is necessary to perform a trade study. By identifying the problem, brainstorming different solutions, assessing important criteria, and then comparing the various designs by these criteria and their importance, a design decision is achieved. Numerous trade studies have been performed over the course of the project. Here is an example to demonstrate the methodology with which design decisions are approached.

Trade Study Example

Background: Linear Actuator vs. Solenoid for the Solar Panel Release Mechanism

> Originally, the SPRM was planned to be driven by a pull-type solenoid, not a linear actuator. A solenoid would be very similar in function to a linear actuator: once current flows to the solenoid, it would retract its solenoid pin, just like the linear actuator. In fact, solenoids are often used for one-time releases like this application. Solenoids are simpler – and therefore more reliable – than linear actuators, and usually much less expensive.
>
> However, a linear actuator offers distinct advantages over a solenoid. For one, linear actuators can be more mass efficient than solenoids of similar sizes. In addition, a linear actuator exerts a relatively constant force throughout its stroke, whereas the force a solenoid exerts on its pin is proportional to the fraction of the pin inside the solenoid. This is especially important to consider, given that for this application, the maximum force is needed in the beginning at the largest extension of the pin.
>
> But by far the most significant advantage of a motorized linear actuator over a solenoid is the fact that the motion of the solenoid's pin cannot as easily be constrained before release. The linear actuator's pin is often held in place with a stiff mechanical locking system, whereas solenoid pins are generally held in place with springs and can therefore move more easily during launch. Because of this problem, using a solenoid increases the risk of premature deployment of the solar panels and failure of the SPRM.
>
> For these reasons, a motorized linear actuator will be used instead of a solenoid.

The chart below, similar to a Pugh chart, is the type of trade comparison done which was described in the paragraphs above. The characteristics of the component are listed as well as the level of importance of each characteristic. Then the components are compared on each category on a scale from 1 to 5, 5 being preferred. In this case the linear actuator was chosen over the solenoid because it performed better in the driving category of minimizing risk, and the total score took importance weighting into account. Even though the solenoid was cheaper, simpler and more reliable, it did not have the same level of safety which is most important when preventing premature panel deployment during launch.

Characteristic	Importance	Solenoid Rank	Linear Actuator Rank
Simplicity	Med	4	3
Cost	Low	3	2
Reliability	Med	5	4
Mass	Med	2	4
Risk (Premature Deployment)	High	2	5
TOTAL		**31**	**39**

2.5.2 RISK MANAGEMENT

In order to mitigate risk, potential difficulties must be identified, quantified, tracked and analyzed. A risk tracking spreadsheet (see Appendix 9.4) serves as the backbone of CASTOR's risk management system. These require continuous monitoring and thorough analysis for the purpose of risk reduction.

2.5.2.1 DEFINING RISK

Risk: The inability to achieve mission objectives - comprised of failure probability and consequences [1].

There are several types of risk. In order to consider them, a careful definition was determined by consulting NASA, Air Force, and MIT documentation [1,4]. *Programmatic* risk consists of any risk involving the program, including all external and internal risk. Subsets of programmatic risk include *technical* risk, *cost* risk, and *schedule* risk. Tradeoffs between the types of risk constitute risk management. Risks differ from issues in that they are problems that have not yet occurred. Once a risk becomes a reality, it is an issue and requires immediate action.

Successful risk management comes from continuous work. In order to mitigate risk, careful identification, analysis and tracking must be completed to ensure safety.

The management process can be broken into stages:

1) Planning
2) Assessment
3) Handling

4) Monitoring

Risk planning involves creating a framework to identify and track risks, along with their mitigation strategies. Documentation, such as the risk management file in Appendix 0, falls under this category. Planning also includes scheduled meetings with team leads to discuss risks.

Assessment consists of the actual identification and analysis of risks, including their likelihood and perceived consequence. Assessments are generally conducted by subsystem personnel, at the request of risk management managers. Updating the documentation created in the planning stage is a part of assessment.

Risk handling is the response to risk assessment. It involves distribution of responsibility of risk mitigation, to team leads for instances, as well as a plan forward to reduce or respond to risks. Higher risk items shall be brought to the attention of everyone in the systems team to increase involvement.

Finally, risk monitoring is the process by which the entire system risk is checked, allowing for a comparison to metrics to show improvement. This allows one to see the effectiveness of risk handling measures. For CASTOR, the current metric is 'risk level,' measured as a function of likelihood and consequence. Each risk item receives a score from 1-5 for both likelihood and severity of consequence (5 being extremely likely or catastrophic). Risks are considered improved as risks decrease in levels.

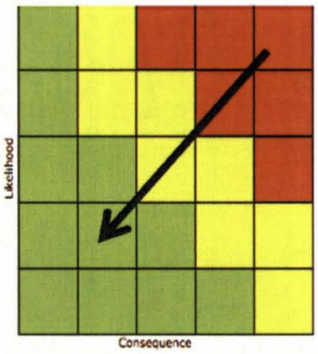


FIGURE 7: RISK LEVEL - LIKELIHOOD VS. CONSEQUENCE

The above chart depicts the five levels of likelihood and risk, and shows the breakdown into risk level. Green indicates low risk, yellow medium risk, and red shows high risk. By this point in the design, there should be no high risk items, as risk items should flow in the direction of the arrow. Monitoring helps in tracking this flow.

2.5.2.2 APPROACH

By improving CASTOR's management process, risk shall be reduced. The implemented system includes a tracking spreadsheet and a process of listing components and their technical risks. The last person to update the item is also tracked in the system.

An initial project-wide risk assessment was completed to determine where components stand and what areas needed additional focus. This involved contacting leaders of each subsystem and discussing risks and mitigation strategies. Next, further progress was made by discussing the list of risks with team leads to increase the robustness of the spreadsheet.

Further enhancement of the risk management spreadsheet is an ongoing process. Care must be taken not to overload the process by delving too deeply into compounded problems (combinations of failures), and to focus on the most critical risks. While initially adding risks to the database was encouraged, feedback from CDR showed that risks should be limited to twenty or thirty important risks, rather than nearly a hundred detailed risks. Thus the database is undergoing reduction to produce a more condensed form that brings focus to the true concerns for the project.

2.5.2.3 ASSESSMENT MODEL

Various characteristics of risk should be tracked to gain a sense of risks. These include the area of risk (hardware, software, operational, programmatic, manufacture, transport, etc.), the risk dependency (what else must fail first), likelihood, consequence, mitigation, diagnostic, and repair or backup method. Subsystems are asked to self-report estimates of their risks and address these categories. In considering risks, personnel should be aware that critical changes that affect multiple systems can have far-reaching effects. These can cause other subsystems to make numerous changes to their system and thus increases risk level. Since the level of risk is measured by the likelihood and consequence, changes such as this increase the consequence level and thus are reflected in the tracking process.

Relationships between risks are shown as 'dependencies.' Direct links between subsystems can lead to similar probabilities, and a simplification of risk tracking.

Consistency is somewhat maintained between subsystems, as team members updating the spreadsheet are asked to consider the following scheme:

TABLE 5: RISK LEVELS LEGEND

Level	Likelihood	Consequence
1	<< 1%	Inconvenience

2	~1%	Causes difficulties/delays, but can be corrected or dealt with
3	~10%	Compromises mission
4	~25%	Mission Failure or Partial Mission Failure
5	~50%	Injures people or harms launch vehicle & payloads; Total Mission Failure

Further work should involve tracking the assurance level of the evaluator (whether this is a tested likelihood or a complete guess).

2.5.2.4 TECHNICAL RISK

Currently all teams have updated the risk assessment spreadsheet. Some teams failed to fill in all requested information, and work is being conducted to track down answers to these missing pieces. Each item is looked at individually and considered for thoroughness. Higher risk items are initially flagged so as to prioritize them. Currently higher-risk items (level six or seven) include the anode (high voltage affecting system), and camera lens degradation. The next set of high risk items includes magnetometer failure, schedule slips, reaction wheel malfunctions, torque coil failures, solar panel deployment failure, and others. Mitigation strategies range from using the engine to de-saturate to modifying the duty cycle to account for low power input.

Meetings with subsystem team members can provide additional insight into potential risks. A meeting with the Power team took place to discover the relationship between power and voltage converter failures and various components. A single converter failure could cause an entire system, for instance ADCS, to become inoperable. Since most ADCS components work on 5V power, only the torque coils will operate should there be a failure. Thus analysis of the discussion also led to the discovery of unlisted risks, such as inhibits, and the difference between the battery charging circuit and the MPPT. Careful checking must be conducted to avoid errors, and to discover relationships between failures.

2.5.2.5 COST ESTIMATE

Assessment of costs is more straightforward, in that spending has been tracked over the last year and a spreadsheet has been implemented to track expenditures. Details regarding expenditures are tracked. Income, or available funds, is constrained, and shall be determined based on a detailed cost projection plan (see Appendix 9.3). The current method for dealing with this limitation is to delay the purchase of expensive, high TRL components, and instead test with engineering mockups until funding can be secured. It has been noted that for FCR in January, does not expect a flight-ready satellite, but a proto-flight satellite. Instead, high-cost flight hardware can be purchased later, as long as the interfaces and controllability can be modeled. For instance, purchase of one reaction wheel and a demonstration of functionality will suffice, rather than purchasing (and integrating) all three reaction wheels. Functionality of the other two reaction wheel should be verified by integrating engineering models into the system. This provides the advantage of reduced cost as well as sufficient testing.

Summary of Cost Risks:

- Limited Budget
    - Consequence: students spend excessive amounts of time re-creating COTS components to reduce costs; adverse effect on schedule adherence
    - Dependent on stringent monetary control and limited donations
    - Mitigation: Ask companies for material donations (such as solar cells) to reduce costs while not impacting student workload
- Exceeding budget
    - Consequence: Strain on resources; could lead to lack of funding for testing and manufacture of satellite, as well as purchase of components
    - Dependant on insufficient tracking and spending policies; inability to accurately project costs
    - Mitigation: include margining in cost projections; outline of all large-cost items & cost estimates; delay purchase of expensive items until funding is secured; test with less costly 'engineering units'
- Lack of funding for testing and manufacture of satellite
    - Consequence: serious delays which will adversely affect progress along UNP schedule
    - Dependencies: insufficient funds (lack of donors); going over budget
    - Mitigation: Promote satellite to potential donors; careful not to drastically exceed budget

Other methods for dealing with cost risk that are already under implementation include cost margining and purchasing restrictions. Costly items must be approved by faculty and staff. Garrett Fritz has done some work on cost projection modeling for the future of the program.

2.5.2.6 SCHEDULE RISK

Throughout the project great attention has been given to compiling schedules from teams and integrating them with a systems master schedule. Freeze dates have been created to help track design phases and keep teams at the same stage in design. Essentially the chosen method for reducing schedule-slip risk involves early identification of slips, re-working of schedule to reflect realistic delays (and flow-down to other systems), and reallocation of labor and resources to meet changing demands. Margins in the schedule allow for improved schedule-tracking, along with advanced freeze dates and compilation deadlines. Sub-teams are additionally encouraged to adhere to the schedule by taking part in schedule creation and thus being held responsible. Additional information on schedule can be found in Appendix 9.5.

TABLE 6: SCHEDULE ITEMS OUTLINE

Item	Risk Level (low/med/high)
Design Document Draft (4/23)	Low
Integrate Power w/Avionics (4/29)	Med
Design GSE (5/7)	Low
PPU Testing (5/7)	Med

2.5.3 BUDGET MANAGEMENT

The Systems team also tracks the purchase orders that are submitted to the professor and is responsible for ordering components and updates the MEL part status to “delivered”. Additionally, a systems team member must approve all purchases before submission to the professor. Purchases are approved only if the component is listed on the MEL. This provides a method of cross-checking to avoid unnecessary purchases.

The accrued costs of all purchased items are being tracked, not just those of flight hardware. An item is added to the spending tracking sheet once the purchase order has been approved, not when the actual debt has been incurred. This allows the team to anticipate the need to request more funding in a timely manner, should it become necessary. The Systems team must approve purchase orders in order to prevent unauthorized purchases. A student who wishes to purchase hardware must completely fill out a standardized Purchase Order or PO form. This PO is then checked on the MEL to verify the part is accounted for. If it is, then the PO is submitted to the purchasing professor for ordering. If the part is not accounted for in the MEL, then it must first be submitted for approval to the MEL before being approved for purchase. If it is subsequently added to the MEL, the PO will then be accepted.

This past March each sub-team provided a list of components that still need to be purchased before FCR next January. An estimated $101,108.64 of hardware and test expenditures is anticipated through FCR. A more short-term cost projection can be found in Appendix 9.3.

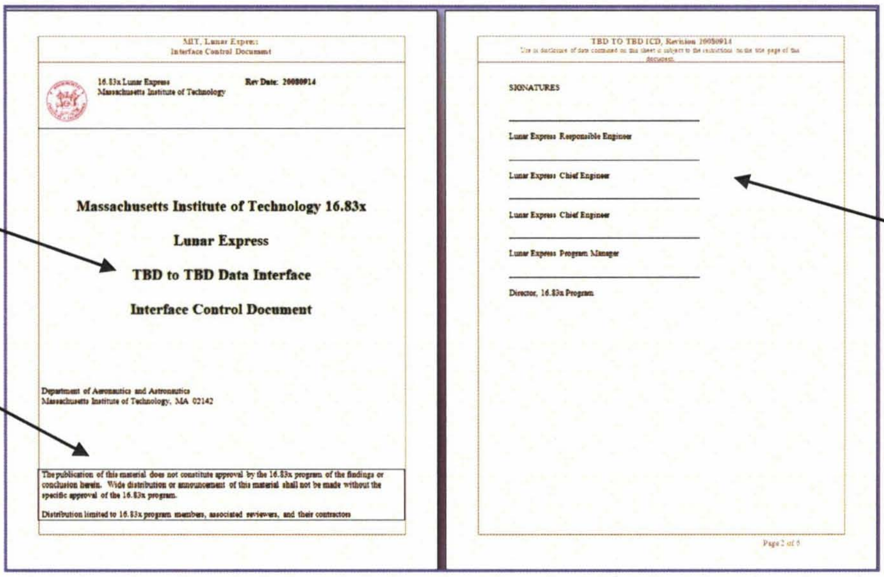
2.5.4 INTERFACE MANAGEMENT

Given the complexity of the CASTOR system, interface control documents (ICDs) are used to assist in modeling interfaces to ease integration efforts. The purpose of an ICD is to document and explain all of the possible inputs to and all potential outputs from a system or subsystem. This documentation is helpful not only for the future user of the system, but also for each sub-team designing the system. These documents help the designers determine what information they need to request from each team as well as how their design changes may affect the other teams.

Below is a template for the MIT format ICD as well as explanations for each component. Formatting is often times just as important as the technical content because improper formatting can easily make the technical message confusing or completely not interpretable.

The title page gives basic information such as which two components are being discussed.

It may also have instructions for distribution of the information contained in this document.



MIT, Lunar Express
Interface Control Document

16.83x Lunar Express
Massachusetts Institute of Technology

Rev Date: 20080914

Massachusetts Institute of Technology 16.83x

Lunar Express

TBD to TBD Data Interface

Interface Control Document

Department of Aeronautics and Astronautics
Massachusetts Institute of Technology, MA 02142

The publication of this material does not constitute approval by the 16.83x program of the findings or conclusion herein. Wide distribution or announcement of this material shall not be made without the specific approval of the 16.83x program.

Distribution limited to 16.83x program members, associated reviewers, and their contractors

TBD TO TBD ICD, Revision 20080914
Use or disclosure of data contained on this sheet is subject to the restriction on the title page of this document.

SIGNATURES

Lunar Express Responsible Engineer

Lunar Express Chief Engineer

Lunar Express Chief Engineer

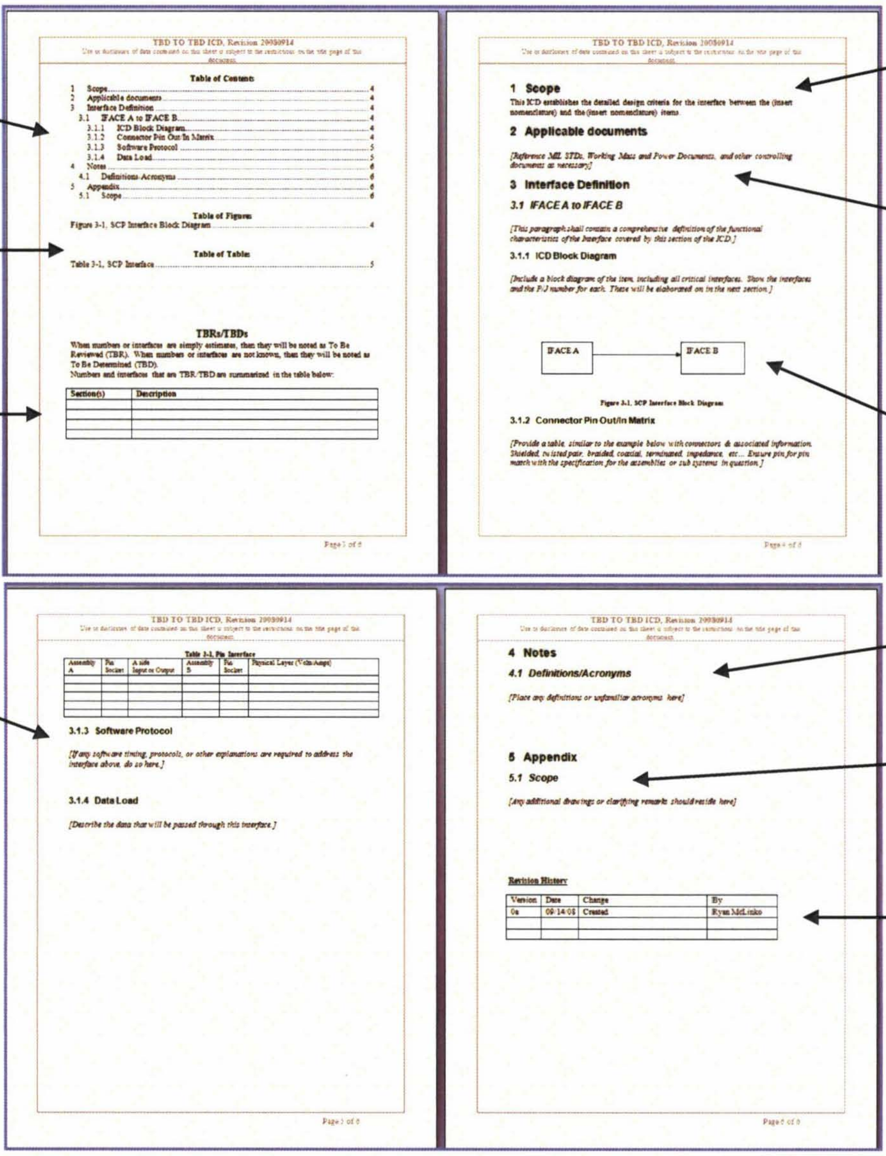
Lunar Express Program Manager

Director, 16.83x Program

Page 2 of 5

The signature page needs to have the names of key persons relevant to this document.

These people may be the relevant subsystem team leads, systems lead, chief engineer, etc.



TBD TO TBD ICD, Revision 20080914

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Table of Contents

TBRs/TBDs

When numbers or interfaces are simply estimates, then they will be noted as To Be Reviewed (TBR). When numbers or interfaces are not known, then they will be noted as To Be Determined (TBD).
Numbers and interfaces that are TBR/TBD are summarized in the table below:

Section(s)	Description

Page 3 of 6

TBD TO TBD ICD, Revision 20080914

Use or disclosure of data contained on this sheet is subject to the restrictions on the title page of this document.

1 Scope

This ICD establishes the detailed design criteria for the interface between the (insert nomenclature) and the (insert nomenclature) items.

2 Applicable documents

[Reference MIL STDs, Working Mass and Power Documents, and other controlling documents as necessary]

3 Interface Definition

3.1 IFACE A to IFACE B

[This paragraph shall contain a comprehensive definition of the functional characteristics of the Interface covered by this section of the ICD.]

3.1.1 ICD Block Diagram

[Include a block diagram of the item, including all critical interfaces. Show the interfaces and the P/J number for each. These will be elaborated on in the next section.]

Figure 3-1, SCP Interface Block Diagram

3.1.2 Connector Pin Out/In Matrix

[Provide a table, similar to the example below with connectors & associated information. Shielded, twisted pair, braided, coaxial, terminated, impedance, etc... Ensure pin for pin match with the specification for the assemblies or sub systems in question.]

Page 4 of 6

TBD TO TBD ICD, Revision 20080914

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Table 3-1, Pin Interface

Assembly A	Pin Socket	A side Input or Output	Assembly B	Pin Socket	Physical Layer (Volts/Amps)

3.1.3 Software Protocol

[If any software timing, protocols, or other explanations are required to address the interface above, do so here.]

3.1.4 Data Load

[Describe the data that will be passed through this interface.]

Page 5 of 6

TBD TO TBD ICD, Revision 20080914

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4 Notes

4.1 Definitions/Acronyms

[Place any definitions or unfamiliar acronyms here]

5 Appendix

5.1 Scope

[Any additional drawings or clarifying remarks should reside here]

Revision History

Version	Date	Change	By
0a	09/14/08	Created	Ryan McLinko

Page 6 of 6

Make sure the table of contents is correct. ICDs are updated frequently and pages are constantly shifting.

List all of the figures and tables as well as their locations for quick reference

While ICD is being created there will be many TBR and TBDs during the system design process. Explicitly document these so that they will not be overlooked later on.

The specific sections of the ICD will be different for each type of subsystem. For example, avionics will have a section for Software Protocol while the Structures team would have no need for that section

The Scope section should be a relatively short description of what systems this ICD covers

Applicable Documents are important to point out especially if the expected audience is not familiar with them or do not have explicit access to the reference documents

ICD block diagrams should be an extremely simple, non-technical diagram which eliminates any ambiguity about what system interfaces are being discussed.

Make sure to define all acronyms. Assume that the reader does not know any of them.

Here is an opportunity to add more diagrams, notes, etc. to help define the scope of this ICD in more detail.

Document all changes so that everyone working on the ICD knows who has made the change and when.

ICD Management

Storage: The ICDs which are available for editing by the sub-teams are stored in the CASTOR fileshare. This is where the sub-teams can view their ICDs and make changes as they see fit. When the sub-teams want to submit these changed ICDs for approval they send them to their systems team liaison. The systems teams performs an initial screening of the ICDs and also passes them on to TAs who can point out any missed mistakes. Once the inconsistencies have been fixed, the ICDs are then placed in the UNP section under 4.2.4.2-Documenation-ICDs which will eventually be submitted to UNP.

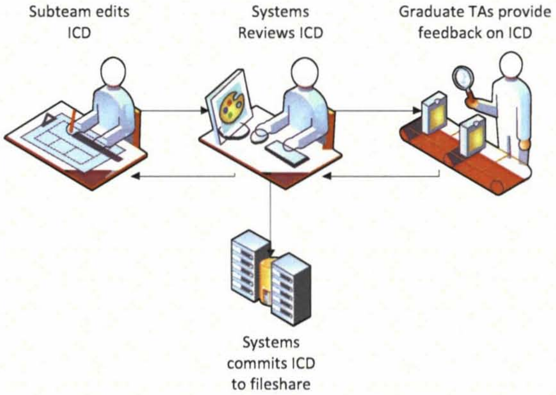


FIGURE 8: ICD REVIEW PROCESS

Tracking Changes: When an ICD is edited the author needs to list the date of change as well as the topic of change in the "Revision History" section of the ICD itself. This way, when the document is reviewed, any questions can be directed to the original author. This facilitates ease and speed of the ICD change approval process.

Types of ICDs

The Mechanical ICD identifies the hardware for the system or subsystem, and identifies to what it will be connected. For each piece of hardware, the ICD contains three main subsections: ICD Block Diagram, Physical Envelopes, and Hardware Mounting. The ICD Block Diagram identifies and shows all critical interfaces for the item. The Physical Envelopes section gives the initial (and, if applicable, final) current best estimate dimensions of the item: length, width, height, volume, and mass. The Hardware Mounting section provides a CAD drawing (if applicable) of each item, and describes the surface location, the hole locations, and the mounting hardware to be used. For many pieces of hardware, a fourth subsection, modeling, is included; this section describes any analysis (e.g. CAD drawings, finite element analysis) that was used.

The Power ICD identifies the hardware necessary to power each system or subsystem, and identifies to what the hardware will be connected. The ICD contains four subsections: ICD Block Diagram, Connector Pin Out/In Matrix, Grounding, and Load. The ICD Block Diagram identifies and shows all interfaces and connections for the hardware. The Connector Pin Out/In Matrix lists the in and out pins used for each connection, as well as the amount of amperage passing through the connections. Diagrams of the pin connections are included. The Grounding section identifies the type of grounding connections (i.e. analog, digital, or both). The Load section identifies the amount of power each piece of hardware will receive during the mission, and how often the power will be received.

The Thermal ICD identifies the surface connections (i.e. metal on metal contact) for each system or subsystem. The ICD contains four subsections: ICD Block Diagram, Heat Transfer Method, Thermal Path, Heat Loads and Fluxes, and Modeling. The ICD Block Diagram identifies the connections between the surfaces. The Heat Transfer Method section defines the method of heat transfer that will take place, the Thermal Path section identifies the path the heat load will travel, and the Heat Loads and Fluxes section identifies the amount of heat load that will be transferred during the mission, as well as the hardware limits. The Modeling section lists the types of analyses used.

The Data ICD identifies the hardware for each subsystem and to what it will be connected. For each piece of hardware, the ICD contains four sections: ICD Block Diagram, Connector Pin Out/In Matrix, Software Protocol, and Data Load. The ICD Block Diagram shows all interfaces and connections between the hardware. The Connector Pin Out/In Matrix lists the physical pin or socket connections for each piece of hardware, and whether the connection is in or out, as well as the voltage and amperage of each connection. The Software Protocol section describes how the software will interact with the hardware, and the Data Load section lists the type and amount of data that will flow between the hardware, and how often, during the mission.

Interface Diagram

The following diagram provides a visual representation of the relationships between all of the sub-teams and the subsequent ICDs which need to be managed for each relationship.

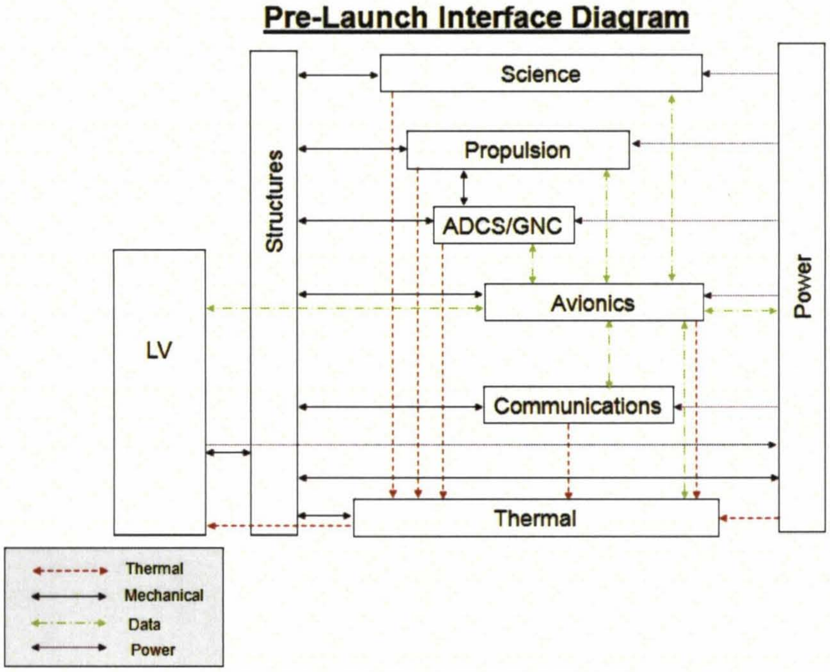


FIGURE 9: INTERFACES DIAGRAM

2 5 5 DATA MANAGEMENT

All of the CASTOR Command Media is stored on a subversion repository which is broken down as follows

- Management
- Systems
- Subteams
- Shared

Each of these sections has different levels of access Sub-team folders, for example, offer space for each of the systems to work on their command media before submitting it to systems for approval The systems team then makes the determination of whether or not that document is ready for submission to UNP Those final documents are then stored in a systems level folder

The structure of the repository prevents multiple editors from overwriting changes if they are working on a document at the same time If there is a conflicted copy then the repository will advise the author to update to the newest version before submitting their changes

CASTOR Design Document

The CASTOR design document provides detailed descriptions for all aspects of the design process for each sub-team It explains both the technical concepts, team organization and development processes for everything including design, schedule, budget, scope, testing, manufacturing, etc This document will be compiled at the end of the semester and will provide both a work history for the semester and a sense of the current status and future work which needs to be done Transitioning a project between one group of engineers and another allows presents a challenge, one which CASTOR faces each semester, as information regarding design decisions can be lost and experts are replaced with novices The design document attempts to mitigate these transition difficulties, by providing a means of passing design information to new members and thus helps with project continuity

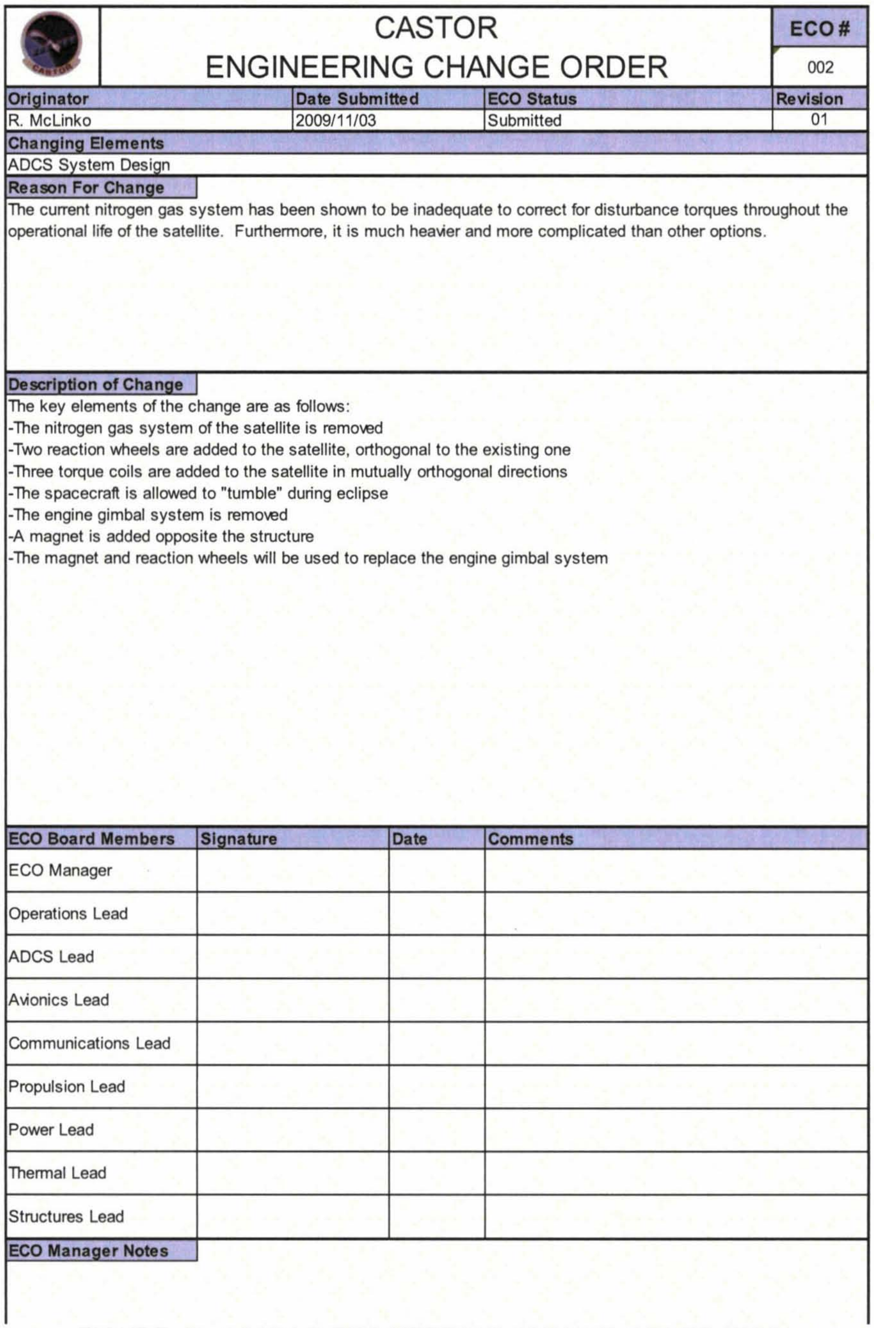
Engineering Change Orders

An Engineering Change Order (ECO) is the documentation process followed to implement significant changes that affect multiple subsystems Its purpose is to ensure continuity of design and to resolve potential conflicts which may arise from the design changes The ECO creation process serves as a mini-review for significant changes so that all the sub-teams are on the same page This process is to

- Deliver the proposed ECO to all directly affected subsystems for review

- Subsystems change specifics and inform the systems team
- Deliver the current proposed ECO to all other teams for review
- Check with systems team again
- Perform a sign-off of the ECO at a team leads meeting

This process managed by "ECO Manager" member of Systems Team who is responsible for making sure that all relevant parties are committed to the new design change before it is signed off. There have been six ECOs throughout the CASTOR program and there have been none so far this semester. However, the process is still in place in case significant changes still need to be made.



CASTOR
ENGINEERING CHANGE ORDER

ECO #
002

Originator	**Date Submitted**	**ECO Status**	**Revision**
R. McLinko	2009/11/03	Submitted	01

Changing Elements

ADCS System Design

Reason For Change

The current nitrogen gas system has been shown to be inadequate to correct for disturbance torques throughout the operational life of the satellite. Furthermore, it is much heavier and more complicated than other options.

Description of Change

The key elements of the change are as follows:
-The nitrogen gas system of the satellite is removed
-Two reaction wheels are added to the satellite, orthogonal to the existing one
-Three torque coils are added to the satellite in mutually orthogonal directions
-The spacecraft is allowed to "tumble" during eclipse
-The engine gimbal system is removed
-A magnet is added opposite the structure
-The magnet and reaction wheels will be used to replace the engine gimbal system

ECO Board Members	**Signature**	**Date**	**Comments**
ECO Manager			
Operations Lead			
ADCS Lead			
Avionics Lead			
Communications Lead			
Propulsion Lead			
Power Lead			
Thermal Lead			
Structures Lead			

ECO Manager Notes

FIGURE 10: SAMPLE ENGINEERING CHANGE ORDER (ECO)

2 5 6 MASS MANAGEMENT (MEL)

The mass budget for CASTOR is tracked through the use of the Master Equipment List or MEL This list is an Excel Spreadsheet documenting components either on the flight model of the satellite or used for testing It also tracks components that still need to be acquired

Each sub-team has a dedicated section of the MEL Through regular meetings with Systems and the team leads, the MEL is always an up to date representation of the components on the satellite When any component is updated on the MEL the person responsible for the change will document his name and the date onto that component's row so that others can verify the change in the future Each team can use the MEL to identify particular part numbers or types of components used by other teams should they need to interface with them in their designs

The MEL has the ability to hold mass margins for every component listed The margining scheme is

Exact (0-5%)

> Mass component has been weighed and integrated into the satellite

Fine Estimate (5%-10%)

> The mass has been quoted by the manufacturer or found on a specification sheet

Coarse Estimate (15% - 35%)

> Number based on SMAD or other approximation not yet verified by manufacturer

Guess (35% +)

> The component is still largely unknown, such as bolts/nuts in the current design

2 5 7 TECHNICAL PERFORMANCE

One important aspect of system control involves quantifying technical performance of components In order to measure progress and identify system weaknesses, tracking of the Technological Readiness Level (TRL) of components was implemented Before design freezes, as well as at various scheduled times in the program, each item is reviewed to assess its TRL, based on the NASA TRL chart shown in Figure 11

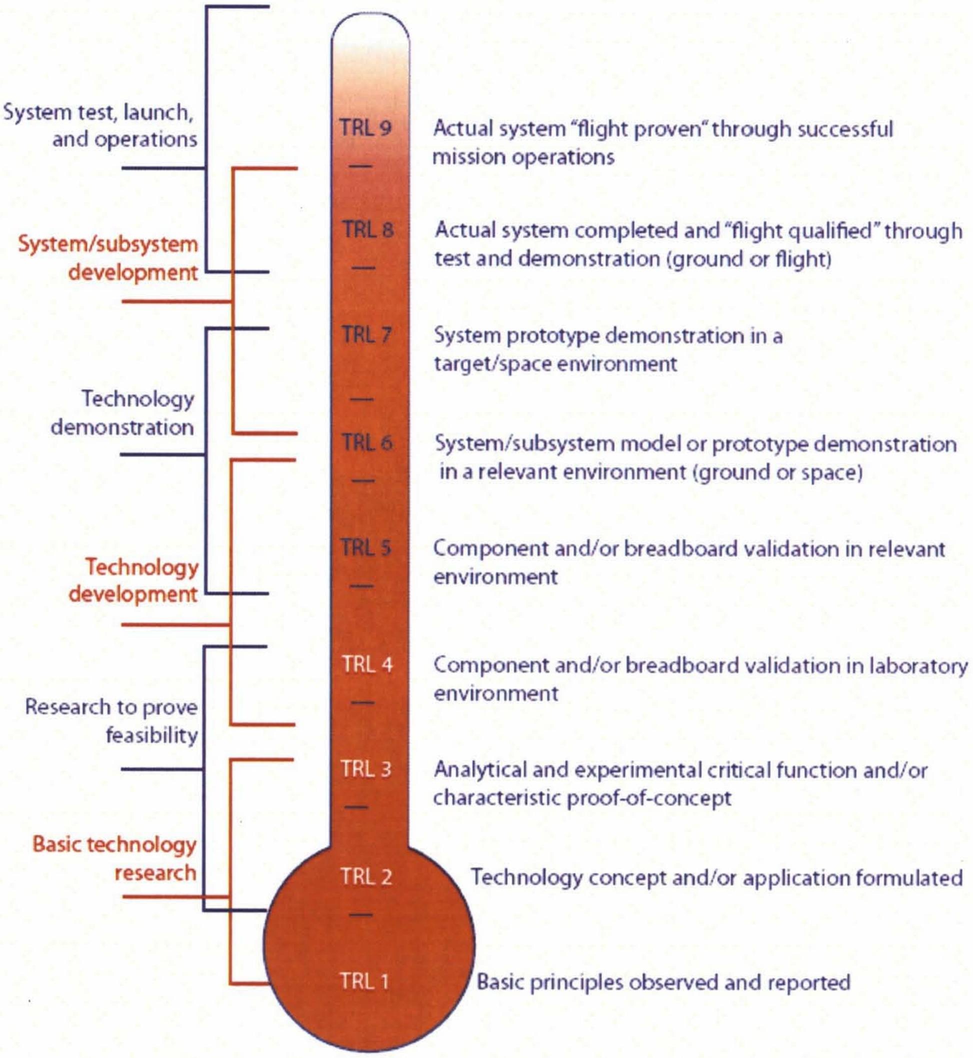


FIGURE 11: NASA TECHNOLOGICAL READINESS LEVEL ASSESSMENT TOOL (1)

Since most CASTOR components have no space heritage, a TRL of 6 is the upper bound for qualification and the target for systems leading to FCR. Listing the TRL of the critical components (Table 7) provides a technical overview of the CASTOR system.

TABLE 7: CRITICAL COMPONENTS TRL

Component	TRL
Sun Sensors	9
Reaction Wheels	9
PIC Communications	5
Thruster	5
Power Processing Unit (PPU)	4
Antenna	3
Camera	3

TRL incorporates the testing of the component into a metric. For instance, taking a system and putting it through thermal vacuum chamber testing might increase the TRL of the system, should it perform as expected. Should an item fail a test, it also fails to move up the TRL scale until the root of the problem is corrected. By monitoring both the TRL and the risk level of a component, efforts can be focused on low TRL, high risk (or critical) components, allowing for efficient allocation of resources.

3 TRANSITIONING CRITICAL TECHNOLOGIES

This section describes how key technologies were chosen and integrated into CASTOR and what risks stem from them.

3.1 DIVERGING CUSPED-FIELD THRUSTER

Criteria

The propulsion system onboard CASTOR will use electric propulsion to propel the small satellite. Using the Diverging Cusped Field Thruster (DCFT) as its primary propulsion system, CASTOR must operate for throughout the mission lifetime of 1500 hours. Hence, the propulsion system must likewise be operable for the same amount of time so that on-orbit performance, efficiency, and degradation of the DCFT can be measured and compared to thrusters of similar technologies.

The DCFT is believed to have better overall performance and lifetime than other electric thrusters for the following reasons:

- No central body
- Improved anode design
- Better plasma confinement
- Use of permanent magnets as opposed to electromagnets

For these reasons, it was chosen as the propulsion system for CASTOR. The purpose of the mission will be to validate the performance.

Activities

The thruster being used on CASTOR is a Diverging Cusped Field Thruster that was designed by Dan Courtney, a graduate student at MIT. A prototype of this thruster was built by MIT students in the spring of 2008 and it was modified and tested the in the summer of 2008. The thruster uses Xenon propellant and will produce an I_{SP} that scales with the amount of power sent to the thruster. For this mission, the thruster will be operating with an I_{SP} around 1200 s.

The thrust that is produced by the thruster also scales positively with the amount of power given to the thruster. Testing at 162.6 W (the previous operating power of the thruster), the thruster produces .0071 N of thrust. However, our new operating power for the DCFT is 100 W, but thrust output tests at this power have yet to be completed. The thruster will be fired continuously while CASTOR is in sunlight and will be turned off during eclipse periods. The engine's heater that runs at 36 W will remain running during eclipse periods in order to prevent the need for reconditioning when the satellite enters sunlight periods again. However, we are currently looking into ways to conserve power by not operating the heater during eclipse but instead running the keeper in the cathode, which uses only 15 W of power.

The cathode is part of the electric propulsion engine and the DCFT. The cathode emits charged particles that interact with the Xenon particles leaving the thruster to neutralize them and create a plasma beam leaving the engine. A cathode identical to the one used for thruster tests will be purchased from Busek, Inc. The cathode must be run with 15 W of power whenever the thruster is firing. The DCFT is shown in Figure 12.

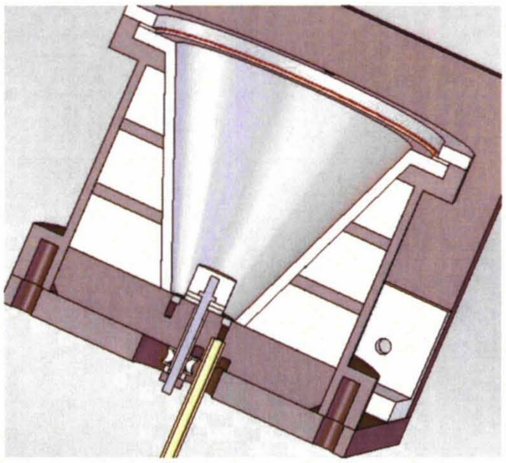


FIGURE 12: SOLIDWORKS DESIGN OF THRUSTER

Risks

The primary risk inherent in the DCFT is that it is still in the development and characterization stage. Not only does this lead to technical risks, but also programmatic risks in that there are many unknowns and fabrication/testing could lead to schedule slips. The primary technical risks include poisoning of the cathode, failure of the heater/keeper, anode material degradation, and lack of power to the anode. Each of these risks is being mitigated as much as possible at this point, but this is largely in flux due to the current testing of the DCFT.

3.2 XENON FEED SYSTEM

Criteria

The criteria for choosing the Xenon Feed System (XFS) were primarily based around:

- Functionality of the system
- Mass of the components
- Cost of the components
- Risk of the system

It should be noted that the alternative to the XFS is a custom feed system that was developed by the CASTOR team. This system had a mass of nearly double that of the XFS. Furthermore, the system is provided to CASTOR by NASA at no cost and the XFS will be extensively tested prior to being delivered to the CASTOR program.

Activities

The feed system is the controller for the mass flow rate of Xenon gas into the cathode and DCFT (anode) of the propulsion system, as seen in Figure 13. It regulates the flow ensuring the optimum amount of xenon continues through the system so that the maximum amount of xenon ions are produced when the gas flows through the DCFT creating the most efficient use of the propellant.

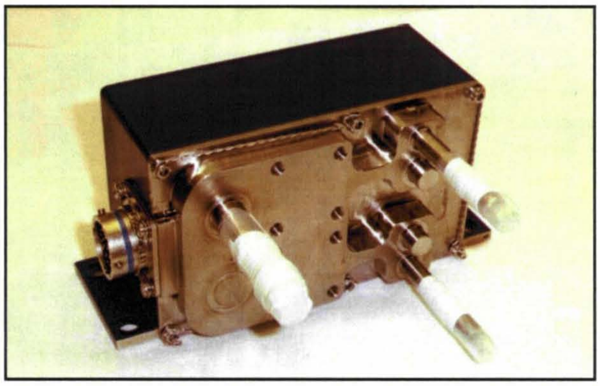


FIGURE 13: NASA XENON FEED SYSTEM

The NASA system, seen in Figure 13, was developed by Gray Research and NASA and is currently still in a testing phase at NASA with a last reported Technology Readiness Level (TRL) of 5. It weighs 0.73 kg in total, taking in gas at an inlet pressure of 3000 psi and releasing it at 15 psi. The system can regulate the flow between 0 and 10 sccm. Due to thermal expansion and contraction the Pressure Control Module (PCM) that Castor will be using as its primary flow control device has a constrained operation temperature of 0-50 degrees Celsius under normal operation from 30-3000 psi inflow to the module. As temperature increases above the operating range, the feed system begins to a have small steady state error in its control loop response with little response time variation and good stability nonetheless.

Risks

Given that the XFS is being provided to the CASTOR program by NASA, it is projected to have a much lower level of technical risk due to the construction and testing it will undergo by professionals. However, delivery by NASA also implies significant programmatic and schedule risk given that NASA may fail to meet CASTOR program deadlines. Technical risks include xenon feed rate not being accurate and inability to adjust mass flow rate into the thruster. Mitigations for these risks are being explored and developed, but much of this will continue as the XFS is integrated into the propulsion system.

3.3 SOLAR PANEL DEPLOYMENT

Criteria

Given the UNP's requirement of surviving 20G loading, the mechanisms connecting each solar panel to the primary structure of the satellite must be able to withstand a certain load to meet that requirement and survive launch. Specifically, if each Solar Panel is estimated to have approximately 1kg of mass (an upper estimate, based on mock-up models), then all of the brackets connecting to each Solar Panel must support 200N of force in total without failing. Assuming that each solar panel will be supported by 6 or more connectors and approximately equal loading distribution, each connector must therefore be able to support at least 34N.

In addition, because deployable solar panels are necessary to meet minimum power requirements, a mechanism for reliably deploying 2 of the solar panels must be included.

Furthermore, given that the solar array deployment is critical for complete achievement of the CASTOR mission, it is necessary that the mechanism be able to deploy with high reliability. More importantly, it must be able to not deploy in the Launch Vehicle environment and therefore potentially endanger other payloads.

Activities

In designing a new Solar Panel Release Mechanism (SPRM), the following factors were considered: (1) striving for simplicity to maximize the probability of successful Solar Panel deployment; (2) lowering mass and power requirements to minimize impact on the mass and power budgets; (3) incorporating a reasonable margin for error, (4) ease of manufacturing.

Each SPRM will be driven by a linear actuator. Once activated, the actuator will retract its pin, after which the two solar panel pins attached to each of the adjacent Solar Panels will be released. Then, with the help of an external spring mechanism, the Solar Panels will be able to deploy. This SPRM will constrain the deploying Solar Panels in the X, Y, and Z directions and will be much more robust than the previous release mechanism.

The SPRM will consist of the following components: 2 solar panel pins, 1 linear actuator, and one bracket to hold everything together and attach the mechanism to the primary structure. The bracket will be made of several 1/4" and 1/8" thick aluminum extrusions for ease of fabrication. There will be two SPRMs in total, all located on the farthest point of Truss 1 in the –Z direction. The SPRM, if made from 6061 Aluminum, has a mass of 0.08kg including the full linear actuator assembly.

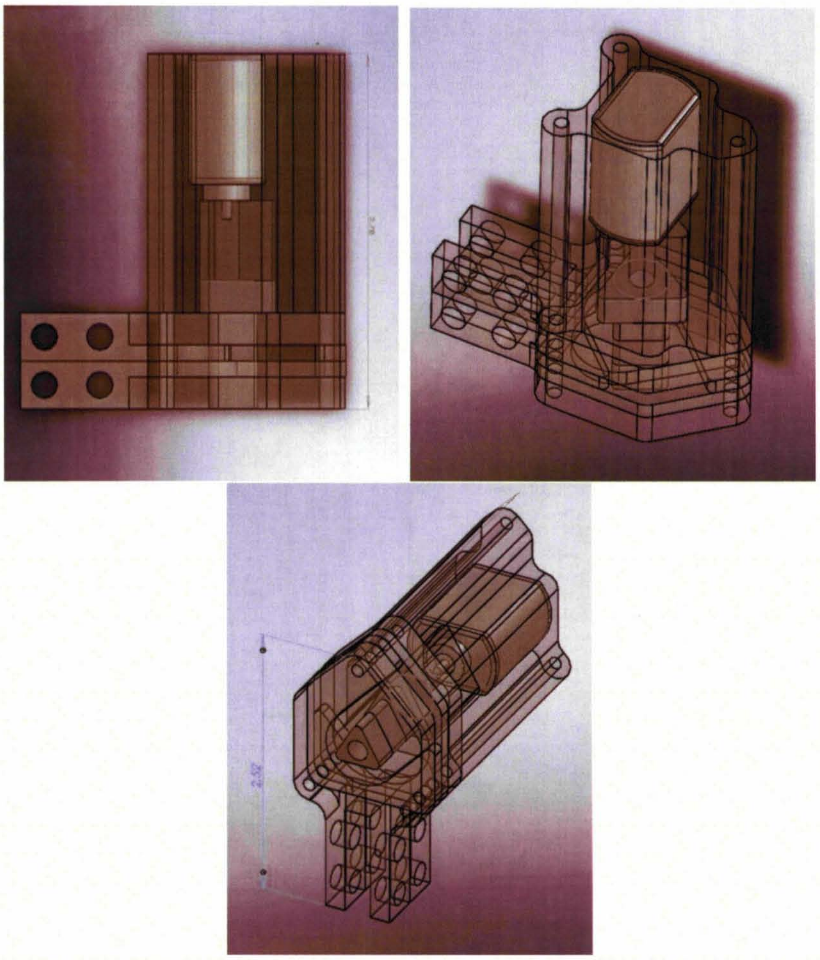


FIGURE 14: SOLAR PANEL RELEASE MECHANISM

THE SECOND ITERATION OF THE SOLAR PANEL RELEASE MECHANISM, SIDE VIEW (LEFT), ISOMETRIC VIEW (CENTER), BOTTOM VIEW (RIGHT). THE CURRENT DESIGN INCORPORATES AN INDUSTRY LINEAR ACTUATOR AND IS MORE MASS EFFICIENT.

Risks

The primary risk of the deployment system is that the deployment mechanism fails during launch and therefore puts other payloads at risk. Since this is an unacceptable occurrence, it is necessary to ensure the deployment system is designed with high safety factor, contains as much redundancy as possible, and is extensively tested. The second main risk is that the deployment system will fail to deploy when on-orbit. This is also mitigated primarily through testing since failure to deploy would result in a serious penalty to mission objectives.

4 INTEGRATION OF SYSTEMS ENGINEERING EFFORT

4.1 REVIEWS AND FREEZES

During production there comes various times where the design must be reviewed and checked. Attendees to these reviews include professors, people in industry, and University Nanosatellite reviewers. For reviews it is important that every team member is operating with the most up to date information. Thus, design freezes are implemented for these reviews typically two weeks in advance.

At the reviews, each part of the design of the CASTOR satellite is reviewed and comments are noted and addressed. After each review, a Systems compiled list of action items collected from the review is sent out to each team, informing them of what changes must be implemented into our design with a priority set on each one.

Additionally, design freezes serve as a method for checking in with each team. It is easy for teams to lose track of what changes have been made to the design if they are not directly related to their section of the satellite. Because of this there can be mistakes made when moving forward as teams may design for out of date components. When the design is frozen, there are updated data sheets, design documents, equipment lists and other command media Systems manages that are available to each sub-team as a point of reference as the project moves forward.

4.2 CONCURRENT ENGINEERING OF HARDWARE/SOFTWARE

Both hardware and software for CASTOR are constantly evolving. As such, it is important to make sure that any changes in either aspect of design is tracked and noted. Most of the interfaces between hardware and software fall under the responsibility of the avionics sub-team managed by the systems team. The hardware provides the physical connections and logic circuits necessary for connecting to sensors and actuating devices. The software provides the logic for ensuring that the sensor data is acted upon properly.

When a sub-team determines that they require a hardware component for their operations and need to control it, they inform the Systems who will make assign responsibility to someone on avionics. However, if any changes are made to either the physical component or the type of software implementation, it is crucial that both the avionics team and team responsible for the component are kept up to date. This is done through the team leads meetings as well as direct communication with Systems and the sub-teams throughout the week.

4.3 SUBSYSTEM TESTS, INTEGRATED TESTS, PLANNED INTEGRATION PERIODS

Since the design of the CASTOR satellite is relatively mature, each team is now taking on the task of integration with other teams. During this phase of design it is particularly important for team communication to be facilitated through the Systems Team. When sub-teams need to schedule joint lab time they can submit their requests at the team leads meetings held by Systems each week.

The integrated testing is managed by the Systems team to allow for streamlined operation during the test. Integrated tests include thermal vacuum and shake table tests were components from multiple teams are integrated. These tests take place off MIT campus at MIT Lincoln Laboratory. In order to reserve time at these labs the tests must be scheduled ahead of time and must have sufficient personnel to run the experiments.

4.4 CRITICAL PATH MANAGEMENT

One approach that CASTOR has used to improve the robustness of schedule management is to introduce Critical Path Management (CPM). A simple Gantt chart shows the expected run time of each task or project and displays them against a calendar. This is useful for visualizing the time breakdown of individual tasks but this does not give very much insight to a program manager as to what tasks may be high risk for creating a bottleneck in the process if they aren't completed in time.

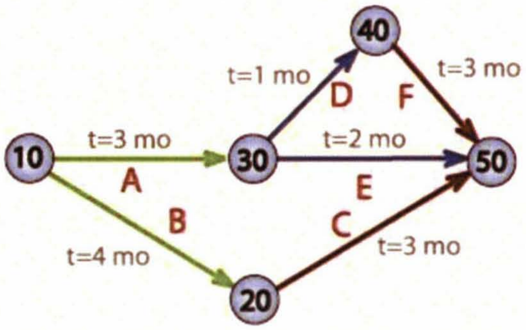


FIGURE 15: CRITICAL PATH MANAGEMENT

Critical path management displays each task as a state in a state diagram and lists the expected early start, early finish, late start and late finish times. This state diagram incorporates dependencies that certain tasks have with others. For example, the Master Equipment List (MEL) cannot be finished and submitted until ADCS determines which brand of sun sensor to use. If the systems team is constantly aware of these dependencies then they will know the extent of the consequences if, say, the ADCS team falls behind. Once this state flow is created the critical path can be determined. The critical path is defined as the flow path through the states from project start to finish which, in total, takes the longest time to complete.

This gives the program manager a visual reference to decide if they want to shuffle tasks around to have more risk adverse schedule. More complicated forms of CPM can morph into PERT analysis and Design Space Matrices (DSM) which incorporate possible design iterations into the schedule. These have not yet been incorporated into the program.

5 IMPLEMENTATION TASKS

5.1 TESTING

The CASTOR satellite must undergo extensive testing to create mission assurance. Mission assurance is defined as the general system engineering, quality, and management principles towards the goal of achieving mission success, and, toward this goal, provides confidence in its achievement. Mission success is defined as the achievement of a system to singularly or in combination meet not only specified performance requirements, but also expectations of the users and operators in terms of safety, operability, suitability, and supportability. Mission assurance focuses on the detailed engineering of the acquired system, and, toward this objective, uses independent technical assessments as a cornerstone throughout the entire concept and requirement definition, design, development, production, test, deployment, and operation phases.

There are three key reasons why a test should be performed. These reasons and the rationale behind them are listed below.

1 Functionality verification
  1.1 Evaluate that the as-built system (including interfaces) satisfies the requirements and specification baseline.
  1.2 Identify issues with the proposed test, integration, and verification plans and procedures
2 Reduce Risk
  2.1 Evaluate appropriateness and risk of verification by any method other than testing.
  2.2 Evaluate risks associated with deviations from environmental testing standards (e.g., MIL-STD 1540) and other applicable standards or best practices.
  2.3 Evaluate the fidelity to the "test like you fly" (TLYF) and "test what you fly" philosophies, especially at the system and higher levels of integration, and identify risks associated with deviations from these philosophies. This includes implications to accurate modeling and simulation.
3 Unfamiliar Area
  3.1 Evaluate analysis, simulation, inspection, and test results to determine readiness to proceed to subsequent test or program activities.

All testing will follow begin at the component level, progress through the subsystem level, and finish at the assembly level. There may be additional tests between the three major levels, but as a minimum, all aspects of the design will be tested in this order for the reasons listed above.

All test plans can be found in the associated test plans The three system level tests are the Balloon SHOT (II), Vibration, and Thermal Vacuum test and are listed with the subsystem performing them

5 1 1 INDEX OF TESTS

- Avionics
    - EMC/EMI August 2010
    - FlatSat I (Ground station Communications) November 2009
    - FlatSat II (Read Thermal/Power Sensor Data) May 2010
    - FlatSat III (Read/Operate ACS sensors) May 2010
    - FlatSat IV (PPU/Linear Actuators/Inhibits) May 2010
    - FlatSat V (Operate XFS) May 2010
    - FlatSat VI (Radiation effects) May 2010
    - Balloon SHOT (II) June 11-13th 2010
- Communications
    - Antenna April 2010
- ACS
    - GPS November 2009
    - Magnetometers March 2010
    - Reaction Wheels March 2010
    - Torque Coils June 2010
    - Sun Sensors October 2010
- Power
    - Integrated PPU May 2010
    - MPPT July 2010
    - On-board Charger May 2010
    - PDU April 2010
    - FlatSat August 2009
    - Solar Power April 2010
- Structures
    - Vibration March 2009, February 2010, October 2010
    - Thermal-Vacuum March 2010, October 2010
- Science
    - Camera Avionics May 2010
    - Camera Functional September 2010
    - Camera Thermal-Vacuum April 010
    - Camera Vibration April 2010
- Propulsion
    - DCFT Efficiency April 2010
    - Feed System June 2010
    - Integrated PPU May 2010

The key tests are as described in following sections

5 1 2 SOLAR ARRAY TESTING

Due to the high power requirements of CASTOR and the fact that students are assembling the solar arrays, it is critical to perform extensive testing of the solar arrays The current configuration next needs to be tested to see if it gives enough power to run each team's equipment If the voltage, current, and resulting power provided encompasses the power needs, then the solar panel setup is properly designed

This initial test will verify that the solar cells provide the correct voltage, currents, and power that are equivalent with the documentation The light source used should illuminate the entire solar panel Since the CASTOR design involves two solar panels at 45° to the sun, it is also necessary to test the effects of having the light falling on the solar cells at different angles other than straight overhead The light source used should illuminate the entire solar panel Finally, it is necessary to ensure that the amount of power that each subsystem expects is correctly supplied The light source used should illuminate the entire solar panel As this test involves the complete setup, a light source similar to a spotlight is recommended

5 1 3 FLATSAT TESTING

Furthermore, it is necessary to perform a Flatsat of the satellite, which ensures that all components in the satellite are able to communicate with each other This involves demonstration of the ground station's ability to transmit commands and the satellite's ability to receive commands and execute as expected CASTOR has chosen to split the Flatsat testing up into a series of tests that can be performed in sequence as different parts of the system are ready for testing This helps to ensure that the program remains on schedule and minimizes critical paths These tests range from Flatsat I, which demonstrates basic ground station capabilities to Flatsat VI, which demonstrates the avionics system's capability to withstand the radiation environment of space

5 2 COTS VERIFICATION

Due to inconsistencies in COTS products matching precisely with their documentation, testing of COTS components is required to ensure reliability as well as proper integration with the overall system One example of verification of COTS components is testing of the communication antennas Since the 8 and 11 dBi antennas responsible for communications with the ground station are COTS, anechoic chamber testing was performed to ensure that first, the antenna met the specifications, and second, that modifications to the antenna would not be detrimental to the system Testing the antenna by itself, and then as a system with the satellite would lead to increased TRL. Testing was performed at MIT Lincoln Laboratory (a professional facility located about half an hour from MIT). A comparison between actual performance and the specifications is shown below.

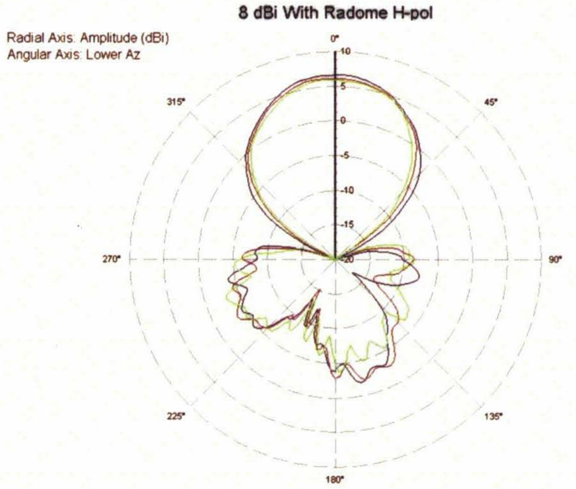


FIGURE 16: ANTENNA TEST RESULTS

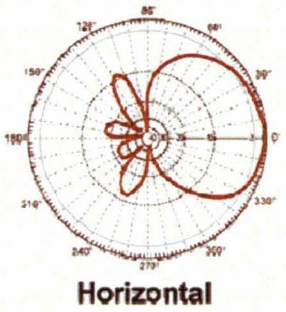


FIGURE 17: ANTENNA SPECIFICATIONS SHEET

From the graph of the radiation pattern, it is apparent that the quality of the antenna does not quite meet the specifications, but it was concluded to be sufficiently high to meet subsystem communication requirements.

6 ADDITIONAL SYSTEMS ENGINEERING ACTIVITIES

Because of limitations in the CASTOR budget and the significant expense of flight model components, it is important to confine purchases and ensure that savings are found wherever possible. Team members manufacture most components on our satellite, saving the team a significant amount of money. We are also able to generate several donations from companies who wish to sponsor our satellite. However, being participants in a competition, we must account for the possibility that our design might not be selected for flight. Because of this there are some components that may be imprudent to purchase at this phase in our design. Massachusetts Space Grant also helps support undergraduate students for their research contributions to the project, as well as unique testing projects run related to CASTOR organized by students.

The current design calls for the use of three reaction wheels and four sun sensors. Due to the extremely high cost of these components, we have decided to rent engineering models from the manufacturers. These components have the same interfaces, mass, and functionality as the flight model version but are not as precise or expensive. Because we have decided to do this we are operating within our budget and able to demonstrate the functionality of our satellite.

Ordered components are largely delivered in the span of a couple of days. There are very few long-lead items that we need to account for, but those that need to be purchased have been done so early in the design, and those components that are not in our possession are not limiting factors as we can continue design with a mock up until the component arrives.

7 CONCLUSION

The CASTOR mission is a complex project requiring the deep involvement of systems engineering concepts in its conception and development. Through careful systems planning, analysis and implementation, CASTOR continues to move forward as a project with the aim of improving efficiency of electric propulsion systems. High-performance propulsion systems have application to missions beyond GEO, allowing more efficient access to LaGrange Points, the Moon and beyond. With its strong mission relevance to the future of space exploration, CASTOR shall continue to progress towards the project requirements and objectives. After accomplishing post-CDR feedback, the CASTOR team will begin fabricating the satellite components for its prototype qualification review (PQR) in August of 2010. Finally, the complete satellite will be built for flight competition review (FCR) in January of 2011, and hopefully a launch soon after.

Finally, CASTOR's importance lies not only in its technical demonstration, but also in its application of making small spacecraft design a reality for not just NASA and the military, or even commercial industry, but also university students. Providing students with the opportunity to learn how to design, implement and operate space systems while thinking with a systems-perspective greatly contributes to their education as engineers, and shall serve them in their future careers.

8 WORKS CITED

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9 APPENDICES

9.1 MEL

Master Equipment List **Updated on 04/20/2010**

Subsystem	Item name	Description (Vendor, part #, etc.)	# Items	Total Cost ($)	Cost Margin	Margined Cost	Total Mass (kg)	Mass Margin	Margined Mass
Systems	Testing		1	5,000.00		5,000.00			
Systems	Travel to PQR	Flight hotel and food	1	3,516.00	25%	4,395.00			
Systems	Travel to FCR	Flight hotel and food	1	3,516.00	25%	4,395.00			
Systems	Shipping Satellite		2	1,000.00	25%	1,250.00			
Add rows above this row, do not delete this row									
Total				5,000.00		5,000.00	0.00		0.00
Allocation				12,000.00	40%	16,800.00	0.00	0%	0.00
Orbits									
Add rows above this row, do not delete this row									
Total				0.00		0.00	0.00		0.00
Allocation				0.00		0.00	0.00	0%	0.00
Operations	Labor	cost of labor at ground station (free student labor)	0	0.00	0%	0.00	0.00	0%	0.00
Operations	HETE	ground station	1	15,000.00	25%	18,750.00	0.00	0%	0.00
Operations	MIT Control Center		1	6,000.00	25%	7,500.00	0.00	0%	0.00
Add rows above this row, do not delete this row									
Total				21,000.00		26,250.00	0.00		0.00
Allocation				25,000.00	15%	28,750.00	0.00	0%	0.00
ACS	IMU	Analog Devices, solid state gyros, tri- axis ADIS 16355/AMLZ	1	620.00	10%	682.00	0.02	10%	0.02
ACS	Reaction Wheel Assembly	small wheel for roll maneuvers; Sinclair Interplanetary	3	90,000.00	10%	99,000.00	0.68	10%	0.74
ACS	Sun Sensor	SS-411 from Sinclair Interplanetary	4	40,000.00	15%	46,000.00	0.14	15%	0.16
ACS	Torque Coil		3	750.00	20%	900.00	0.75	20%	0.90
ACS	MicoMag 3-axis Magnetometer	SparkFun Electronics; SEN-00244	2	480.00	5%	504.00	0.04	0%	0.04
ACS	Magnet		1	1,000.00	15%	1,150.00	0.25	25%	0.31
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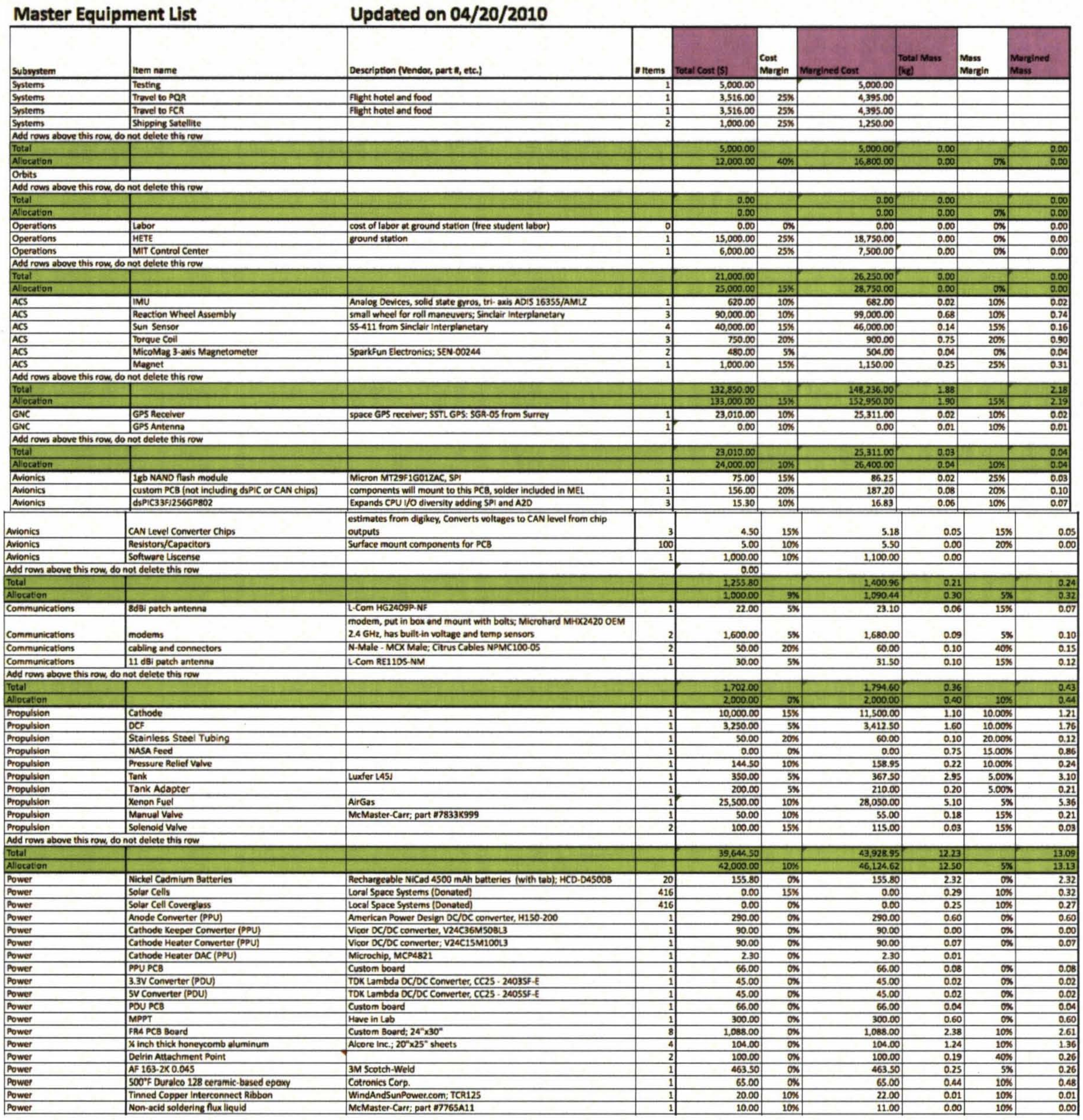
Total				132,850.00		148,236.00	1.88		2.18
Allocation				133,000.00	15%	152,950.00	1.90	15%	2.19
GNC	GPS Receiver	space GPS receiver; SSTL GPS: SGR-05 from Surrey	1	23,010.00	10%	25,311.00	0.02	10%	0.02
GNC	GPS Antenna		1	0.00	10%	0.00	0.01	10%	0.01
Add rows above this row, do not delete this row									
Total				23,010.00		25,311.00	0.03		0.04
Allocation				24,000.00	10%	26,400.00	0.04	10%	0.04
Avionics	1gb NAND flash module	Micron MT29F1G01ZAC, SPI	1	75.00	15%	86.25	0.02	25%	0.03
Avionics	custom PCB (not including dsPIC or CAN chips)	components will mount to this PCB, solder included in MEL	1	156.00	20%	187.20	0.08	20%	0.10
Avionics	dsPIC33FJ256GP802	Expands CPU I/O diversity adding SPI and A2D	3	15.30	10%	16.83	0.06	10%	0.07
Avionics	CAN Level Converter Chips	estimates from digikey, Converts voltages to CAN level from chip outputs	3	4.50	15%	5.18	0.05	15%	0.05
Avionics	Resistors/Capacitors	Surface mount components for PCB	100	5.00	10%	5.50	0.00	20%	0.00
Avionics	Software Liscense		1	1,000.00	10%	1,100.00	0.00		
Add rows above this row, do not delete this row				0.00					
Total				1,255.80		1,400.96	0.21		0.24
Allocation				1,000.00	9%	1,090.44	0.30	5%	0.32
Communications	8dBi patch antenna	L-Com HG2409P-NF	1	22.00	5%	23.10	0.06	15%	0.07
Communications	modems	modem, put in box and mount with bolts; Microhard MHX2420 OEM 2.4 GHz, has built-in voltage and temp sensors	2	1,600.00	5%	1,680.00	0.09	5%	0.10
Communications	cabling and connectors	N-Male - MCX Male; Citrus Cables NPMC100-05	2	50.00	20%	60.00	0.10	40%	0.15
Communications	11 dBi patch antenna	L-Com RE11DS-NM	1	30.00	5%	31.50	0.10	15%	0.12
Add rows above this row, do not delete this row									
Total				1,702.00		1,794.60	0.36		0.43
Allocation				2,000.00	0%	2,000.00	0.40	10%	0.44
Propulsion	Cathode		1	10,000.00	15%	11,500.00	1.10	10.00%	1.21
Propulsion	DCF		1	3,250.00	5%	3,412.50	1.60	10.00%	1.76
Propulsion	Stainless Steel Tubing		1	50.00	20%	60.00	0.10	20.00%	0.12
Propulsion	NASA Feed		1	0.00	0%	0.00	0.75	15.00%	0.86
Propulsion	Pressure Relief Valve		1	144.50	10%	158.95	0.22	10.00%	0.24
Propulsion	Tank	Luxfer L45J	1	350.00	5%	367.50	2.95	5.00%	3.10
Propulsion	Tank Adapter		1	200.00	5%	210.00	0.20	5.00%	0.21
Propulsion	Xenon Fuel	AirGas	1	25,500.00	10%	28,050.00	5.10	5%	5.36
Propulsion	Manual Valve	McMaster-Carr; part #7833K999	1	50.00	10%	55.00	0.18	15%	0.21
Propulsion	Solenoid Valve		2	100.00	15%	115.00	0.03	15%	0.03
Add rows above this row, do not delete this row									
Total				39,644.50		43,928.95	12.23		13.09
Allocation				42,000.00	10%	46,124.62	12.50	5%	13.13
Power	Nickel Cadmium Batteries	Rechargeable NiCad 4500 mAh batteries (with tab); HCD-D4500B	20	155.80	0%	155.80	2.32	0%	2.32
Power	Solar Cells	Loral Space Systems (Donated)	416	0.00	15%	0.00	0.29	10%	0.32
Power	Solar Cell Coverglass	Local Space Systems (Donated)	416	0.00	0%	0.00	0.25	10%	0.27
Power	Anode Converter (PPU)	American Power Design DC/DC converter, H150-200	1	290.00	0%	290.00	0.60	0%	0.60
Power	Cathode Keeper Converter (PPU)	Vicor DC/DC converter, V24C36M50BL3	1	90.00	0%	90.00	0.00	0%	0.00
Power	Cathode Heater Converter (PPU)	Vicor DC/DC converter; V24C15M100L3	1	90.00	0%	90.00	0.07	0%	0.07
Power	Cathode Heater DAC (PPU)	Microchip, MCP4821	1	2.30	0%	2.30	0.01		
Power	PPU PCB	Custom board	1	66.00	0%	66.00	0.08	0%	0.08
Power	3.3V Converter (PDU)	TDK Lambda DC/DC Converter, CC25 - 2403SF-E	1	45.00	0%	45.00	0.02	0%	0.02
Power	5V Converter (PDU)	TDK Lambda DC/DC Converter, CC25 - 2405SF-E	1	45.00	0%	45.00	0.02	0%	0.02
Power	PDU PCB	Custom board	1	66.00	0%	66.00	0.04	0%	0.04
Power	MPPT	Have in Lab	1	300.00	0%	300.00	0.60	0%	0.60
Power	FR4 PCB Board	Custom Board; 24"x30"	8	1,088.00	0%	1,088.00	2.38	10%	2.61
Power	¼ inch thick honeycomb aluminum	Alcore Inc.; 20"x25" sheets	4	104.00	0%	104.00	1.24	10%	1.36
Power	Delrin Attachment Point		2	100.00	0%	100.00	0.19	40%	0.26
Power	AF 163-2K 0.045	3M Scotch-Weld	1	463.50	0%	463.50	0.25	5%	0.26
Power	500°F Duralco 128 ceramic-based epoxy	Cotronics Corp.	1	65.00	0%	65.00	0.44	10%	0.48
Power	Tinned Copper Interconnect Ribbon	WindAndSunPower.com; TCR125	1	20.00	10%	22.00	0.01	10%	0.01
Power	Non-acid soldering flux liquid	McMaster-Carr; part #7765A11	1	10.00	10%	11.00	0.00	10%	0.00

9 APPENDICES

9.1 MEL



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Allocation				12,000.00	40%	16,800.00	0.00	0%	0.00
Orbits									
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Total				0.00		0.00	0.00		0.00
Allocation				0.00		0.00	0.00	0%	0.00
Operations	Labor	cost of labor at ground station (free student labor)	0	0.00	0%	0.00	0.00	0%	0.00
Operations	HETE	ground station	1	15,000.00	25%	18,750.00	0.00	0%	0.00
Operations	MIT Control Center		1	6,000.00	25%	7,500.00	0.00	0%	0.00
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Total				21,000.00		26,250.00	0.00		0.00
Allocation				25,000.00	15%	28,750.00	0.00	0%	0.00
ACS	IMU	Analog Devices, solid state gyros, tri- axis ADIS 16355/AMLZ	1	620.00	10%	682.00	0.02	10%	0.02
ACS	Reaction Wheel Assembly	small wheel for roll maneuvers; Sinclair Interplanetary	3	90,000.00	10%	99,000.00	0.68	10%	0.74
ACS	Sun Sensor	SS-411 from Sinclair Interplanetary	4	40,000.00	15%	46,000.00	0.14	15%	0.16
ACS	Torque Coil		3	750.00	20%	900.00	0.75	20%	0.90
ACS	MicoMag 3-axis Magnetometer	SparkFun Electronics; SEN-00244	2	480.00	5%	504.00	0.04	0%	0.04
ACS	Magnet		1	1,000.00	15%	1,150.00	0.25	25%	0.31
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Total				132,850.00		148,236.00	1.88		2.18
Allocation				133,000.00	15%	152,950.00	1.90	15%	2.19
GNC	GPS Receiver	space GPS receiver; SSTL GPS: SGR-05 from Surrey	1	23,010.00	10%	25,311.00	0.02	10%	0.02
GNC	GPS Antenna		1	0.00	10%	0.00	0.01	10%	0.01
Add rows above this row, do not delete this row									
Total				23,010.00		25,311.00	0.03		0.04
Allocation				24,000.00	10%	26,400.00	0.04	10%	0.04
Avionics	1gb NAND flash module	Micron MT29F1G01ZAC, SPI	1	75.00	15%	86.25	0.02	25%	0.03
Avionics	custom PCB (not including dsPIC or CAN chips)	components will mount to this PCB, solder included in MEL	1	156.00	20%	187.20	0.08	20%	0.10
Avionics	dsPIC33FJ256GP802	Expands CPU I/O diversity adding SPI and A2D	3	15.30	10%	16.83	0.06	10%	0.07
Avionics	CAN Level Converter Chips	estimates from digikey, Converts voltages to CAN level from chip outputs	3	4.50	15%	5.18	0.05	15%	0.05
Avionics	Resistors/Capacitors	Surface mount components for PCB	100	5.00	10%	5.50	0.00	20%	0.00
Avionics	Software Liscense		1	1,000.00	10%	1,100.00	0.00		
Add rows above this row, do not delete this row				0.00					
Total				1,255.80		1,400.96	0.21		0.24
Allocation				1,000.00	9%	1,090.44	0.30	5%	0.32
Communications	8dBi patch antenna	L-Com HG2409P-NF	1	22.00	5%	23.10	0.06	15%	0.07
Communications	modems	modem, put in box and mount with bolts; Microhard MHX2420 OEM 2.4 GHz, has built-in voltage and temp sensors	2	1,600.00	5%	1,680.00	0.09	5%	0.10
Communications	cabling and connectors	N-Male - MCX Male; Citrus Cables NPMC100-05	2	50.00	20%	60.00	0.10	40%	0.15
Communications	11 dBi patch antenna	L-Com RE11DS-NM	1	30.00	5%	31.50	0.10	15%	0.12
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Total				1,702.00		1,794.60	0.36		0.43
Allocation				2,000.00	0%	2,000.00	0.40	10%	0.44
Propulsion	Cathode		1	10,000.00	15%	11,500.00	1.10	10.00%	1.21
Propulsion	DCF		1	3,250.00	5%	3,412.50	1.60	10.00%	1.76
Propulsion	Stainless Steel Tubing		1	50.00	20%	60.00	0.10	20.00%	0.12
Propulsion	NASA Feed		1	0.00	0%	0.00	0.75	15.00%	0.86
Propulsion	Pressure Relief Valve		1	144.50	10%	158.95	0.22	10.00%	0.24
Propulsion	Tank	Luxfer L45J	1	350.00	5%	367.50	2.95	5.00%	3.10
Propulsion	Tank Adapter		1	200.00	5%	210.00	0.20	5.00%	0.21
Propulsion	Xenon Fuel	AirGas	1	25,500.00	10%	28,050.00	5.10	5%	5.36
Propulsion	Manual Valve	McMaster-Carr; part #7833K999	1	50.00	10%	55.00	0.18	15%	0.21
Propulsion	Solenoid Valve		2	100.00	15%	115.00	0.03	15%	0.03
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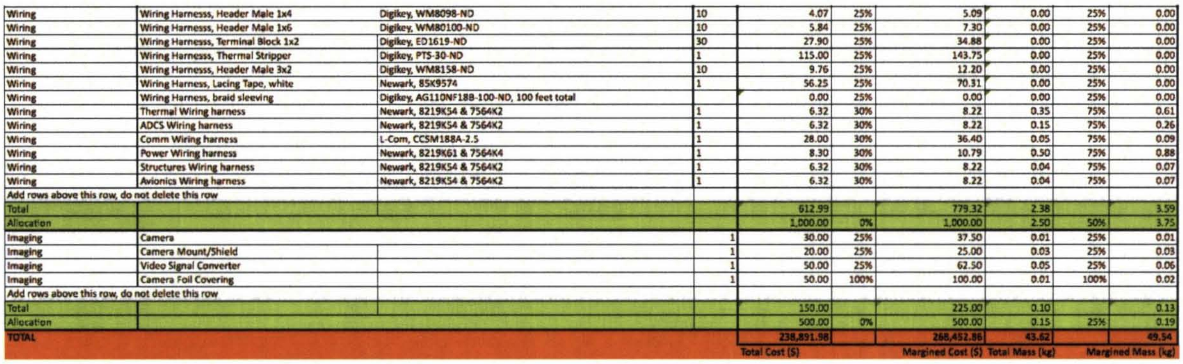
Total				39,644.50		43,928.95	12.23		13.09
Allocation				42,000.00	10%	46,124.62	12.50	5%	13.13
Power	Nickel Cadmium Batteries	Rechargeable NiCad 4500 mAh batteries (with tab); HCD-D4500B	20	155.80	0%	155.80	2.32	0%	2.32
Power	Solar Cells	Loral Space Systems (Donated)	416	0.00	15%	0.00	0.29	10%	0.32
Power	Solar Cell Coverglass	Local Space Systems (Donated)	416	0.00	0%	0.00	0.25	10%	0.27
Power	Anode Converter (PPU)	American Power Design DC/DC converter, H150-200	1	290.00	0%	290.00	0.60	0%	0.60
Power	Cathode Keeper Converter (PPU)	Vicor DC/DC converter, V24C36M50BL3	1	90.00	0%	90.00	0.00	0%	0.00
Power	Cathode Heater Converter (PPU)	Vicor DC/DC converter; V24C15M100L3	1	90.00	0%	90.00	0.07	0%	0.07
Power	Cathode Heater DAC (PPU)	Microchip, MCP4821	1	2.30	0%	2.30	0.01		
Power	PPU PCB	Custom board	1	66.00	0%	66.00	0.08	0%	0.08
Power	3.3V Converter (PDU)	TDK Lambda DC/DC Converter, CC25 - 2403SF-E	1	45.00	0%	45.00	0.02	0%	0.02
Power	5V Converter (PDU)	TDK Lambda DC/DC Converter, CC25 - 2405SF-E	1	45.00	0%	45.00	0.02	0%	0.02
Power	PDU PCB	Custom board	1	66.00	0%	66.00	0.04	0%	0.04
Power	MPPT	Have in Lab	1	300.00	0%	300.00	0.60	0%	0.60
Power	FR4 PCB Board	Custom Board; 24"x30"	8	1,088.00	0%	1,088.00	2.38	10%	2.61
Power	¼ inch thick honeycomb aluminum	Alcore Inc.; 20"x25" sheets	4	104.00	0%	104.00	1.24	10%	1.36
Power	Delrin Attachment Point		2	100.00	0%	100.00	0.19	40%	0.26
Power	AF 163-2K 0.045	3M Scotch-Weld	1	463.50	0%	463.50	0.25	5%	0.26
Power	500°F Duralco 128 ceramic-based epoxy	Cotronics Corp.	1	65.00	0%	65.00	0.44	10%	0.48
Power	Tinned Copper Interconnect Ribbon	WindAndSunPower.com; TCR125	1	20.00	10%	22.00	0.01	10%	0.01
Power	Non-acid soldering flux liquid	McMaster-Carr; part #7765A11	1	10.00	10%	11.00	0.00	10%	0.00



Wiring	Wiring Harnesss, Header Male 1x4	Digikey, WM8098-ND	10	4.07	25%	5.09	0.00	25%	0.00
Wiring	Wiring Harnesss, Header Male 1x6	Digikey, WM80100-ND	10	5.84	25%	7.30	0.00	25%	0.00
Wiring	Wiring Harnesss, Terminal Block 1x2	Digikey, ED1619-ND	30	27.90	25%	34.88	0.00	25%	0.00
Wiring	Wiring Harnesss, Thermal Stripper	Digikey, PTS-30-ND	1	115.00	25%	143.75	0.00	25%	0.00
Wiring	Wiring Harnesss, Header Male 3x2	Digikey, WM8158-ND	10	9.76	25%	12.20	0.00	25%	0.00
Wiring	Wiring Harness, Lacing Tape, white	Newark, 85K9574	1	56.25	25%	70.31	0.00	25%	0.00
Wiring	Wiring Harness, braid sleeving	Digikey, AG110NF18B-100-ND, 100 feet total		0.00	25%	0.00	0.00	25%	0.00
Wiring	Thermal Wiring harness	Newark, 8219K54 & 7564K2	1	6.32	30%	8.22	0.35	75%	0.61
Wiring	ADCS Wiring harness	Newark, 8219K54 & 7564K2	1	6.32	30%	8.22	0.15	75%	0.26
Wiring	Comm Wiring harness	L-Com, CCSM188A-2.5	1	28.00	30%	36.40	0.05	75%	0.09
Wiring	Power Wiring harness	Newark, 8219K61 & 7564K4	1	8.30	30%	10.79	0.50	75%	0.88
Wiring	Structures Wiring harness	Newark, 8219K54 & 7564K2	1	6.32	30%	8.22	0.04	75%	0.07
Wiring	Avionics Wiring harness	Newark, 8219K54 & 7564K2	1	6.32	30%	8.22	0.04	75%	0.07
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Total				612.99		779.32	2.38		3.59
Allocation				1,000.00	0%	1,000.00	2.50	50%	3.75
Imaging	Camera		1	30.00	25%	37.50	0.01	25%	0.01
Imaging	Camera Mount/Shield		1	20.00	25%	25.00	0.03	25%	0.03
Imaging	Video Signal Converter		1	50.00	25%	62.50	0.05	25%	0.06
Imaging	Camera Foil Covering		1	50.00	100%	100.00	0.01	100%	0.02
Add rows above this row, do not delete this row									
Total				150.00		225.00	0.10		0.13
Allocation				500.00	0%	500.00	0.15	25%	0.19
TOTAL				238,891.98		268,452.86	43.62		49.54
				Total Cost ($)		Margined Cost ($)	Total Mass (kg)		Margined Mass (kg)

9.2 RVM

	Mission Statement				**Legend**	
MS.1	The mission of the MIT Nanosatellite (CASTOR) is to validate the performance and application of Diverging Cusped Field Thruster (DCFT) technology and the Xenon Feed System (XFS). This will be achieved by taking on-orbit state data to compare the degradation experienced by the DCFT to that of similar technologies.				Mission Statement	Mission Requirement
	Constraints				Constraint	System Requirement
MC.1	Satellite program and hardware must comply with UNP Requirements				Subsystem Requirement	Requirement NOT met
					Requirement Met	Requirement Met but not verified
	Mission Requirements	**Source**	**Justification**	**Status**		
M.1	Measure the on-orbit performance, efficiency, and degradation of the DCFT during orbital maneuvers	MS.1	Validates the performance and application of the DCFT	🟩		
M.2	Operate the DCFT on orbit for 1500 hours	MS.1	Proves the DCFT lifetime is comparable to similar technologies	🟩		
M.3	Give the Xenon Feed System flight heritage by incorporating it into the propulsion plumbing.	MS.1	Validates the performance and application of the Xenon Feed System	🟩	Verification Source Document	Test/ Analysis Number
	System Requirements: MIT Satellite (CASTOR)					
S1.1	CASTOR shall have a DCFT as the primary propulsion system, which shall operate throughout the mission lifetime	M.1, M.2	A DCFT must be flown to measure and compare its on-orbit performance characteristics to similar thrusters	🟩		
S1.2	The CASTOR bus must be able to support on-orbit mission operations for the mission lifetime of at least 6 months	M.2	Proves the DCFT can function as a propulsion system for small satellite operations. A six month lifetime allows for 1500 hours of engine operations	🟩		
S1.3	CASTOR shall provide sufficient state data to measure the change of performance, efficiency, and degradation over the DCFT's operational lifetime	M.1	Allows the satellite to function for as long as needed to measure DCFT degradation	🟩		
S1.4	CASTOR shall utilize the XFS to perform closed-loop control of flow to thruster.	M.3	XFS is incorporated into the system	🟩		
	CASTOR Propulsion					
S1.1.1	The propulsion system will be the DCFT	S1.1	As per the Mission requirement	🟩	CASTOR Design Document	Design Requirement
S1.1.1.1	DCFT must operate at a minimum of 40 to a nominal 100 Watts of power supplied to the PPU	S1.1.1	The lowest power DCFT will fire is 40 Watts [minimum success mission]. At 165 Watts, DCFT is comparable to other thrusters of similar degradation	🟩	CASTOR Design Document	Integrated PPU test
S1.1.1.2	DCFT components must be operable for full mission lifetime	S1.1.1	The ceramic cone and other DCFT components must survive 1500 hours of operating	🟨	CASTOR Design Document	Simulation
S1.1.1.3	DCFT will undergo cathode conditioning prior to operating	S1.1.1	To clean the engine of debris and contamination	🟨	CASTOR Design	Con-ops

				🟨	Document	
S1.1.1.4	DCFT must remain in a heating or thrusting mode after cathode conditioning	S1.1.1	When not operating, DCFT must be in heating mode. If power is not available for heating, the DCFT will be turned off entirely	🟨	CASTOR Design Document	Con-ops
S1.1.2	The propulsion system will use the XFS as part of its propulsion system.	S1.4	As per the Mission requirement	🟨	CASTOR Design Document	Design Requirement
S1.1.2.1	The XFS which must be able to regulate and vary mass flow to DCFT	S1.1.2	Mass flow to DCFT allows control of electron flow and ionization efficiency. Mass flow to cathode controls current flow, power draw.	🟨	CASTOR Design Document	Feed System Test
S1.1.2.2	The plumbing system on the propulsion system must have a minimum of three electrically controlled mechanical gas flow inhibits	S1.1.2	To ensure that the gas does not vent from the plumbing system	🟨	CASTOR Design Document	Design Requirement
S1.1.2.3	The plumbing system will maintain the pressure below 4000 (TBR) psi.	S1.1.2	For DCFT to function at its highest efficiency, it must maintain a low pressure	🟨	BHC-1500 Operation Manual	DCFT efficiency Test
S1.1.2.4	The fuel in the propulsion system must have a purity of 99.999%	S1.1.2	For DCFT to function at its highest efficiency, it must be fed pure and uncontaminated Xenon	🟨	BHC-1500 Operation Manual	Xe spec sheet
S1.1.3	The propulsion system must output current, voltage, and mass flow data to avionics	S1.3	Requirements for determination of performance and efficiency of DCFT	🟨	CASTOR Design Document	FlatSat V
	CASTOR Imaging					
S1.2.1	The imaging system must be able to take still pictures of the DCFT plume to determine if ionization is occurring	S1.3	Evidence of ionization can be seen in the exhaust plume within a few inches of the DCFT nozzle	🟨	CASTOR Design Document	camera functionality
S1.2.1.1	The imaging system shall be able to take color pictures	S1.2.1	An ionized exhaust plume is blue/purple, while a non ionized plume is red	🟫	CASTOR Design Document	propulsion imaging test
S1.2.1.2	The imaging system shall have a spectral resolution of 200 nm	S1.2.1	The camera must be able to distinguish between red and blue	🟨	CASTOR Design Document	propulsion imaging test
S1.2.1.3	The imaging system shall use a minimum resolution of 320x240 pixels to ensure that there is enough detail for spectral analysis.	S1.2.1	The camera must be able to pick out the plume from other objects in the frame of view	🟫	CASTOR Design Document	Initial camera testing
S1.2.1.4	The imaging system camera must be mounted to the structure and pointed towards the DCFT nozzle to analyze plume shape and color	S1.2.1	Camera must be secured enough and directed correctly to analyze plume	🟨	CASTOR Design Document	Engineering Model
S1.2.1.5	The thruster monitoring camera shall have a field of view between 50° and 70° (diagonally).	S1.2.1	A field of view in this range will allow camera images to capture the cathode, the anode, and a significant portion of the plume.	🟨	CASTOR Design Document	Camera Spec Sheet
S1.2.1.7	The thruster monitoring camera shall be sufficiently protected and kept within spec	S1.2.1	The camera must be working in order to collect data	🟨	CASTOR Design Document	Balloon SHOT (II)
S1.2.1.7.1	The thruster monitoring camera must operate between 3.0 V and 3.6 V, and at 60 mA	S1.2.1.7	C328R-7640 camera specifications	🟫	CASTOR Design Document	camera avionics testing

S1.2.1.7.2	The thruster monitoring camera must operate between -20°C and 60°C	S1.2.1.7	C328R-7640 camera specifications		CASTOR Design Document	Thermal Vacuum Test
S1.2.1.7.3	The thruster monitoring camera shall be sufficiently shielded to survive and operate for 6 months	S1.2.1.7	The camera must provide continuous monitoring of the thruster and thruster plume to obtain a complete performance data set. The high radiation environment around the thruster will tend to degrade the camera and its electronics, so it must be protected.		CASTOR Design Document	Aluminum Degradation Test
S1.2.2	The imaging system must be able to transmit and store image data in avionics system memory	S1.2	Imaging data must be stored so it can be transmitted to ground for study		CASTOR Design Document	FlatSat I/ Camera Avionics
S1.2.2.1	Imaging must be able to interface with the avionics and communications subsystems to transmit stored image data to ground station	S1.2.2	Imaging data must be analyzed on ground		CASTOR Design Document	FlatSat I/ Camera Avionics
S1.2.3	Imaging system must be able to capture images at least once per orbit and store images for up to two weeks	S1.2	Imaging data must be collected regularly to monitor DCFT outflow		CASTOR Design Document	FlatSat I/ Camera Avionics
S1.2.3.1	Imaging must be able to send image data to ground station at least every two weeks	S1.2.3	Image data may only be stored for two weeks, images older than two weeks may not be stored and transferred.		CASTOR Design Document	FlatSat I/ Camera Avionics
	CASTOR Power (EPS)					
S1.3.1	EPS must generate, store, regulate, and distribute power to the spacecraft	S1.1, S1.2	The spacecraft (to include the DCFT) require power to complete the mission		CASTOR Design Document	power FlatSat 1
S1.3.1.1	EPS must provide 85W to DCFT, specifically 16W to the Cathode keeper and 59W to the anode.	S1.1.1	We are not constantly operating the anode. The Cathode Keeper will always be on. This requires that EPS provide 16W.		CASTOR Design Document	power FlatSat 1
S1.3.1.2	EPS must provide sufficient power to run power generation, communications, and status of health monitoring, indefinitely.	S1.3.1	The satellite must be able to operate indefinitely to account for any failures		CASTOR Design Document	power FlatSat 1
S1.3.1.3	EPS must provide 100 W to the PPU while operating and 40 W while heating	S1.3.1	The DCFT requires power to the anode and cathode during different operational states		CASTOR Design Document	power FlatSat 1
S1.3.1.4	EPS must be able to generate 113.7W in a fully operational state.	S1.3.1, S1.3.1.2	All critical systems require 85.91W and batteries require 27.79W to charge		Power Budget	solar panel test
S1.3.1.5	Batteries shall have a capacity of 40Wh to support spacecraft operations over mission lifetime	S1.3.1	Total battery capacity is a consumable, and batteries must be able to store enough energy to run heater and supporting components when in eclipse		CASTOR Design Document	power FlatSat 1
S1.3.1.6	EPS shall regulate bus voltage and distribute power to operate subsystem components	S1.3.1	Different components require different input voltages, so the power must be regulated		CASTOR Design Document	power FlatSat 1
S1.3.2	EPS shall provide state data to determine DCFT state, track DCFT power efficiency, and to monitor bus health	S1.3	EPS data is necessary for monitoring system state and downlinking information for performance analysis		CASTOR Design Document	power/launch FlatSat
S1.3.3	EPS shall be in a safe launch state and shall power on the flight processor after separation	S1.2	Mitigate interference with launch vehicle		UNP User's Guide	power/ launch FlatSat

S1.3.3.1	EPS shall be powered off during launch	S1.3.3	To provide a safe interface with the launch vehicle, the satellite will be powered down at launch	🟨	UNP User's Guide	power/ launch FlatSat
S1.3.3.2	EPS shall provide power to the bus after detaching from Lightband	S1.3.3	Upon separation from the Lightband, the satellite systems must be powered	🟨	CASTOR Design Document	power/ launch FlatSat
S1.3.3.3	The battery shall be launched discharged	S1.3.3	A fully charged battery at launch is a safety concern for the launch vehicle and range	🟨	UNP User's Guide	power/ launch FlatSat
	CASTOR Structures					
S1.4.1	The structure must support interfaces with all subsystems	S1.2	Must use materials that are compatible with thermal requirements; must allow C&DH to control latches and actuators	🟩	CASTOR Design Document	Design Requirement
S1.4.1.1	The structure must provide a means of attachment for all components that does not rely solely on friction	S1.4.1	Every component should be rigidly mounted to the structure	🟩	CASTOR Design Document	Design Requirement
S1.4.1.2	CASTOR components must comply with outgassing, corrosion resistance, and flammability resistance requirements	S1.4.1	Materials must not have excessive outgassing, must not deteriorate, and must not be significantly flammable.	🟨	CASTOR Design Document	Master Materials List
S1.4.2	The satellite structure must survive the launch environment and interface with the LV	S1.2	The structure must be intact after separation	🟩	CASTOR Design Document	Vibration Test
S1.4.2.1	The satellite shall have a natural frequency of at least 100 Hz in each direction	S1.4.2	Designing to be above the natural frequency for all launch vehicles	🟨	CASTOR Design Document	Vibration Test
S1.4.2.2	The satellite shall withstand a load of 20 g's in each direction	S1.4.2	Designing to be above the acceleration loads for all launch vehicles	🟨	CASTOR Design Document	Vibration Test
S1.4.2.3	The CG for the satellite shall be less than 0.5 cm from the Lightband centerline, including manufacturing tolerances	S1.4.2	The CG must be near the Lightband centerline to ensure the satellite behaves predictably during separation	🟩	CASTOR Design Document	Vibration Test
S1.4.2.4	The CG must lie less than 40 cm above the SIP (+Z axis)	S1.4.2	The CG must be near the LV to ensure the satellite behaves predictably during separation	🟩	CASTOR Design Document	Vibration Test
S1.4.2.5	The satellite shall be mounted to the LV interface via a PSC Motorized Lightband system	S1.4.2	The Lightband is the separation mechanism and LV interface identified for use for UNP-6 and CASTOR	🟩	CASTOR Design Document	Vibration Test
S1.4.3	The structure shall support deployable solar panels	S1.2, S1.3.1.3	Body-mounted solar panels do not provide the power required by EPS	🟩	CASTOR Design Document	FlatSat IV
S1.4.4	The satellite structure at launch shall fit into a 50 cm x 50 cm x 60 cm volume, not including Lightband interface	MC.1	UNP User's Guide requirement	🟩	CASTOR Design Document	Design Requirement
S1.4.5	The mass of the satellite shall not exceed 50 kg	MC.1	UNP User's Guide requirement	🟨	CASTOR Mass Budget	CASTOR Mass Budget
S1.4.6	The factor of safety for analysis must be above 2 for yield and 2.6 for ultimate	MC.1	UNP User's Guide requirement	🟨	CASTOR Design Document	Vibration Test

	CASTOR Thermal					
S1.5.1	The satellite must have adequate thermal protection during all mission phases to keep all components within operational temperature ranges	S1.2	Components must keep in certain temperature ranges so that their functionality or structural integrity is not compromised and they can carry our their intended task		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1	CASTOR thermal system will keep components within 2 °C of the upper and lower operating limits during operations, and within 5 °C of survivable limits at all times.	S1.5.1	This gives some leeway		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.1	NiCd Batteries shall operate between (0 to 70) °C, and shall be kept within survival range of (-20 to 75) °C at all times	S1.5.1	NiCd Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.2	MPPT shall operate between (-40 to 60) °C, and shall be kept within survival range of (-45 to 80) °C at all times	S1.5.1	MPPT Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.3	PPU shall operate between (-45 to 85) °C, and shall be kept within survival range of (-45 to 95) °C at all times	S1.5.1	PPU Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.4	PDU shall operate between (-55 to 100) °C, and shall be kept within survival range of (-65 to 110) °C at all times	S1.5.1	PDU Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.5	MEMS IMU shall operate between (-40 to 85) °C, and shall be kept within survival range of (-55 to 85) °C at all times	S1.5.1	MEMS IMU Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.6	Reaction Wheels shall operate between (-20 to 60) °C, and shall be kept within survival range of (-35 to 70) °C at all times	S1.5.1	Reaction Wheel Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.7	GPS unit shall operate between (-20 to 50) °C, and shall be kept within survival range of (-30 to 60) °C at all times	S1.5.1	GPS Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.8	Camera shall operate between (-20 to 60) oC, and shall be kept within survival range of (-35 to 85) oC at all times	S1.5.1	Camera Spec Sheet		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.9	DCFT shall operate between (0 to 200) °C, and shall be kept within survival range of (-50 to 300) °C at all times	S1.5.1	Testing see document		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.1.10	Xenon gas shall remain above (23) °C during DCFT operations	S1.5.1	Nasa requirement		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.2	UNP compliant optical materials (surfaces finishes and insulations) shall be used where possible/necessary to passively control the tank, solar panels, and critical components	S1.5.1			CASTOR Design Document	Master Materials List
S1.5.1.3.1	Thermal models of the satellite shall be supplied to AFRL and at a minimum shall consist of a simplified model that includes nodes for each of the temperature critical components	MC.1	UNP User's Guide		CASTOR Design Document	Thermal Model/T-Vac
S1.5.1.3.4	A list of all payload external surface properties, including area (size), material/process, absorptivity, and emissivity, shall be provided	MC.1	UNP User's Guide		CASTOR Design Document	Master Materials List
S1.5.2	The satellite's components shall be monitored by thermal sensors, which shall interface with the avionics system and be compatible with the available power	S1.2	To monitor component's temperature in order to determine if reorientation is necessary to keep components within specified temperature ranges as well as monitor the status of the DCFT engine		CASTOR Design Document	FlatSat II

S1.5.2.1	The satellite shall have 20 number of thermal sensors consisting of 6 K-type thermocouples and 14 LM19 analog sensors in order to accurately monitor the temperature of components.	S1-2	See Design Doc.		CASTOR Design Document	Design Requirement
S1.5.2.1.3	All Thermal Hardware on the satellite shall be calibrated for an accuracy to +/- 2 oC degrees.	S1-2			CASTOR Design Document	FlatSat II
S1.5.2.1.4	All Thermal Hardware on the satellite shall take readings every 120 seconds.	S1-2	This will ensure that the temps are in the specified ranges. This will be sent down to the ground station.		CASTOR Design Document	FlatSat II
S1.5.2.2	Thermal readings shall be provided to the ground station from the satellite every 90 minutes.	S1-2	needed for analysis purposes		CASTOR Design Document	FlatSat I
	CASTOR ADCS					
S1.6.1	ADCS shall provide pointing knowledge to distinguish DCFT efficiency changes from pointing errors, to allow for attitude control, and to enable effective communications with the ground station. Objective: 1 degree, Threshold: 5 degrees	S1.3, S1.10.3	The orientation of the engine firing angle with respect to the body and inertial space must be known to account for loss of delta-V efficiency; there is less than 0.4% error for 5 degree of knowledge. Additionally, sensing must be finer than control authority and communication system requires attitude knowledge		CASTOR Design Document	ADCS Simulation/Magnetometer Test/ Reaction Wheels Test/ FlatSat III/ GPS Test
S1.6.1.1	ADCS sensors shall provide position data to processor. Objective: 1Hz, Threshold: 0.2Hz	S1.6.1	Sensing in control loop must be fast enough in order to meet pointing requirements		CASTOR Design Document	FlatSat III
S1.6.2	ADCS shall provide 3-axis attitude control authority to enable proper pointing of the body, solar arrays, and engine. Objective: 5 degree, Threshold: 25 degrees	S-2, S-3	Control affects solar panel output and operational predictability and safety, 25 degrees pointing represents less than a 10% loss in power generation or thrust direction		CASTOR Design Document	Torque Coils Test/ Reaction Wheels Test
S1.6.2.1	ADCS shall be able to slew 18 deg/min	S1.6.2	The DCFT will not be operating in eclipse and the worst case orientation is 180 degrees. To ensure the thrust is in the proper direction, the satellite must be able to be pointed in the correct orientation within 10 minutes		CASTOR Design Document	tested using reaction wheel models and air bearing
S1.6.2.2	ADCS shall have sufficient components to store and manage angular momentum	S1.6.2	In order to have proper control throughout the lifetime of CASTOR, angular momentum must be managed by the ACS		CASTOR Design Document	Torque Coils Test/ Reaction Wheels Test
S1.6.2.3	The ADCS subsystem shall apply net forces to the spacecraft under 10^{-3} N.	S1.6.2	Minimize disturbance to GNC and engine system		CASTOR Design Document	ADCS Simulation/Magnetometer Test/ Reaction Wheels Test/ FlatSat III/ GPS Test
S1.6.2.4	ADCS actuators shall follow a commanded torque from processor. Objective: 1Hz, Threshold: 0.2Hz	S1.6.2	Actuator must be commanded fast enough in order to meet pointing requirements		CASTOR Design Document	FlatSat III

S1.6.3	ADCS components must comply with material and structural requirements	S1.4.1.2	ADCS components will meet or exceed mass and power minimum requirements. Physical interfaces will be verified.		CASTOR Design Document	Vibration Test/Master Material List
S1.6.3.1	ADCS components must comply with requirements for outgassing, corrosion resistance, and flammability resistance	S1.4.1.2	Materials must not have excessive outgassing		CASTOR Design Document	Master Materials List
S1.6.3.2	ADCS components must meet UNP vibration requirements	S1.4.1.2	ADCS components must not cause or be damaged during launch		CASTOR Design Document	Vibration Test
S1.6.3.3	ADCS components must minimize power usage	S1.6.2	In order to meet mission requirements, ADCS power must be conserved and minimized		CASTOR Design Document	engineering model testing
	CASTOR GNC					
S1.7.1	CASTOR shall have on-orbit GNC knowledge to manage DCFT operations and measure real-time position and velocity	S1.2	GNC information is necessary for autonomous commanding of thrusting times and desired engine pointing vector, and gives data on the change in the orbit		CASTOR Design Document	FlatSat III/GPS Test/ IMU test
S1.7.1.1	GNC system shall be able to have on-orbit positioning knowledge within 1km while operating DCFT	S1.7.1	Accurate positioning knowledge		CASTOR Design Document	GPS Test
S1.7.1.2	GNC system shall be able to have velocity knowledge within 10 m/s while operating DCFT	S1.3, S1.7.1	Accurate velocity knowledge and sensing orbital changes		CASTOR Design Document	IMU Test
S.1.7.2	GNC system shall provide orbital state data to the avionics system to manage communications and determine the sun angle	S1.2	Satellite must know when it is over the ground station to initiate communications and the position of the sun is necessary for power generation		CASTOR Design Document	FlatSat III
	CASTOR Avionics					
S1.8.1	Avionics system shall provide the necessary data interfaces to support all subsystems	S1.2	Satellite requires operational controls		CASTOR Design Document	FlatSat X
S1.8.1.1	Avionics will continually monitor the propulsion system to ensure that the thruster does not spuriously activate	S1.8.1	Sensor data required for accurate determination of satellite state.		CASTOR Design Document	FlatSat II
S1.8.1.2	Avionics will run the propulsion system's engine firing logic twice per orbit.	S1.8.1	Engine firing control required to keep stable orbit.		CASTOR Design Document	FlatSat III
S1.8.1.3	Avionics will interface with the ADCS subsystem to execute a Kalman Filter using sensor data to accurately determine the satellite state and implement a PD control law for state corrections at a frequency of 1 Hz.	S1.8.1	Attitude control necessary for propulsion and imaging to operate as required.		CASTOR Design Document	FlatSat IV
S1.8.1.4	Avionics will provide the computation necessary for navigation control through the use of GPS data collection and an SGP4 Propagator at a frequency of 1 Hz.	S1.8.1	Interface crucial for accurate determination of satellite position.		CASTOR Design Document	FlatSat IV
S1.8.1.5	The Avionics subsystem shall interface with the communications subsystem to send and receive data when communications capabilities are available.	S1.8.1	Data must be downlinked from the DCFT and it must be possible for commands to be uplinked to the satellite.		CASTOR Design Document	FlatSat I
S1.8.1.5.1	In order for communications to occur the Avionics system will packetize, send, and verify that all data is sent and received.	S1.8.1.5	It is critical to ensure that data is not lost in the communications channel		CASTOR Design Document	FlatSat I

S1.8.1.6	Avionics will provide the interface for power systems to monitor critical power levels and execute fail safes if necessary at a frequency of 4 Hz.	S1.8.1	Avionics will provide the control logic to ensure that power is properly distributed around the satellite	🟨	CASTOR Design Document	FlatSat III
S1.8.1.7	Avionics will interface with the imaging device to facilitate the capture and storage of images.	S1.8.1	Images of the DCFT plume will be used to verify proper operation of the thruster, avionics will be in charge of ensuring that the imaging system accomplishes this	🟨	CASTOR Design Document	FlatSat II
S1.8.1.7.1	Avionics will be capable of capturing and storing at least 1 image per orbit without overriding the data for 2 weeks.	S1.8.1	The avionics must be robust enough to store the imaging data through an elongated period without communicating with the ground station	🟨	CASTOR Design Document	FlatSat II
S1.8.2	Avionics system shall provide the computing power and data storage capacity to process and store all necessary state data.	S1.2, S1.3	The computing power is necessary for ACS/GNC and general system tasks, and data storage is necessary for downlinking desired state data	🟨	CASTOR Design Document	FlatSat x
S1.8.2.1	The avionics system's processors must be able to handle all of the calculations required to run all subsystems in real time.	S1.8.2	Three dsPIC's are necessary for load balancing and redundancy.	🟨	CASTOR Design Document	FlatSat x
S1.8.2.2	There will be enough flash memory available for storage of critical data and operational code.	S1.8.2	1 GB of flash memory used for storage of large data sets and images. Onboard memory used for transient storage of data.	🟨	CASTOR Design Document	FlatSat x
S1.8.3	Avionics system shall be fault tolerant and able to recover from SEU failure.	S1.2	Satellite will be flying in LEO and be subject to radiation	🟨	CASTOR Design Document	SEU test
S1.8.3.1	SEU failures shall be detected by checksums of the memory and storage to determine data integrity at a frequency of 0.01 Hz.	S1.8.3	Checksums can detect discrepancies caused by SEU failures.	🟨	CASTOR Design Document	SEU test
S1.8.3.2	Through reprogramming or rebooting the avionics system shall be able to recover from an SEU fault in under 1 minute from the time of detection.	S1.8.3	It is critical that the avionics system be able to quickly recover after a SEU.	🟨	CASTOR Design Document	SEU test
S1.8.4	Avionics system shall retain programming and state when unpowered	S1.2	Satellite must be able to power on after being powered off for storage and launch	🟩	UNP User's Guide	Datasheet
S1.8.5	Avionics system shall permit software updates for upgrading running software and recovering from SEU faults.	S1.2	Software needs to be replaced or changed to allow for upgrades	🟨	CASTOR Design Document	avionics FlatSat
	CASTOR Software					
S1.9.1	Software shall be capable of performing a cold startup, self-test, and establish a comm link	S1.2	Satellite hardware must be activated after separation from the launch vehicle	🟨	CASTOR Design Document	avionics FlatSat
S1.9.2	Software shall support communications, operations, scheduling, and health monitoring	S1.2	Software is necessary for managing all system tasks, to include engine operations, attitude, data storage, and communications	🟨	CASTOR Design Document	FlatSat x
S1.9.2.1	Software will have access to enough memory to support all operations	S1.9.2	Adequate memory (both RAM and Mass Storage) will be provided to the avionics software to support all operations.	🟨	CASTOR Design Document	FlatSat x

S1.9.2.2	Software shall integrate ADCS/GNC data to perform estimation and control	S1.2, S1.9.2	The engine should be pointed before being fired and the satellite should know its location for operations scheduling	🟨	CASTOR Design Document	ACS FlatSat
S1.9.2.2.1	Software will implement a Kalman filter to perform estimation necessary and implement a PD control law to establish control of the vehicle for ADCS.	S1.9.2.2	Attitude control necessary for propulsion and imaging to operate as required.	🟨	CASTOR Design Document	ACS FlatSat
S1.9.2.2.2	Software will process GPS data and implement an SPG4 propagator to provide GNC estimation.	S1.9.2.2	Crucial for accurate determination of satellite position.	🟨	CASTOR Design Document	ACS FlatSat
S1.9.2.3	Software shall interface with the DCFT/PPU	S1.1, S1.9.2	The engine must be controlled in software since it requires complex timings and feedback for verification	🟨	CASTOR Design Document	FlatSat II
S1.9.2.4	Communications support will include storing data, packetizing data, and ensuring the integrity of the data received by the ground station.	S1.9.2	Communications with the ground station is vital for mission success, so that image data can be downlinked and commands uplinked	🟩	CASTOR Design Document	FlatSat I
S1.9.2.5	Software shall execute the processes necessary to collect sensor data to ensure the necessary information is available for all subsystem operations.	S1.9.2	Maintaining health data for all subsystems is critical to ensuring proper functionality of the satellite	🟨	CASTOR Design Document	FlatSat II
S1.9.2.6	Software will use a RTOS to implement the scheduling of all processes required by satellite subsystems to ensure accurate timing constraints are met.	S1.9.2	The strict scheduling requirements of the spacecraft require the use of a RTOS for timing purposes	🟨	CASTOR Design Document	software test
S1.9.2.7	Software will implement continual checksums of available memory to monitor for SEU faults and other errors in operations.	S1.9.2	To avoid errors due to SEUs, the Avionics software will continually be looking out for errors	🟨	CASTOR Design Document	SEU Test
S1.9.3	Software should provide the ability to reprogram the flight computers	S1.8.3	Software needs to be replaced in the event of SEU or errors	🟨	CASTOR Design Document	software test
S.1.10	**CASTOR Communications**					
S.1.10.1	The communications subsystem shall provide the ability to transmit commands from the ground station to the satellite.	S1.2	Ground station must be able to command and control the satellite	🟩	FlatSat1 Result Document	FlatSat I/Antenna Testing
S1.10.1.1	The communications subsystem shall be equipped with a dish and a modem at the ground station.	S1.10.1	Minimum equipment necessary to perform the functionality required by 1.10.1	🟩	CASTOR Design Document	Design Requirement
S1.10.1.2	The communications subsystem shall provide the ability for the satellite to receive commands from the ground station.	S1.10.1	Ground station must be able to command and control the satellite	🟩	FlatSat1 Result Document	FlatSat I/ Antenna Testing
S1.10.1.2.1	The communications subsystem shall be equipped with at least one antenna and one modem on the satellite.	S1.10.1.2	Minimum equipment necessary to perform the functionality required by 1.10.1.2	🟩	Castor Design Document	Design Requirement
S1.10.2	The communications system shall be able to establish a robust and periodic link	S1.2	Ground station contact with HETE only lasts for 8-12 minutes per pass and communications interruptions must be handled gracefully	🟨	CASTOR Design Document	FlatSat I

S1.10.2.1	The communications subsystem shall recognize correct packets from incorrect packets and be able to request retransmission if the packet is faulty.	S1.10.2	In order to request retransmission and to avoid the execution of wrong commands	🟨	CASTOR Design Document	FlatSat I
S1.10.2.1.1	The link layer protocol, from the modem, shall be able to recognize correct packets from incorrect packets and be able to request retransmission if the packet is faulty.	S1.10.2.1	Derived from 1.10.2.1	🟩	CASTOR Design Document FlatSat1 Result Document	FlatSat I
S1.10.2.1.2	The upper layer protocol, from the software on the satellite and ground station, shall be able to recognize correct packets from incorrect packets and be able to request retransmission if the packet is faulty.	S1.10.2.1	Derived from 1.10.2.1	🟨	CASTOR Design Document	FlatSat I
S1.10.2.2	The satellite shall be able to receive a set-up ACK from the ground station and start a communications link	S1.10.2	The ground station will start the communication session, but the satellite has to be able to react and to start transmitting data	🟩	CASTOR Design Document , FlatSat 1 Result Document	FlatSat I
S1.10.2.2.1	The modem shall be able to wake up from sleeping mode when commanded to so as to start a communications link.	S1.10.2	Modem will be in sleep mode(for power reasons) until the system is ready to communicate	🟨	CASTOR Design Document	FlatSat I
S1.10.2.3	The communications subsystem shall be able to store packets to prevent overflow.	S1.10.2	The communication sessions will be limited up to a maximum of 30 minutes per day, hence packets need to be stored before the transmission	🟨	CASTOR Design Document	FlatSat I
S1.10.2.3.1	The communications protocol shall be able to set up packet queues on the satellite and the ground station.	S1.10.2.3	Derived from 1.10.2.3	🟨	CASTOR Design Document	FlatSat I
S1.10.2.4	The communications subsystem shall be able to identify missing packets and out of order packets.	S1.10.2	Especially for telemetry and commands, both ground station and satellite need to recognize if some piece of the transmission have been lost, in order to ask for retransmission	🟨	CASTOR Design Document	FlatSat I
S1.10.2.4.1	The communications protocol shall be able to identify missing packets and out of order packets.	S1.10.2.4	Derived from 1.10.2.4	🟨	CASTOR Design Document	FlatSat I
S1.10.3	The communications subsystem shall be able to support a bandwidth and data rate necessary to transmit all telemetry (67bps) and pictures (2 per orbit 640*480 pixels).	S1.3	Series of complete pictures necessary for measurement of engine degradation. Engine operation verification at the ground station requires sufficient system health data as well as detecting problems	🟩	CASTOR Design Document	Design Requirement
S1.10.4	The communications subsystem shall be fully redundant	S1.2	To counteract loss of coverage or single element failure which can cause loss of mission	🟩	CASTOR Design Document	Design Requirement
S1.10.4.1	The communications subsystem shall be equipped with 2 antennas	S1.10.4	Derived from previous requirement	🟩	CASTOR Design Document	Design Requirement
S1.10.4.2	The communications subsystem shall be equipped with 2 modems	S1.10.4	Derived from previous requirement	🟩	CASTOR Design Document	Design Requirement
	CASTOR Ground					

S2-1	Ground must be able to control the satellite	M.1, M.2	Ground-based command necessary to schedule engine firing and problem recovery		Con-Ops Document& Castor Design Document	FlatSat x
S2-2	Ground must be able monitor satellite performance and efficiency	M.2	Comparing operational data to simulation permits verification of the validity of our models		Con-Ops Document	FlatSat I
	CASTOR Ground Communications and Operations					
S2.1.1	Ground shall provide the capability to communicate with the satellite	S2-1	To control the satellite, ground station must establish communications with the satellite		CASTOR Design Document	FlatSat I/ Antenna Testing
S2.1.2	Ground should provide the functionality to upload new programs to the satellite	S2-1	Software upload capability requirement comes from the requirement of the avionics to be reprogrammable in-flight		CASTOR Design Document	FlatSat I
S2.1.3	Ground should implement closed loop ACK on commands	S2-1	Operational control requires full, lossless upload of command data		CASTOR Design Document	FlatSat I
S2.1.4	Ground shall have the ability to identify errors in pictures and request retransmit	S2-1	Images of engine firing must be usable for engine degradation analysis		CASTOR Design Document	FlatSat I
S2.1.5	Ground must be manned by qualified staff while in communications with CASTOR	S2-2	An operator must be on hand to interpret satellite data, issue commands, and debug problems		CASTOR Design Document	License
S2.1.6	Ground must be able to simulate the satellite and predict future state	S2-2	Simulation permits verification that DCFT performance meets expectations		CASTOR Design Document	FlatSat x
	CASTOR Mobile Ground Support Equipment					
S2.2.1	CASTOR shall have a battery charging and monitoring devices	MC.1	UNP User's Guide			
S2.2.6	Maintain class 100,000 clean conditions	MC.1	UNP User's Guide			
S2.2.7	Provide electrostatic discharge (ESD) protection to the satellite	MC.1	UNP User's Guide			
S2.2.8	Have a means for grounding the container from an external grounding point before opening container	MC.1	UNP User's Guide			
S2.2.9	Enable Shipping both with and without the Planetary Systems Corporation (PSC) Lightband integrated to the nanosatellite.	MC.1	UNP User's Guide			
S2.2.10	Measure the shock environment experienced by the satellite during shipping through the use of shock sensors in all 3 axes.	MC.1	UNP User's Guide			
S2.2.11	Must function with inhibited satellite system	MC.1	UNP User's Guide			
S2.2.12	Must provide power to the satellite while it is inhibited	MC.1	UNP User's Guide			
S2.2.13	Must charge/discharge batteries while inhibited	MC.1	UNP User's Guide			
S2.2.14	Must support subsystem functional testing	MC.1	UNP User's Guide			
S2.2.15	Must have fully protected circuitry and communications	MC.1	UNP User's Guide			
S2.2.2	CASTOR shall have a transportation case	MC.1	UNP User's Guide			

S2.2.2.1	The transportation case must be portable	MC.1	UNP User's Guide			
S2.2.3	CASTOR shall have a lifting harness	MC.1	UNP User's Guide			
S2.2.3.1	Castor shall have a lifting harnesses designed to lift the nanosatellite from a single point above its center of gravity, in every orientation except upside down (+-X, +-Y, +Z)	MC.1	UNP User's Guide			
S2.2.3.2	Castor shall have lifting equipment that is designed such that it will not contact the Lightband during integration and ground handling operations	MC.1	UNP User's Guide			
S2.2.3.3	Lifting Harness shall be shipped in the shipping container	MC.1	UNP User's Guide			
S2.2.3.4	Lifting Harness shall engage the 4 trusses of the satellite.	MC.1	UNP User's Guide			
S2.2.4	Castor shall have Tabletop MGSE stands that are able to support the nanosatellite with, without, and with only half of the Lightband	MC.1	UNP User's Guide			
S2.2.5	CASTOR's MGSE shall be designed using a factor of safety of 5.0 for ultimate failure, and be proof loaded to twice the design load	MC.1	UNP User's Guide			

9.3 COST PROJECTION THROUGH SUMMER 2010

Sub-team	ITEM DESCRIPTION	ESTIMATED COST
ADCS	Torque Coil	$225.00
ADCS	Sun Sensor	$90.00
ADCS	Microprocessor	$105.00
Avionics	Camera x2	$500.00
Avionics	DSC Board	$150.00
Comm	Antennas	$200.00
Power	Lambdas Converters	$400.00
Power	PCB for new PXU	$132.00
Power	Other Inverter expenses	$150.00
Power	Solar Cell Test Boards	$660.00
Power	Solar Panel Electrical Construction Items	$100.00
Power	NiCd Battery Charging Chips and Test Boards	$170.00
Power	MPPT components/new one	$450.00
Power	Test Batteries (possibly different types)	$500.00
Power	Miscilaneous Parts and Components	$450.00
Propulsion	Flow Controllers (X2)	$1,400.00
Software	GPS Simulator (Terrestrial)	$100.00
Software	Miscellaneous Electronics for Ground Station (heavy margin)	$500.00
Structures	SEM Aluminum	$850.00
Structures	SEM Fasteners	$400.00
Structures	Machining- Tank Clamps (Material,	$750.00
Thermal	Thermal Sensors	$100.00
Thermal	Thermocouples	$300.00
Thermal	Thermalcouple control board	$100.00
Thermal	Test Materials	$200.00
Thermal	Surface Finishes	$200.00
Thermal	Software	$300.00
Integrated Systems	Lincoln Laboratory Test Campaign	$4,500.00
	TOTAL:	**$13,982.00**
	Additional: Clean Room and Electronics Room Tools	$2,500.00

9.4 RISK ASSESSMENT MATRIX

ADCS	Category	Component	Failure Mode	Description	Dependencies
2-01	Hardware	GPS	GPS Failure	GPS provides incorrect position data or no position data	Power (or converter) Failure
2-02	Hardware	Sun Sensor	Sun Sensor Single Failure	One Sun Sensor provides incorrect sun position or no sun position	Power (or converter) Failure
2-05	Hardware	IMU	IMU Rate Sensor	Rate Sensor provides incorrect rate data or no rate data	Power (or converter) Failure
2-06	Hardware	Magnetometer	Magnetometer	Magnetometer provides incorrect magnetic field information or no magnetic field information	Power (or converter) Failure
2-07	Operational	Reaction Wheel	Reaction Wheel Single Failure	One Reaction Wheel fails to operate properly	Power (or converter) Failure
2-10	Hardware	Torque Coil	Torque Coil Single Failure	One Torque Coil does not provide expected magnetic dipole, or provides no magnetic dipole	Power (or converter) Failure
2-13	Hardware	Wiring Harness	ADCS Wiring Harness	Incorrect wiring that leads to any of the issues mentioned above	avionics malfunction
2-14	Hardware	Sun Sensor	Sun sensor output failure	Outputs only one or two angle instead of three	interface malfunction

2-15	Software	Magnetometer	Magnetometer Miscalibration	Magnetometer readings do not match expected values from IGRF Model	control law avionics
2-16	Software	Torque Coil	Torque Coil Polarity Inversion	Torque coils provide opposite torque than expected	control law, avionics
2-17	Software	Software	General Software Errors	Software errors that lead to any of the issues mentioned above	control law, avionics

Continuation of ADCS Risks

ADCS	**Mitigation**	**Diagnostic**	**Repair**	**Backup**	**TRL**	**Severity**	**Likelihood**	**Risk Level**	**Date**	**Updated By**
2-01	Satellite orbital position can be found by propagating TLEs	thorough testing	None	TLR		2	2	low	4/9/2010	Danielle DeLatte
2-02	Thorough testing and evaluation of sun sensor functionality and interface design	thorough testing	none	other sun sensors	8	2	2	low	4/9/2010	Danielle DeLatte
2-05	Functionality testing and interface testing IMU is not necessary for measuring attitude but it provides more assurance This is a redundant system	no readings	none	GPS, sun sensors		2	2	low	4/9/2010	Danielle DeLatte
2-06	Functionality testing interface testing and calibration against a known magnetic field	no readings	none	sun sensors IMU GPS		4	2	MED	4/9/2010	Danielle DeLatte

2-07	Functionality testing and interface testing If a single wheel fails, required slew maneuvers can be completed over longer period of time using the torque coils	no readings	none	torque coils can control attitude but it's very slow		3	2	MED	4/9/2010	Danielle DeLatte
2-10	Thorough testing and evaluation of torque coil functionality and interface design If one torque coil fails the other two coils will be able to provide enough torque to desaturate the reaction wheels in an extended period of time	no readings	none	rely on other two		3	3	MED	4/9/2010	Danielle DeLatte
2-13	Individual and integrated wiring tests to ensure expected functionality Avionics in charge of this	thorough testing	none	avionics		4	2	MED	4/9/2010	Danielle DeLatte

2-14	140° field of view having more helps but is not necessary	thorough testing	software patch, control algorithm	available angles sufficient		2	2	low	4/9/2010	Danielle DeLatte
2-15	Careful calibration of magnetometer If calibration is off can be recalibrated on orbit	error exception	recalibrated in orbit	software patch recalibrated in orbit		2	2	low	4/9/2010	Danielle DeLatte
2-16	Dipole testing before and after integration If polarity is reversed can be corrected on orbit	error exception	software patch	software patch		2	2	low	4/9/2010	Danielle DeLatte
2-17	Thorough software testing before and after integration If problems arise in software, new versions can be uploaded on orbit	error exception	software patch	software patch		3	3	MED	4/9/2010	Danielle DeLatte

Avionics	Category	Component	Failure Mode	Description	Dependencies
3-01	Operational/Design	PIC	PIC Failure	PIC hardware failure	
3-02	Operational	PIC SEU	PIC SEU	Ions/Radiation causes a transistor to flip	
3-03	Design	PIC Communications	Inter PIC Communications	PIC communications failure	Software/Hardware implementation error
3-04	Design	PIC Deadlock	RTOS Software Deadlock	Multiple threads lock waiting for eachother s signals	ThreadX software implementation error
3-05	Operational	Wires	Wire separation	Wire connections fail during operation	Wiring harnesses breaks Solder connections fail
3-06	Operational	Memory	Memory corruption	Data in memory becomes corrupted	Data stored in memory becomes unreliable
3-07	Design	Memory	Memory overflow	Data buildup over time without deletion	Data not correctly offloaded when appropriate
3-08	Operational	PIC	Invalid command	Incorrect/unusable commands are sent to avionics hardware	Incorrect software implementation
3-09	Operational	Avionics Board	Environmental Damage	Thermal/Vibrational/etc damage to avionics equipment	Heat/Vibration reach beyond controllable levels

Avionics	**Mitigation**	**Diagnostic**	**Repair**	**Backup**	**TRL**	**Severity**	**Likelihood**	**Risk Level**	**Date**	**Updated By**
3-01		PIC fails to respond	hardware reset	Redundant PICs	9	4	1	MED	3/15/2010	Steven Gomez
3-02	Radiation hard components chosen	Software checksums	Software reset		8	2	3	MED	3/15/2010	Steven Gomez
3-03	Robust inter communication interface redundant data channels	Impossible messages received		backup simple data bus	5	3	1	low	3/15/2010	Steven Gomez
3-04	Software implementation designed to avoid deadlocks	Software recognize	Software recovery	Software reset	4	3	1	low	3/15/2010	Steven Gomez
3-05	Care in construction and design of wire connections					4	1	MED	3/15/2010	Steven Gomez
3-06		Data checksums	Deletion of unreliable data			1	3	low	3/15/2010	Steven Gomez
3-07	Ensure data is off loaded correctly in testing	Memory Full	Deletion of unnecessary data			1	2	low	3/15/2010	Steven Gomez
3-08	Enforce strict and clear API for commanding avionics	Hardware Interrupts		disregard further commands from offending		2	2	low	3/15/2010	Steven Gomez

	hardware			process						
3-09	pre build testing	Failure to operate				4	1	MED	3/15/2010	Steven Gomez

Comm	Category	Component	Failure Mode	Description	Dependencies
4-01	Design	Antenna	Single patch antenna on outside before deployment	If the new patch antenna configuration is used before deployment there will only be one operational antenna on the outside hence there will be no redundancy Still can communicate but less opportunity to communicate	failure to deploy solar panels
4-02	Hardware	Antenna	Antenna switching fails(look at previous risk)	System is set up to switch between antennas depending on which one provides a better communications link	
4-03	Hardware	Interfacing	Interference between components	There could be interference on the communications subsystem due to other components of the satellite	
4-04	Hardware	11 dBi Antenna	Plastic antenna cover damaged	Plastic cover of antenna might be damaged in space which could make the antenna inside perform sub optimally	Debris from another satellite component or space dust harsh launch environment
4-05	Hardware	8 dBi Antenna	Plastic antenna cover damaged	Plastic cover of antenna might be damaged in space which could make the antenna inside perform sub optimally	Debris from another satellite component or space dust harsh launch environment
4-06	Hardware	Wires	Connections failure	A connection between antenna modem or a PIC could fail	bad manufacturing
4-07	Hardware	Modems	Modem damaged	Modem could be short circuited	bad manufacturing, improper hardware integration

4-08	Hardware	Modems	2 Modems damaged/fail	Both Modems could be short circuited	two modem failures or combination of modem and wire failures,

Communications continued

Comm	Mitigation	Diagnostic	Repair	Backup	TRL	Severity	Likelihood	Risk Level	Date	Updated By
4-01	A possible solution is to put a 6dBi antenna on the outside however this would require a switch between the 2 antennas A 3dB loss would be incurred but the link budget would remain fine				3	3	3	MED	3/15/2010	Michael Munoz
4-02	There is no way to overcome the failure of the switching mechanism however it is safer than having no switch and no second antenna to solve the previous risk	more corrupt packets, higher occurrence of signal loss	reset from ground		3	3	3	MED	3/30/2010	Michael Munoz
4-03	An EMI test will be performed to model and characterize the interference due to other components				2	unknown	1	#VALUE!	3/30/2010	Michael Munoz
4-04	Testing will be done at MIT Lincoln Lab on the antennas without their plastic covers to analyze their performance				5	1	1	low	3/30/2010	Michael Munoz

4-05	Testing will be done at MIT Lincoln Lab on the antennas without their plastic covers to analyze their performance				5	1	1	low	3/30/2010	Michael Munoz
4-06	Need to verify that the different connections between antennas modems and PICs are all strong and in a position where the connection cannot be lost	send commands	none	redundancy	3	3	1	low	3/30/2010	Michael Munoz
4-07	Need to ensure that the board where the modem will be placed on is properly designed to avoid such possibilities	send commands	none	redundancy	3	3	2	MED	3/30/2010	Michael Munoz
4-08	careful manufacturing & testing	no incoming data or response		redundancy	3	4	2	MED	3/30/2010	Michael Munoz

Propulsion	Category	Component	Failure Mode	Description	Dependencies
5-01	Hardware	NASA PCS	feed system failure	xenon is not fed at the rate expected	none
5-02	Hardware	NASA PCS	feed adjustment failure	cannot adjust the mass flow of xenon to the thruster	none
5-03	Hardware	Cathode	cathode poisoned	if not conditioned properly cathode material may be irreparably damaged	conditioning procedure not followed
5-04	Hardware	Cathode	keeper/heater failure	if the keeper or heater does not maintain the cathode at the appropriate temperature the conditioning procedure must be repeated or the thruster cannot be fired without risking damage to the cathode	none if failure is in subcomponent power system failure could fail to deliver requisite power to heater/keeper
5-05	Hardware	Anode	anode material degradation	after long periods of operation anode material will slowly degrade will eventually cease to operate	none
5-06	Hardware	Anode	no power to anode	with no power to anode no potential across thruster and thus thruster will not operate	power system failure
5-07	Hardware	Plumbing System	electrical inhibit failure	one or more electrical inhibits fails to open	power system failure or failure in the components themselves

5-08	Hardware	Plumbing System	tank adapter failure	faulty tank adapter could allow xenon to leak	none

Propulsion continued

Propulsion	**Mitigation**	**Severity**	**Likelihood**	**Risk Level**	**Date**	**Updated By**
5-01	during XFS integration testing will test to ensure feed system works as expected If system fails on orbit thruster will still operate as long as some minimum amount of Xenon is delivered to the thruster	3	2	MED	3/26/2020	Keith Loebner
5-02	same as above	3	2	MED	3/26/2010	Keith Loebner
5-03	Conditioning procedure has been tested repeatedly and is effective If cathode is poisoned it is unlikely that it will be able to operate at all leading to mission failure	5	1	MED	3/26/2010	Keith Loebner
5-04	will test heater/keeper functionality during thruster testing, and try to mitigate possible power failures during integration testing with PPU	4	2	MED	3/26/2010	Keith Loebner
5-05	normal part of DCFT operation, will not affect mission during expected lifetime	1	1	low	3/26/2010	Keith Loebner

5-06	with no power, thruster cannot operate, but can operate on reduced power by firing for less time	4	2	MED	3/26/2010	Keith Loebner
5-07	will test inhibits during integration testing but on orbit failure would end mission if xenon flow to thruster cannot be initiated	4	1	MED	3/26/2010	Keith Loebner
5-08	will test component to try to guarantee space-worthiness if it does leak it will shorten mission lifetime but a small leak should still allow DCFT testing on orbit	3	1	low	3/26/2010	Keith Loebner

Power	Category	Component	Failure Mode	Description	Dependencies
6-01	Operational	Anode	High voltage from anode couples into system		
6-02	Operational	Batteries	Batteries get memory	Memory degrades in time, Less power storage capability as time goes on	
6-03	Operational	PPU 200 Voltage Converter	Voltage converter fails	All components that get power from converter can't get power, Anode failure	short circuited
6-04	Operational	PPU 15 Voltage Converter	Voltage converter fails	heater for propulsive heater fails	short circuited
6-05	Operational	PDU 3 3 Voltage Converter	Voltage converter fails	All components that get power from converter can't get power, avionic board, thermal sensors & thermal sensors	short circuited
6-06	Operational	PDU 5 Voltage Converter	Voltage converter fails	ADCS except torque coils (don't need converter, comm modem, linear actuator for deployment	short circuited
6-07	Operational	Wires	Wire becomes disconnected	that component will fail	
6-08	Operational	Solar Panels	Solar panels do not point at the sun	reduced power input	ADCS failure or deployment

					failure
6-09	Operational	MPPT	MPPT fails	Tracks max power in solar panels, distributes to components while charging batteries	
6-10	Operational	Battery Charging Circuit	Charger fails to turn off	batteries overcharge and stop working	
6-11	Operational	Solar Panels	Solar cell breaks, strand of cells becomes inoperational		

Power continued

Power	Mitigation	Diagnostic	Repair	Backup	TRL	Severity	Likelihood	Risk Level	Date	Updated
6-01	isolated					4	1	MED	4/9/2010	Manal Habib
6-02	testing, planned cycle change for improve performance, chosen battery for high performance during first year		go through max-charge and deep discharge cycle			1	3	low	4/9/2010	Manal Habib
6-03	testing careful manufacturing	component failed/ no power			4	4	2	MED	4/9/2010	Manal Habib
6-04	testing careful manufacturing	component failed/ no power			4	4	2	MED	4/9/2010	Manal Habib

6-05	testing careful manufacturing	component failed/ no power			6	4	2	MED	4/9/2010	Manal Habib
6-06	testing careful manufacturing	component failed/ no power			6	3	2	MED	4/9/2010	Manal Habib
6-07						3	2	MED	4/9/2010	Manal Habib
6-08						3	2	MED	4/9/2010	Manal Habib
6-09	testing add charging circuit to improve performance	no power to all components				4	2	MED	4/9/2010	Manal Habib
6-10	careful manufacturing and testing	no power to batteries		yes		4	2	MED	4/9/2010	Manal Habib
6-11						3	2	MED	4/9/2010	Manal Habib

Thermal	Category	Component	Failure Mode	Description	Dependencies
7-01	Operational	Thermal Sensor	Sensor Failure	no data	connection breaks
7-02	Operational	Thermal Sensor	Erroneous Sensor Data	data from one sensor is noticibly different from another	one of sensor failure, software failure, power failure calibration error
7-03	Operational	Component	Component Outside Temperature Range	Componenet exceeds operational temp range	none

Thermal	Mitigation	Diagnostic	Repair	Backup	TRL	Severity	Likelihood	Risk Level	Date	Updated
7-01	careful transport	no temperature data	Replace/Repair Sensor	spares on hold other sensors on satellite	9	2	2	low	3/14/2010	George Sondecker
7-02	careful transport	erroneous temperature data	Replace/Repair Sensor	spares on hold other sensors on	9	3	2	MED	3/14/2010	George Sondecker
7-03	turn off/on high-power consumption units	temp sensor	None	none	N/A	4	2	MED	3/14/2010	George Sondecker

Structures	Category	Component	Failure Mode	Description	Dependencies
8-01	Transport	Solar Panels	Cracking	Cover glass cracks during transport/launch	None
8-02	Operational	Solar Panels	Deployment Failure	Linear actuator fail to operate or the panels become impinged on deployment mechanism	Manufacturing failure linear actuator failure, or power to release mechanism failure
8-03	Manufacturing	Solar Panels	Buckling	Panel crushes near bolts	None
8-04	Operational	Fastener	Fastener breaks	Bolt nut, insert failure during launch could significantly damage the launch vehicle and payloads	Structural failure
8-05	Operational	Member	member failure	Excessive yielding or fracture during launch could significantly damage the launch vehicle and payloads	Structural failure
8-06	Operational	Pressure Vessel	vessel ruptures	Rupture or rapid depressurization of the Xenon tank	Burst disk fails to operate

Structures continued

Structures	Mitigation	Diagnostic	Repair	Backup	TRL	Severity	Likelihood	Risk Level	Date	Updated By
8-01	careful transport, plexiglass standoffs	visual inspection	replace cells	spares on hold	9	2	4	MED	3/14/2010	George Sondecker

8-02	Build & Test Prototype release mechanisms, outward-facing panels modify duty cycle is occurs to mitigate adverse effects	low power	try sending power to actuators again	none	5	3	3	MED	3/14/2010	George Sondecker
8-03	Use inserts in panels	visible test	replace panel	none	6	3	1	low	3/14/2010	George Sondecker
8-04	Installing certified, NAS rated fasteners torqued to NASA specified values on Flight Model	vibe test	replace hardware	spares on hold	9	4	2	MED	3/14/2010	George Sondecker
8-05	Conducted hand calculations, finite element modeling and vibrational tests to ensure structure meets g loading and vibe requirements Certified aluminum stock will be used on the flight model	vibe test	replace structure	remake part	9	4	2	MED	3/14/2010	George Sondecker
8-06	Tank will be loaded below its max rated pressure Burst disks on tank prevent catastrophic failure	thruster does not operate	replace tank	none	9	3	2	MED	3/14/2010	George Sondecker

Sci/Pay	Category	Component	Failure Mode	Description	Dependencies
9-01	Operational	C328 Camera Lens	Lens Degradation	Lens degrades due to ion bombardment from thruster	Accelerated if shutter failure (open) occurs

9-02	Operational	C328 Module	Overheat	Module overheats due to solar radiation	
9-03	Operational	Shutter	Shutter Failure	Shutter either stays closed or stays open	
9-04	Transport	C328 Camera	Misalignment	Camera misaligns with shutter opening	

Science & Payload continued

Sci/Pay	**Mitigation**	**Diagnostic**	**Repair**	**Backup**	**TRL**	**Severity**	**Likelihood**	**Risk Level**	**Date**	**Updated**
9-01	Protection via aluminum shield box shutter	Blurry image				4	3	MED	3/15/2010	Adriel Fidone
9-02	Heat is dispersed through truss	Improper Functionality				3	2	MED	3/15/2010	Adriel Fidone
9-03	Extensive shutter testing careful handling	No visible image or Blurry image				3	2	MED	3/15/2010	Adriel Fidone
9-04	Careful transportation, securely fastened	Images of shield box				3	2	MED	3/15/2010	Adriel Fidone

April 23, 2010

9.5 SCHEDULE