Design Proposal for a CubeSat Based Solar Sail Testing Platform

Submitted to:  Dr. Wallace Fowler

In Response to Request for Proposal: ASE 274L/174M

Submitted by: Phillip Hempel
Daniel Parcher
Paul Mears
Taffy Tingley

October 2, 2001
Executive Summary

Objectives

To design a 10cm sided cubic picosatellite for the purposes of solar sail testing while maintaining compliance with the Stanford sponsored CubeSat program. This objective will be carried out in the following manner:

- Determine the size and material of the solar sail to be used.
- Design a picosatellite capable housing the solar sail.
- Determine necessary packing configuration of the sail.
- Determine the impact that the packing configuration has on the sail’s efficiency.
- Design the necessary deployment apparatus
- Design apparatus for identifying the orientation and position of the satellite.
- Create an orbital trajectory simulation for the satellite design

Design Restrictions Adopted

- The satellite will have no attitude control
- The satellite will have no communication systems
- The satellite will require no power in addition to the power requirements prescribed by the CubeSat program
- Position, velocity and orientation will be performed from ground stations by analyzing light reflected from corner cube reflectors on the solar sail.

Deliverables

Upon completion of this project, PaperSat will have delivered a feasible design for a picosatellite capable of solar sail testing. The design will enable the determination of thrust and efficiency of a solar sail through orbital trajectory analysis.

Proposed Budget

<table>
<thead>
<tr>
<th>Expense Item</th>
<th>Predicted Expense (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel (based on an estimated 150 hrs. worked, 14 hrs. for consultants)</td>
<td>15,653</td>
</tr>
<tr>
<td>Materials / Electronics</td>
<td>5,000</td>
</tr>
<tr>
<td>Testing</td>
<td>2,000</td>
</tr>
<tr>
<td>Launch</td>
<td>50,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>72,653</strong></td>
</tr>
</tbody>
</table>

Team Members

Phillip Hempel – Mechanical Specialist  Paul Mears – Orbit Trajectory Specialist
# Table of Contents

Executive Summary ............................................................................................................... i  
Table of Tables ................................................................................................................... iv  
1.0 Introduction ................................................................................................................... 1  
   1.1 Problem statement ..................................................................................................... 1  
   1.2 Purpose ..................................................................................................................... 2  
2.0 Design Methodology .................................................................................................... 3  
3.0 Design Factors ............................................................................................................. 4  
   3.1 Design Criteria ........................................................................................................ 4  
   3.2 Design Restrictions ................................................................................................. 5  
4.0 Candidate Solutions .................................................................................................... 6  
5.0 Deliverables ................................................................................................................... 9  
   2.1 Mid-Contract ....................................................................................................... 9  
   2.2 End of Contract .................................................................................................. 9  
6.0 Project Schedule .......................................................................................................... 11  
7.0 Management Organization .......................................................................................... 12  
   7.1 Company Management Structure ....................................................................... 12  
   7.2 Design Conflict Resolution Procedure ............................................................... 14  
8.0 Proposed Budget ......................................................................................................... 15  
   8.1 Personnel Budget Description ............................................................................. 15  
   8.2 Material and Electronics Budget Description ...................................................... 15  
   8.3 Testing Budget Description ................................................................................. 15  
   8.4 Launch Budget Description ................................................................................. 16  
   8.5 Budget Summary ................................................................................................. 16  
9.0 Conclusion .................................................................................................................... 18  
10.0 Literature Survey ........................................................................................................ 19  

Appendix – A (Team Members)  
Appendix – B (PaperSat Contract Schedule)  
Appendix – C (CubeSat Requirements)
Table of Figures

Figure 1 – Examples of various solar sail and corner cube reflector design candidates ........8
Figure 2 – PaperSat Engineering Management Structure..................................................12
Figure 3 – Analysis of Proposed Budget.............................................................................17

Table of Tables

Table 1 - PaperSat Personnel Responsibilities.................................................................13
Table 2 - Proposed Budget.................................................................................................16
1.0 Introduction

PaperSat Engineering proposes to design a picosatellite in accordance with the regulations of the CubeSat program hosted by Stanford University. The CubeSat program offers educational institutions the opportunity to design a cubic satellite with 10 cm sides and, for a relatively low cost, the CubeSat program arrange for the launch of the satellite. The proposed picosatellite’s mission is entirely at the discretion of the educational institution sponsoring the satellite. This scenario offers the students working on each satellite design a large amount of control over the satellites mission and design. Because of the CubeSat program's freedom with design criteria and mission objectives, educational institutions and students involved in the program have an excellent opportunity to develop a satellite for actual application.

1.1 Problem statement

The PaperSat Engineering CubeSat design will fulfill two objectives, an educational objective, and a scientific objective. The educational objective is simply to give students the opportunity to design the systems and mission of a satellite from concept to creation by providing a "real world" application in which the students can apply their design. This educational objective is key to motivating engineering students with a challenging satellite application problem while stimulating them to manage the project from all levels.

The scientific objective is specific to the particular organization developing any particular CubeSat design. PaperSat Engineering will be focusing on the problem of understanding solar sail propulsion capability. PaperSat will be exploring a CubeSat based testing platform to test
solar sail configuration, materials, and efficiency. This project would allow any interested company to test their solar sail design on a picosatellite before they invest their resources into a full sized, more expensive satellite. In this manner, companies wishing to develop solar sail technology can protect their investment. In the same manner, the academic community will benefit from solar sail research. As tests are performed, the results show the scientific community how certain materials reflect light, how that property can be used to navigate a spacecraft, and how to implement that technology. Solar sails have not been utilized as a major propulsion system by any spacecraft to date. The technology is largely untested and theoretical. Testing of this technology may prove to be an important step in space flight, and small satellites are an excellent testing platform for this technology.

1.2 Purpose

The purpose of the solar sail CubeSat design will be to test solar sail capabilities in an inexpensive manner. To achieve that purpose, PaperSat will design a small satellite complies with CubeSat regulations and that can deploy a solar sail for thrusting purposes. Once deployment is achieved the spacecraft's position, velocity and attitude will be monitored from the ground so that the acceleration provided by energy transferred from light striking the surface of the sail to the spacecraft can be measured.
2.0 Design Methodology

Spacecraft and mission design projects such as PaperSat have many goals that may seem elusive at first. The key to achieving the goals is for the team to have in-depth knowledge of the design process. The following explanation presents the principles of the design process that the PaperSat team will use.

The first step of the design process is to establish the problem statement. Preliminary research is the next principle used by the team. Recognizing the fundamental physical, orbital, logistical, and organizational requirements of the project comes from preliminary research. After the requirements are understood, the problem statement can be redefined into its final form. As an example, the PaperSat team realized early on that incorporating a solar sail into a CubeSat was an appealing design project. Our initial design involved attitude control of our solar sail. After some research, it became apparent that integrating an attitude control system sensors, the deployment apparatus, and the solar sail material into a 10cm sided cube would be very complex and less likely to function properly. In light of this discovery, we decided not to incorporate an attitude control system with our satellite design. We have determined that without an attitude control system, we can still get valuable thrust information from a tumbling, rotating solar sail.

With a clearly defined problem statement, PaperSat uses the next principle of the design process – generate potential solutions through team brainstorming. With the recorded ideas in hand, the team chooses several candidate solutions, which will be further researched and
analyzed in detail. To shorten the list candidate solutions, the team will develop criteria that the each candidate solution must meet to be considered as viable solution for the project.

Throughout the design process, documentation is a key element to maintaining accuracy, organization, and accreditation. Bringing the team’s documented research and analysis into a formal report and presentation is the final phase of the design process. The team will exhibit its excellent written communication skills to clearly define all aspects of the project. Also, the team will demonstrate its breadth of knowledge with verbal and visual presentations.

3.0 Design Factors

3.1 Design Criteria

The following list summarizes the criteria used to aid in evaluating all candidate solutions, and are ranked in order of importance:

1. **Weight.** Pursuant to the CubeSat regulations, a single CubeSat must weight no more than 1 kg.

2. **Volume.** The pods that deploy the CubeSat can fit three 10 cm cubes per pod.

   Preliminary estimations of a Aluminized Mylar solar sail with 100 m² surface area puts the volume of the solar sail within 25% of the total CubeSat volume. Based on this analysis, payload volume will not play as important a role as weight but should still be considered when optimizing the sail size.
3. **Rigidity.** A solar sail is most effective when the path of light is perpendicular to the sail’s surface. A rigid solar sail will maximize efficiency by assuring that the sail is fully perpendicular. In addition, data reduction and orbital trajectory calculations are greatly simplified under a rigid sail assumption.

4. **Number of Folds.** Minimizing the number of folds required to pack the solar sail in the CubeSat will both maximize reflectivity and limit the areas of thermal stress.

5. **Cost.** As with all engineering projects, the design is driven by the money required to produce the product. Because the PaperSat project is intended to be a paper design, cost will not play a crucial role, but must still effect the final design decision.

### 3.2 Design Restrictions

The PaperSat team has developed several design concepts to serve as possible solutions for the project. All design solutions must contain the following components, which are required by CubeSat administrators:

- **Shell** – A shell design made of 7075 aluminum is available on the CubeSat Internet site, and will most likely be recommended for the PaperSat design.

- **Timer/Kill Switch** – In effort to assure that the solar sail does not deploy during the injection phase of the picosatellite orbit, a timing mechanism is required. The kill switch will activate the timer upon release from the pod. The timer will then send a deployment command after a specified time has passed. A previous CubeSat team has already
investigated different timers, and PaperSat will most likely recommend these components.

?? **Power Sources** - At minimum, a battery is required for powering the timer. Because rechargeable batteries require remote transmitter shutdown capabilities, the design will probably use non-rechargeable batteries.

In addition, the PaperSat team placed other base requirements on the CubeSat design:

?? There will be no independent attitude control system. PaperSat will not make special provisions to control attitude. However, limited efforts may be taken to stabilize the rotations, such as geometry modifications.

?? Corner cube reflectors will be used to aid in orbit and attitude determination. Further, ground stations will send signals to these reflectors.

?? Aside from timer requirements, no additional power requirements or systems will be placed on the design.

In general, these restrictions allow the different design concepts to vary only in deployment method and corner cube location. Bearing the above restrictions in mind, PaperSat developed several candidate solutions for the different satellite systems.

**4.0 Candidate Solutions**
For the purpose of determining solutions the satellite design was broken down into three areas: sail shape, deployment, and corner cube reflector configuration.

**Sail Shape.** For the sake of simplicity, only two shapes are going to be considered for this project. Fragmented sails require additional deployment gear, and thus add unwanted weight and volume to the design.

1. Square: As shown in Figure 1 (a)
2. Radial: As shown in Figure 1 (a) and (b)

**Deployment.** The satellite’s size limits the methods of deployment available. Two proposed methods are

1. Inflation: Tiny capillaries within the solar sail fill with gas and then harden. This method has been used in previous spacecraft. Figure 1 Part (c) shows an example of the inflatable concept.
2. Spring: For this concept, a high memory material will be used as a frame for the structure. The deployment will involve the material frame “springing” into its non-deformed, fully deployed configuration. In Figure 1, Parts (a) and (b) are conceptual examples of spring deployment configuration

**Reflector Configuration.** Two configurations are readily apparent for the corner cubes:
1. 3-space: Figure 1 Parts (a) and (c) show the 3-space configuration. Three reflectors are placed perpendicular to each other in a coordinate-axis fashion. A boom is required for one of the reflectors for this configuration, and the other two reflectors are attached to the solar sail.

2. Planar: Figure 1 Part (b) shows a planar configuration. Three or four reflectors are attached to the sail.

![Figure 1 – Examples of various solar sail and corner cube reflector design candidates](image)

(a) Radial Sail with Spring Deployment and 3-space Reflector Configuration. (b) Radial Sail with Spring Deployment and Planar Reflector Configuration. (c) Square Sail with Inflation Deployment and 3-space Reflector Configuration.

The deployment method and corner cube reflector candidate design solutions are currently being evaluated according to the design criteria outlined in Section 3.1.
5.0 Deliverables

The deliverables produced by PaperSat can be broken down into two categories. The first category includes the materials delivered mid-contract, while the second group consists of deliverables produced for the end of the contract.

2.1 Mid-Contract

The mid-contract deliverables consist of a mid-term paper, a mid-term presentation, and a pamphlet. The mid-term paper will describe the basic idea behind the solar sail project, what information is hoped to result from the project, and how the data will be retrieved. The accompanying presentation will follow a similar scheme and will be presented to the class. The mid-term pamphlet will contain a brief summary of what is to be found in the report.

2.2 End of Contract

For the end of the contract, PaperSat will produce a final paper, a final presentation, a final pamphlet, a model of the CubeSat, a poster, and an orbital simulation. The final paper will review the basic concept of the solar sail project, but will differ from the mid-semester report by including PaperSat’s final designs and results. The final presentation will similarly be more detailed in explaining the results the project. The final pamphlet will also reflect the work done by PaperSat in abbreviated form. The model produced by PaperSat will be a scale model of the final design for the CubeSat. The poster will be a visual depiction of the steps to be taken by the CubeSat, starting from deployment through final sail deployment and data gathering. The
orbital simulation will consist of a computer simulation, using Matlab, which will predict the
amount of thrust being produced by the solar sail based upon the data gathered when locating
the solar sail after deployment. Table 1 lists the items to be delivered this semester.

<table>
<thead>
<tr>
<th>Item to be Delivered</th>
<th>Date Item will be Delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposal for Contract</td>
<td>10/03/01</td>
</tr>
<tr>
<td>Presentation for the Departmental Visiting Committee</td>
<td>10/11/01</td>
</tr>
<tr>
<td>First Preliminary Design Review Presentation</td>
<td>10/31/01*</td>
</tr>
<tr>
<td>First Preliminary Design Review Formal Report</td>
<td>11/05/01*</td>
</tr>
<tr>
<td>Second Preliminary Design Review Presentation</td>
<td>11/14/01*</td>
</tr>
<tr>
<td>Second Preliminary Design Review Formal Report</td>
<td>12/03/01*</td>
</tr>
<tr>
<td>Orbital Trajectory Simulation</td>
<td>12/03/01*</td>
</tr>
<tr>
<td>Picosatellite Model</td>
<td>12/03/01*</td>
</tr>
<tr>
<td>Project Poster</td>
<td>12/03/01*</td>
</tr>
</tbody>
</table>

(* indicates that the date is subject to change by the contracting company)

Table 1 - Contract Deliverables

These items together will complete the preliminary design phase for this project.

PaperSat’s goal for this contract is to have a satellite design ready for the final design stages and
construction.
6.0 Project Schedule

To ensure that all of the deliverables are met, PaperSat will adhere to a well-defined schedule. The schedule consists of a proposal, a preliminary design presentation, a preliminary design report (PDR1), a second preliminary design proposal and a second preliminary design report (PDR2).

The schedule PaperSat has prepared for this contract is aggressive. Since the solar sail design contract is restricted to three and a half months, the preliminary design stages must be completed rapidly. The schedule for this semester is included in Appendix B. The dates for the project milestones PDR1 and PDR2 are prescribed by the contractor and will be refined as work progresses.
7.0 Management Organization

7.1 Company Management Structure

The PaperSat Engineering company consists of a system design branch and a systems integration branch. The Figure 2 shows how the branches are divided.

![Figure 2 – PaperSat Engineering Management Structure](image)

With the exception of the orbital trajectory department, which will remain active throughout the contract, the two branches will not be active simultaneously. The project schedule (Appendix-B) shows how the system design branch will only be active until PDR1 is submitted. After PDR1 is complete, the systems integration branch will become active so that the design can be further refined for construction purposes. Once the systems integration branch produces PDR2, the contract requirements will have been fulfilled. Table 1 shows each of the team members’ responsibilities and the corresponding branch.
The project manager will serve as a point of contact for each of the other managers. The project manager is responsible for maintaining the group notebook, moderating evaluation of design conflict solutions, and maintaining the project schedule. Each of the other managers is responsible for ensuring that the work their department is responsible for is completed by the appropriate deadline. The department managers may require additional help from other PaperSat personnel, as has already been the case with the orbital trajectory department.
7.2 Design Conflict Resolution Procedure

The managers of each department of PaperSat Engineering will caucus on Monday, Wednesday and Friday of each workweek while under contract. At each Monday caucus, the managers of each department must present a summary of their objectives for the coming week, completed tasks for the previous week, and any concerns or issues they have with their department’s progress and tasks. The Wednesday and Friday caucuses will be reserved for troubleshooting of issues and concerns. (Note: Summaries do not need to be provided by managers of inactive departments). Once issues are presented, each department manager will present at least one potential solution to the conflict. The candidate solutions will be discussed and an agreement of all departments must be reached before the candidate solution is adopted by department raising the issue. Each department must agree on the proposed solution to the conflict, as many conflicts may impact portions of the project for which other departments are responsible. In this manner, engineering conflicts will be quickly identified and resolved. Weekly reports submitted by the department managers and a log of issues and concerns will be maintained and filed by the project manager in the PaperSat engineering notebook.

In the event of an emergency conflict requiring immediate solution, the project manager will decide a course of action until the next management caucus. In the event of gridlock as candidate solutions are being evaluated, the project manager may override one vote other than his/her own. Poor use of override power may result in the dismissal of the project manager.
8.0 Proposed Budget

8.1 Personnel Budget Description

The cost for personnel will be totaled per hour worked. The salary basis for each employee for a full work year is listed below:

Daniel Parcher $26.0 / hr*
Taffy Tingley $24.5 / hr*
Paul Mears $24.5 / hr*
Phillip Hempel $24.5 / hr*
Dr. Cesar Ocampo (Orbital Determination Consultant) $52.0 / hr*

*This number does not include withholdings for Tax Purposes

8.2 Material and Electronics Budget Description

The materials and electronic costs are not yet fully known. A company wishing to test their material will provide the solar sail. The deployment hardware, shell casing, and electronics will total approximately $5000.

8.3 Testing Budget Description

One of the things that makes a small satellite a good test platform for solar sail technology is that solar sails cannot be tested on earth. The sail will not need to endure the air pressure or gravitational force that it would on earth. The result is that the deployment mechanism, being designed for a micro-gravity environment, will be difficult if not impossible to test on earth. Because of this only vibration testing will be performed. After vibration testing, the systems will be inspected for damage. The estimate for vibration testing cost is roughly $2000.
8.4 Launch Budget Description

The CubeSat launch costs are roughly $50,000 per satellite launched. That cost is expected to increase in the future, but PaperSat will estimate its final budget for one CubeSat launched for the current cost.

8.5 Budget Summary

The Table 2 contains a complete summary of the predicted expenses for the PaperSat Engineering company’s work on this project.

<table>
<thead>
<tr>
<th>Expense Item</th>
<th>Predicted Expense (dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel (based on an estimated 150 hrs. worked, 14 hrs. for consultants)</td>
<td>15,653</td>
</tr>
<tr>
<td>Materials / Electronics</td>
<td>5,000</td>
</tr>
<tr>
<td>Testing</td>
<td>2,000</td>
</tr>
<tr>
<td>Launch</td>
<td>50,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>72,653</strong></td>
</tr>
</tbody>
</table>

Table 3 - Proposed Budget

It is easy to see from the Figure 3 below, that the majority of the expense for this project lies with the launch cost.
Analysis of Proposed Budget

68%
22%
7%
3%

Figure 3 – Analysis of Proposed Budget
9.0 Conclusion

PaperSat Engineering will design a CubeSat based solar sail testing platform. Companies wishing to test their solar sail design can employ PaperSat to integrate their sail design into a picosatellite. The solar sail design will give education institutions and their students the opportunity to participate in a complete satellite development project, and the academic community can benefit from research of the cutting edge propulsion technology. PaperSat is proud to spearhead this endeavor and is optimistic about the opportunity to succeed at this design project and contributing to space propulsion technology research. We at PaperSat engineering thank you for your consideration of our proposal and look forward to working with you on this and future projects.
10.0 Literature Survey


http://www.planetary.org/solarsail/index2.html
Appendix – A (Team Members)
Appendix –B (PaperSat Contract Schedule)
Appendix – C (CubeSat Requirements)