Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

APTERA
System Architecture White Paper

9/28/07

Document History

Release	Date	Description	Name
Initial	9/28/07	White Paper	Jim Dotterweich & Laura Bush

Approval

Title	Name	Signature	Date
Customer			
Advisor #1			
Advisor #2			
CC			

1.0 Information

1.1 APTERA- (Aerobraking Project to Effectively Reduce Altitude)

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2.0 System Architecture

The DANDE (Drag and Atmospheric Neutral Density Explorer) satellite is designed to measure scientific parameters in the upper atmosphere of the Earth. It is being created within the Air Force Research Laboratory's (AFRL) NanoSat competition. The atmospheric data collected by DANDE will give a better understanding of the upper region of the atmosphere. However, the DANDE satellite is a secondary payload and as a result will be launched to a much higher altitude than desired for the data collection. The DANDE satellite is being designed to have a year and half life span. The launch to a higher altitude and short life span creates a need for a drag system. The drag system must be designed to feasibly reduce the altitude of DANDE from the launch altitude of approximately 600 km to 350 km, in a time frame of 300 days. APTERA is a fold out drag device that could be integrated with the DANDE satellite in response to this requirement. The below sections will describe how the fold out drag system architecture was selected.

2.1 Preliminary Design – Design Options

There were five main design options considered. Each of these and why there were or were not chosen is described in the following paragraphs.

On initial inspection, an inflatable drag device seems like viable design architecture. There has been a fair amount of research into inflatable space structures in general. Additionally, inflatable devices have been analyzed for producing drag, but mostly at altitudes lower than our project would use. In this situation, the device is known as a "ballute", the cross between a balloon and a parachute. An inflatable structure would be relatively lightweight and easy to deploy. For our system, a torus shaped balloon would likely be deployed around the base of the DANDE sphere. Another advantage of a ballute is that because it has depth, unlike a very thin sail, it will continue to produce some drag in non optimal orientations. These advantages, however, are meaningless without a way to inflate the device. Due to the AFRL requirements, pressurized gas cannot be used. Airbags, which inflate by mixing dry chemicals, use black powder which certainly would fail the AFRL requirements as well.

Thrust was also considered. This included mass ejection, chemical reaction, the use of a propeller, or ion thrusters. Mass ejection was eliminated due to the small mass allotment from DANDE; 1.2 kg is not enough to produce a sufficient momentum change within a reasonable ejection velocity. The use of chemicals to create thrust was eliminated due to the AFRL requirements which do not allow volatile chemicals to be used in the University NanoSat program. Propellers are not feasible as their use at altitudes above 25km has not been studied. Ion thrusters are an excellent option for space propulsion with specific impulse, Isp, between 2000 and 5000 seconds. The thrust range of 0.5 to 10 mN could produce the necessary drag to lower DANDE's orbit. Additionally, verification of performance only requires a vacuum chamber. While these thrusters can be made as small as 4cm, the lightest mass found of 2kg is far beyond the mass budget.

A tether design consists of a long wire that extends out behind the spacecraft, creating drag. A tether has flight heritage, is available off the shelf, and can be easily integrated with the supplied interface; it can be built nearly independently of other parts of the system due to its simplicity and ability to use. The design is also very lightweight. The primary drawback to this design is that it is impossible to test on Earth with the resources available to the DANDE drag team. Further, modeling the behavior of a long tether in space is beyond the knowledge base of the team. Previous papers suggest that modeling a tethered system is surprisingly hard due to the complex atmospheric interactions in the ionosphere.

The next design type considered was a kite-like structure. Instead of attaching a sail type drag device directly to the DANDE satellite, it would be attached by a cable and trail behind the satellite. The possible benefits of this type of device are reduced shading of the solar panels and a possible increase in stability of the spacecraft. The stability would be increased if the distance between the center of mass and center of pressure was increased. This design also increases the effects of gravity gradient torque that may have a negative effect on the stability of the system. The kite design is a possible option that can meet the safety and design requirements; however the design and implementation of this complex system would be extremely difficult for a team with low skill levels. The reason for the complexity is difficulty in modeling the different vibration modes that would occur in the cable(s) attaching the kite to the light ring.

An attached folded drag device describes a device that is in close proximity to the spacecraft and deployed by some mechanical means to present an acceptable drag area that would complete the mission. This design will use a deployment mechanism to expand rigid structural supports that open the material chosen for the drag area. This design concept can be relatively complex and problems with stowing rigid structures might cause problems with meeting stow size requirements for the drag device along with mass requirements. While in close proximity to DANDE it also has the possibility of blocking the solar cells which provide the spacecraft with power, the amount of solar cells it is allowed to block is yet to be determined. However, the dynamics of rigid structures is known by the team and faculty resources in this area of study are available.

2.2 Preliminary Design – Top level structure trade study

Trade Study Parameters
A trade study was conducted for 5 different design concepts using the following criteria. A scale from 1 to 5 was used to rank the design concept in each area, in which a value of 1 is undesirable, and a value of 5 means that the design meets the criteria. Each category was also given a multiplier which determined its weight in comparison to the other categories. They were ranked from 1 to 3, where 3 is more important and 1 is less important.

AFRL
This category ranks the design to how well it complies with Air Force Research Laboratory requirements. Anything pressurized, combustive, or dangerous to the interfacing vehicles is highly discouraged. Although waivers may be applied for, having materials or systems that are highly discouraged would introduce more risk. Higher values in this category mean that the system would meet all the AFRL nano-satellite requirements. (Weight = 3)

Modeling
This category ranks how well the effects of drag on this system could be modeled. Factors that would increase the rank include if it has been modeled before, if there is existing information on the system, and if there is information about the atmospheric effects on the system. A lower rank means that the system has not been accurately modeled and it would be unreasonably difficult for APTERA to complete an accurate model during 2 semesters. (Weight = 2)

Time
This factor questions if it is feasible to design, build and test the system during the senior projects timeline. A high value in this category means that the concept has been used successfully in the past, there are resources to help us, and that we are confident in our ability to complete the project within the set timeline. A low value means that the concept is still in its preliminary stages, it would be challenging to get help or find resources, and that the design would not fit the senior projects timeline. (Weight = 2)

Number of Cycles
This category ranks how well the system can undergo repeat testing without decreasing its accuracy or reliability. It is undesirable to have a device which requires a part that must be replaced every 20 tries, or a device that cannot be tested at all. (Weight = 2)

DANDE Risk
This category ranks how well the device, APTERA, can interface to DANDE without endangering DANDE. A high rank in the category means that the system meets the mass, size and power requirements.
(Weight = 3)

Resiliency
A low value in this category means that the device has a high risk of being easily harmed, either during building or testing. (Weight = 1)

Large Facilities
This category questions if the device will require facilities that are not easily accessible. A high ranking value in this area means that the APTERA team will be able to easily find the testing facilities at a reasonable cost. (Weight = 1)

Table 1. Preliminary trade study of attached design

	Trade Criteria (Weight)							
Design Concept	**AFRL** (3)	**Modeling** (2)	**Time** (2)	**# Cycles** (2)	**DANDE Risk** (3)	**Resiliency** (1)	**Large Facilities** (1)	**Total Rank**
Inflatable	2	3	5	3	4	2	3	45
Thrust	1	5	5	4	1	5	5	44
Tether	5	2	2	1	5	3	5	48
Kites	5	1	1	2	4	4	3	42
Fold Out	5	3	5	4	4	5	3	59

Based on research, the fold out design was selected. In particular the designs that scored well but failed the AFRL requirements or were beyond the modeling capability of this team were eliminated. The fold out design meets the AFRL requirements if the proper materials are selected; this would qualify the system to fly with DANDE.

2.3 Top Level to Subsystem Architecture

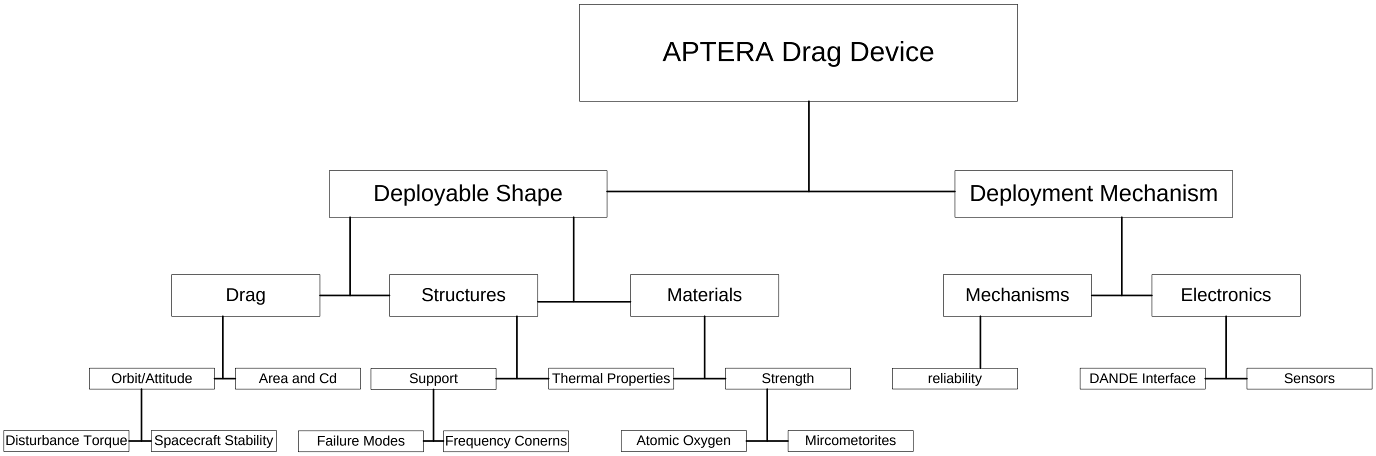

Figure 1: APTERA System Architecture Breakdown

The top level flow down of the design in figure 1 stems from the needs of the drag device. The drag device was then broken down into two basic systems the deployment shape, and the deployment mechanism. The deployment shape is described by the subsystems below:

- Drag- the amount of force needed to lower the satellite to the desired altitude
- Structures- provides the interface to DANDE satellite and structural support to the drag device
- Materials- materials used in each component to survive space environment conditions

The deployment mechanism subsystems are given below:

- Mechanisms- a reliable device that will release the drag structure
- Electronics- provides the interface to DANDE satellite and senses status of deployment device

The top level flow down in figure 1 is an initial break down of the major subsystems. A consideration for the next revision is to examine the importance of a thermodynamics subsystem instead of a thermal component under each of the current subsystems. As the flow down diagram is revised, the subsystems are subject to change.

3.0 Requirements

Table 1: Top-Level Project Requirements

Requirement	Description	Parent Requirement	Verification Method
0.PRJ.1	The device shall adhere to the safety standards set forth by the Air Force's Research Laboratory Space Vehicles Directorate (Nanosat-5 User's Guide: University Nanosat-5 Program).	Air Force Research Laboratory Space Vehicles Directorate.	Inspection by customer.
0.PRJ.2	The drag device shall receive commands and output telemetry.	Customer's system requirements.	Electrical mock-up testing.
0.PRJ.3	The developed drag device shall fit within the dimensional, mass, and power constraints prescribed by the DANDE satellite.	Customer's system requirements.	Inspection.
0.PRJ.4	The device shall be able to survive the extremes of the space environment experienced throughout the duration of the DANDE mission.	Customer's system requirements.	Thermal vacuum and shake table testing.
0.PRJ.5	The DANDE drag device shall theoretically produce the required amount of force to lower the DANDE satellite from 600 km to 350 km within 300 days as demonstrated by the DANDE STK modeling with MSISE-00.	Customer's science requirements.	Analytical modeling as prescribed by customer.
0.PRJ.6	The device shall deploy in the atmosphere at the University of Colorado Engineering Center.	Customer's mission requirements.	Demonstration.

Table 2: Top-Level System Requirements

Requirement	Description	Parent Requirement	Verification Method
0.SYS.1	The system, design and testing shall all be done in English units.	0.PRJ.1	Inspection and quality control.
0.SYS.2	Use of non-metallic materials shall have a maximum collectable volatile condensable material (CVCM) content of 0.1 %, and a total mass loss (TML) of no more than 1.0 %.	0.PRJ.1	Inspection based on NASA specifications found at (http://outgassing.nasa.gov).
0.SYS.3	The drag device shall contain no pyrotechnics.	0.PRJ.1	Inspection.
0.SYS.4	The device shall have a mass of no more than 1.2 kg (2.65 lbm).	0.PRJ.3	Direct weight measurement.
0.SYS.5	The device shall have stowed dimensions not exceeding 23.6" by	0.PRJ.3	Geometric dimensioning and tolerancing (likely via a

	23.6” by 2” in the plane of the Light Ring and accommodate the bottom of the spacecraft.		prebuilt crate).
0.SYS.6	The device shall be able to connect to the main power supply of the DANDE spacecraft and require no greater than 15 W of power at 12 V.	0.PRJ.3	Electrical testing of integration with the DANDE satellite and demonstration.
0.SYS.7	The drag device shall be operable between -40 and 212°F.	0.PRJ.4	Testing by thermal cycling.
0.SYS.8	The drag device shall be able to withstand the launch vehicle environment without premature deployment or structural failure.	0.PRJ.4	Vibration testing.
0.SYS.9	The drag device shall deploy from a folded state to a state where it produces satellite drag.	0.PRJ.6	Repeated deployment mechanism testing and demonstration.

3.1 Fold Out

3.1.1 Pros

- Relative ease of modeling
- Ability to demonstrate deployment
- Resilient to problems during deployment
- On campus resources should be easy to find

3.1.2 Cons

- Will need large facilities for testing

3.1.3 Important Requirements

- 0.PRJ.3
- 0.PRJ.6
- 0.SYS.9

3.2 Tether

3.2.1 Pros

- Relatively large amount of work has been done
- May be able to produce a very large amount of drag

3.2.2 Cons

- Nearly impossible to test with our available facilities
- Nearly impossible to correctly model with our available skills

3.2.3 Important Requirements

- 0.PRJ.6
- 0.SYS.8
- 0.SYS.9

3.3 Inflatable

3.3.1 Pros

- Should be able to find on-campus resources for this design
- Variability of shapes and designs
- Possible weight savings

3.3.2 Cons

- Need for inflation mechanism, may not meet AFRL requirement
- Not particularly resilient, may be harmed during testing/development
- Will need large facilities for testing

3.3.3 Important Requirements

- 0.PRJ.1
- 0.PRJ.4
- 0.SYS.8

3.4 Thrust

3.4.1 Pros

- Long heritage design, it is just a low power thruster
- Available off the shelf

3.4.2 Cons

- Very unlikely to meet the AFRL requirement
- May not meet mass requirements

3.4.3 Important Requirements

- 0.PRJ.1
- 0.PRJ.3
- 0.SYS.2
- 0.SYS.6

3.5 Kite

3.5.1 Pros

- May provide increase in control
- Essentially the same as the fold out design, just attached differently

3.5.2 Cons

- Needs large testing facilities
- Would be nearly impossible to design with current skill level due to perturbation modes and required stiffness of the attachment tethers
- Can not be tested very many times due to complexity
- Would require active control of the deployable

3.5.3 Important Requirements

- 0.PRJ.6
- 0.SYS.5
- 0.SYS.8
- 0.SYS.9

3.6 System Rankings

3.6.1 Foldout

Most likely to meet requirements, easy to model, test, and verify.

3.6.2 Tether

The most attractive option if a way to test it in Boulder could be found, easiest to build and integrate.

3.6.3 Inflatable

The inflatable is attractive due to its ability to be retested and customizability of design; however, it is unlikely to fulfill Air Force requirements and has a relatively high likelihood of being critically damaged during testing.

3.6.4 Thrust

An ion thruster is easy to model, but almost guaranteed to violate Air Force requirements and has a likelihood of violating mass and power requirements.

3.6.5 Kite

Tying a drag device down produces numerous modeling problems that are beyond the scope of senior projects, it cannot be modeled correctly and will be hard to test.

4.0 Feasibility

The foldout device was chosen as the most feasible design option since it most easily fulfills the project requirements. One of the main project requirements (0.PRJ.1), the Air Force safety requirement, is important to meet since any system that does not fall within these requirements will not be chosen to fly as a secondary payload. The foldable drag concept meets this requirement because if designed correctly a fold out rigid structure does not violate the main Air Force safety concerns such as including pyrotechnics, compressed gases, or composites. There are concerns with early deployment while in the launch phase due to vibration shock to the payload. A fold out device does have a risk of deploying early but rigorous design and testing should mitigate this issue. The construction of a fold out device should not be a major technological hurdle as well.

Another reason this foldable device was chosen is that the drag device is based on a rigid structure that presents a drag surface which is better understood by the members of the team. In addition there is faculty support in this area of study. This was not the case with the tether which would be extremely difficult to model the electromagnetic drag force and possible vibration modes that would affect DANDE's flight path. The large planform area of a deployed sail is easier to model and the dynamic equations that control the drag across this surface at this area are better understood. While the atmospheric changes of the Earth at the 600km to 350km are extremely variable it is possible to set the extreme bounds for changes in density and model the possible drag in this region given a frontal area. This modeling of this drag is requirement that must be met as given by (0.PRJ.5), and basic modeling can be seen below:

$$\Delta a = -2\pi C_D \frac{A}{m} \rho a^2 \tag{1}$$

This equation calculates the change in the semimajor axis per orbit. Using this equation iteratively with a detailed empirical density model of the atmosphere, the amount of orbits to change the altitude can be calculated. This modeling is only used to determine the surface area of the drag device, and is not a verification method for the overall design.

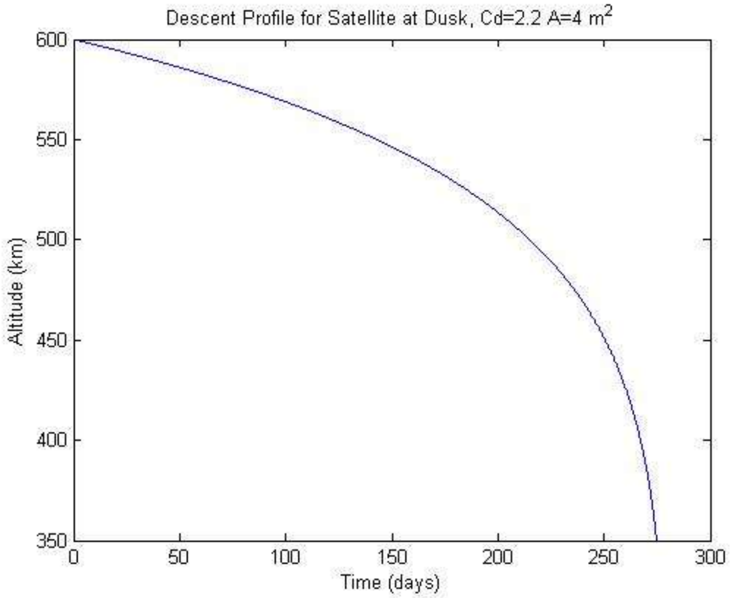

Figure 2: Satellite Descent Profile

Figure 2 shows the descent for DANDE calculated using equation 1. As seen from this graph, a descent time of about 275 days can be obtained with a surface area of 4 square meters. This is under our requirement of a modeled 300 day descent, and thus proves the overall feasibility of this design.

In addition to being technically feasible, APTERA matches well with the requirements of the senior projects course. In particular, APTERA would be a technological innovation because a drag device has never been used before to lower a satellite in Earth orbit before in this fashion.

5.0 Testing and Verification

APTERA will need to be tested and verified per AFRL University NanoSat Program requirements. In order to determine the survivability of the drag system, APTERA will undergo deployment testing, thermal cycling, thermal vacuum testing, impulse testing, and vibration testing. Also, an interface test will be conducted between APTERA and DANDE.

5.1 Deployment Testing

The deployment testing will include all the stages of structural testing. These tests will be conducted at the University of Colorado at Boulder campus. The first tests will test the deployment mechanism by itself, without any structural components. The next stage will be the deployment mechanism with the support structure. Then the remaining drag system material will be added to the structure and deployment mechanism, and the deployment of the entire device will be tested.

The tests will be considered successful if the deployment mechanism functions according to specifications and there is no damage to the structure or material.

5.2 Thermal Cycle Testing

The thermal cycle test consists of subjecting the entire system to a range of temperatures (-40°C to 100°C conservative, -20°C to 60°C minimum). The temperature will be monitored throughout the test using sensors at various critical locations. This may be done separately from thermal vacuum testing in order to determine the system’s response to the range of temperatures. Deployment testing will follow thermal cycling.

This test will be considered successful if the system completes thermal cycling while meeting subsystem thermal requirements. Also, deployment testing following thermal cycling must be successful as defined in 5.1.

5.3 Thermal Vacuum Testing

The thermal vacuum test will consist of thermal cycling the system in a reduced pressure environment, similar to expected atmospheric conditions between 600km and 350km. The temperature will vary as described in 5.2. This test will be useful in understanding how the system will respond in a vacuum environment. Deployment testing will follow thermal vacuum testing.

This test will be considered successful if the system completes thermal vacuum testing while meeting subsystem thermal requirements. Also, deployment testing following thermal vacuum testing must be successful as defined in 5.1.

5.4 Impulse Testing

The impulse test will examine the system’s response to various impulses (values TBD). An impulse hammer, which has a load cell on the tip, will be used to provide the impulse to the system, and sensors at various locations will provide data on the response. Also, visual inspection will be conducted to see if any shifts occur after the impulse. Impulse testing will occur at each structural stage. Deployment testing will then follow each impulse test. The CU ITLL has an available impulse hammer.

The impulse test will be successful if there are no visible shifts during inspection, and if deployment test is successful as defined in 5.1.

5.5 Vibration Testing

The vibration test will determine the system’s response to input vibrations, such as will be encountered during launch. According to AFRL, the system must be able to handle 20g acceleration in each axis. The ITLL Short Stroke Shaker has a maximum force of 50lb, which limits the mass. Therefore, it may be necessary to build a replacement mounting plate that will be less massive, and to test to a lower load. The DANDE satellite will be going through vibration testing at Ball Aerospace on their engineering model in late January. It may be possible to interface an engineering model of APTERA to the satellite and analyze the drag device with the DANDE satellite. Deployment testing will follow the vibration test.

This test will be considered successful if the system stays within the required frequency and amplitude limits (TBD). Also, visual inspection will determine if the system remained properly stowed. Deployment testing following vibration testing must be successful as defined in 5.1.

5.6 Interface Testing

The interface test is necessary to ensure that the drag device will physically and electrically connect to the DANDE satellite. This will be an inspection done using the DANDE mock up and the final APTERA.

This test will be successful if the physical and electrical connections fit properly.

6.0 Risks

6.1 Testing Facilities (0.RSK.1)

6.1.1 To thoroughly verify the design will require thermal vacuum and vibration testing as well as thermal modeling. Significant testing and verification can be difficult on the Earth's surface for space technology.

6.1.2 Effort will be made early in the project to secure access to the necessary testing facilities. A conservative thermal cycle from -40°C to 100°C could be performed in Bioserve's freezer (-80°C) and a boiling water bath, or an oven to (100°C). We can modify the ITL shaker table to accommodate our experiment to simulate the AFRL 100Hz frequency requirement.

6.2 Deployment Mechanism (0.RSK.2)

6.2.1 The DANDE drag device needs a reliable deployment mechanism. An off-the-shelf space rated mechanism may cost more than the project budget, so cost is a risk to our project.

6.2.2 Research various deployment mechanisms, borrow a device to use for testing, raise additional funds, and work with Space Grant's resources.

6.3 Materials (0.RSK.3)

6.3.1 Due to the mass requirements and performance in space, it may be difficult to acquire the materials necessary to construct the drag device. The ideal materials may not exist yet.

6.3.2 If necessary, lower performance materials could be used for prototyping.

Table 3: Risk Analysis

Risk	Description	Mitigation
0.RSK.1	Testing and Verification	Early Reservation & CU Facilities
0.RSK.2	Deployment Mechanism	Fundraising & Borrowing
0.RSK.3	Materials	Lower Performance if Necessary

7.0 Team Qualifications

Table 4: Team Qualifications

Technical Area	Team Member Responsible	Level of Expertise
Structures	**Melina**	Mechanical Design- LASP
	Zach	Mechanical Design- CSGC, Keck
	Amanda	Mechanical Design- CSGC
	Jim	F.I.R.S.T Robotics
Mechanisms	**Anna**	F.I.R.S.T Robotics, Management
	Jake	Research/ Engineering DLC Apprentice
	Amanda	Mechanical Design- CSGC
	Jay	ADCS Subsystem Design
Electronics/ Software	**Matt**	Basic Circuit Design and Construction
	Zach	Circuit Design Characterization and Implementation
	Jay	CSCI Minor
Drag/ Atmosphere	**Laura**	Astronomy Minor, LASP
	Patty	Interest, Coursework
	Matt	ADCS- CSGC

8.0 Response to PDD feedback from PAB

Table 5: Response to PDD Feedback

PAB Comment	Response
limiting to "non-composite" materials odd	The Air Force Research Laboratory requirements document for the NanoSat program strongly advises against any use of composite structural material. To simplify the acceptance of our hardware we are requiring that it not use composite structural materials.
You must define the goal of the senior design project which is limited in time	We will add the time limit to the goal.
The “demonstration of integration with DANDE” will be done, but how if the sub-bullets are not your job?	The “sub-bullets are not sub-bullets; they are separate from Demonstration of Integration with DANDE, not part of it.
The device shall deploy under what conditions?	This requirement will be updated as our system is better defined. We now know that we will have a fold out structure, so the requirement will change to: “The device shall deploy to at least 90% of its total possible drag area” when we define a minimum size for the drag area.
What is your parameter range for vibration testing?	See section 5.5.

9.0 Resources and References

9.1 Facilities

Table 6: Facilities

Facility	Comment
Thermal Cycling	This testing may be conducted in a variety of locations. BioServe has a freezer which goes down to -80^{o}C. This may be available to us, pending contact with BioServe. Another option is to use dry ice to cool the drag device. Heaters can be used to test the upper range.
Thermal Vacuum Chamber	If we meet LASP's clean requirements, we can conduct thermal vacuum testing in their facilities. LASP: CU Boulder Research Park Contact: Ginger Drake (303-492-5899)

9.2 References

Clements, Jared. "NanoSat-5 User's Guide". February 2007

Wertz, James R., Larson, Wiley J., Space Mission Analysis and Design 1999 Microcosm Inc. & W.J. Larson

Gloyer, Paul; Jacobovits, Aaron; Guerrero, Jim; Wilmoth, Richard. "Aerobraking Technology for Earth Orbit Transfers" 16th Annual/USU Conference on Small Satellites, Paper SSC02-VII-2

10.0 Acknowledgements

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10.3 Graduate Students

None

10.4 Undergraduate Students

None

10.5 Others

None

A. Appendices