University of Colorado

Department of Aerospace Engineering Sciences

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Project Definition Document (PDD)

Geocentric Heliogyro Operation Solar-Sail Technology (GHOST)

Approvals

	Name	Affiliation	Approved	Date
Customer	Keats Wilkie	NASA LaRC	W. K. Wilkie	9/16/2013
Course Coordinator	Dale Lawrence	CU/AES		

Project Customers

KEATS WILKIE Phone: 757-864-6420 Email: william.k.wilkie@nasa.gov 4 West Taylor Street, Hampton, VA, 23681	DALE LAWRENCE Phone: 303-492-3025 Email: dale.lawrence@colorado.edu

Team Members

NICHOLAS BUSBEY busbey@colorado.edu 720-254-4838	MARK DOLEZAL mwdolezal@gmail.com 303-956-2265
CASEY MYERS casey.myers101@gmail.com 719-650-9005	LAUREN PERSONS persons.lauren@gmail.com 970-214-8915
EMILY PROANO emproano@gmail.com 925-914-9208	MEGAN SCHEELE megan.scheele@colorado.edu 303-895-8095
TAYLOR SMITH tayljs@colorado.edu 720-556-6791	KARYNNA TUAN karynna.tuan@colorado.edu 303-912-9804

1.0 Problem

Heliogyro configurations show great promise for space missions using solar sails because the sails are stiffened gyroscopically. This means they are lightweight compared to other designs, and therefore produce more acceleration. However, the sails must still have a large surface area, meaning that each solar blade is very long, presenting challenges for packaging and deployment of adequately sized blades. In fact, due to such challenges, to-date there have been no ground demonstrations of systems capable of packaging and deploying of such blades.

To this end, the Geocentric Heliogyro Operation Solar-Sail Technology (GHOST) demonstrator team will design, build, and test a heliogyro solar sail deployment and pitching mechanism packaged into a CubeSat (a low-cost space platform). The CubeSat will be up to 12U (1U = 10×10×10 cm) large and capable of deploying and subsequently pitching adequately sized solar sail blades with a minimum aspect ratio of 100:1 that are capable of providing a minimum total thrust acceleration of 0.1 mm/s^2. While the overall design will be appropriate for four blades, GHOST will build and test a deployment system which will demonstrate the successful unfurling of a minimum of one solar sail bade in a 20 meter high room on earth. In addition, GHOST will build a two blade, coordinated pitching mechanism, which will be tested through pitching blade-equivalent masses.

2.0 Previous Work

In the 1860's, James Clerk Maxwell published his theory of electromagnetic fields radiation, illustrating that light (including sunlight) has momentum and can therefore, exert pressure on various objects. This theory led to the first formal design for a solar sail in 1976, where The Jet Propulsion Laboratory (JPL) designed a mission to rendezvous with Halley's Comet using a heliogyro solar sail. The physical design of JPL's heliogyro solar sail contained 12 blades, each 8 meters wide and 7500 meters long. The blades were to be rolled up during launch and, when in place, the spacecraft would be spun to cause the blades to unroll via angular momentum. [1] In 1989, an MIT design team performed a heliogyro study as an entry into a solar sail race to Mars. The team's design consisted of a small, 8-bladed, 200 meter diameter heliogyro and was almost all solid state, as the blade pitch control would be accomplished using a piezoelectric torsional actuation system at the root of each blade instead of motors. In the end, both JPL and MIT's designs were not chosen mainly due to the large uncertainties and high risks associated with unverified and unproven solar sail technology. [2]

Currently, NASA is working on a "low-cost, CubeSat technology based heliogyro flight demonstration" known as High Performance Enabling Low-cost Innovative Operational Solar Sail (HELIOS). The goal is to look back at the MIT team's concept and reassess the idea with recent small sat and CubeSat technology. Additionally, more "opportunities to reduce mechanical complexity and deployment risk" will be examined with NASA's design concept. The advantages of the heliogyro deployment system lie in the ease of unrolling the solar blades through angular momentum. This method removes the need for structural support on the sails allowing for reduced overall mass. The reduction of the blade chord, number of blades, and use of lightweight material all contribute to the improvement to the MIT 1989 design. The main objectives of HELIOS are to validate critical heliogyro deployment technologies, show controlled heliogyro solar sail flight a characteristic acceleration larger than 0.5 mm/s^2, validate structural dynamics, and determine orbit changing capabilities. The spacecraft bus mass is estimated at 4.5 kg, while the blade deployment and control system 8.4 kg. The total mass of HELIOS is about 18 kg, with a sail area of 1000 m^2. This will produce an approximate acceleration at 1.0 AU of 0.5 mm/s^2, meeting the initial high performance target characteristic acceleration. [3]

The difficulty of solar sails as a propulsion system in space is the lack of testing that has been performed in Earth-based environments. Testing a solar sail to scale within a zero-gravity setting here on Earth is near impossible because of the large surface areas required. In order to further solar sails as a reliable propulsion mechanism, data needs to be collected through flight demonstrations in a space environment. HELIOS will test the concept of the heliogyro solar sails as a low-cost deployment validation flight experiment and, hopefully, will pave the way for future solar sail propulsion spacecraft missions. Due to the lack of literature and testing with heliogyro solar sails, experimental research and construction will be performed by the GHOST team to verify heliogyro solar sail deployment and pitching systems as a potential option for future missions. The GHOST team will consider materials, mechanics, and control systems to design, construct, and test a blade deployment mechanism. Additionally, pitch control of the blade roots will be implemented by control algorithms and tested with two blades to confirm coordination and synchronization of the solar sails.

3.0 Specific Objectives

The objective of this project is to design a four-blade heliogyro CubeSat capable of deploying and pitching all blades. This project will build and test a single deployment mechanism and deploy and test two pitching mechanisms to demonstrate functionality and coordination. The deployment mechanism will be designed to deploy the blade using a motor aided by centrifugal tension, and the blades must demonstrate a pitching motion of 180 degrees. GHOST will design sufficiently sized solar blades in order to produce a characteristic acceleration of 0.1 mm/s^2. The entire structure must be stowable within a standard 12U or smaller CubeSat platform before deployment, with a typical mass limit of 1 kg/U, and is limited by a maximum 10 W of power. As a financial objective, materials, testing, and construction must not exceed the budget of $5000.This deployment and pitch control system will be available for future implementation in the HELIOS projects. It will allow for a small scale, cheaper, and validated development of heliogyro solar sail deployment and control mechanisms.

The main objective for GHOST is to design a system and corresponding mechanisms to package, deploy, and pitch all four solar sail blades in a 12U or smaller CubeSat. However, only one blade will be manufactured and tested for the deployment test, and only two pitching mechanisms will be built and tested to verify pitch actuation. GHOST's overall design will be for a four solar blade system.

For the GHOST solar sail blade deployment mechanism design project to be a success, the blade deployment system must demonstrate successful deployment of a sail blade with a minimum aspect ratio of 100:1 in a 1G environment. While ideal testing would occur in a vacuum, this is unrealistic for something this long in an Earth environment. Therefore, minimizing drag and wind forces will be acceptable. An additional test will show that the blade control system performs controlled pitching by utilizing given user input. The blade will pitch in a range of +/- 90 degrees, which will vector a hypothetical solar thrust due to the effects of solar radiation pressure acting on the sail membrane. This will allow for theoretical orbit change capabilities, which will be discussed conceptually.

The third level objectives include ensuring that the solar sail structural integrity will not be compromised due to exposure to launch conditions, which will be verified via FEM analysis and/or a vibration stand testing. The blade pitch control subsystem, specifically the blade pitch control software, will be able to implement a combination of static and periodic pitch profiles in which each pitch actuator is capable of acting independently of one another. As a result, the pitching of the blades must also exhibit orbit transfer capabilities, including both coplanar and non-coplanar transfers to orbits of differing inclinations and semi-major axis'. Therefore, software will have to validate the response of pitching the blades using the necessary combination of pitch profiles in order to deliver enough thrust to enter and exit a transfer orbit. This requirement will assume that once initial orbit is attained, the rotational axis of the gyro will be oriented with the sun. As thus, further pitching must be controlled in order to offset any third-body perturbations and maintain orbit.

4.0 Functional Requirements

4.1 Functional Block Diagram (FBD)

Figure 1 portrays the deployment and blade pitch control subsystems of GHOST and how they interact. Note that the team is designing only the Solar Sail Deployment Mechanism (SSDM) and the Blade Pitch Control System (BPCS) and associated power subsystem (EPS), communication subsystem (COMM), and controller to fit onto an existing CubeSat.

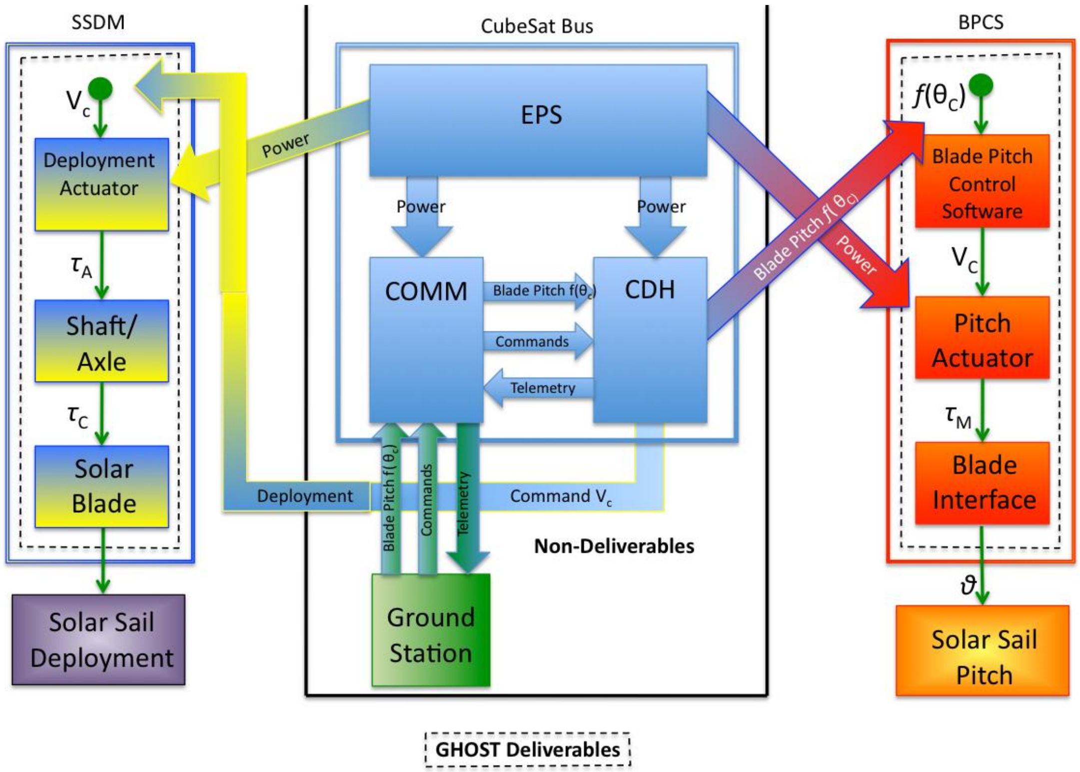

Figure 1. GHOST Functional Block Diagram

The GHOST team will design a Solar Sail Deployment Mechanism (SSDM) and Blade Pitch Control System (BPSC) to fit on a CubeSat. The CubeSat bus may be a purchased COTS CubeSat of less than 12U size or a simulated CubeSat reflecting the desired size specifications. Due to 1G limitations, both the SSDM and the BPCS will be tested separately. The BPSC test will not control a full-sized sail due to aerodynamic forces and testing limitations, and instead will be tested by using an added mass equal to the equivalent blade mass. The SSDM, tested independent of the CubeSat and BPSC, will be tested in a 1G environment in Dr. Frew's 17 m Fleming lab on CU campus and possibly a NASA Langley 20 m vacuum chamber if circumstances so require. The 1G environment on Earth will be used to simulate the centripetal acceleration felt by the sail blades due to the spacecraft's rotation needed in order to maintain the solar sail's gyroscopic stiffness. This will be done by adding a tip mass to correlate 1G acceleration to the centripetal acceleration conditions in space. It will be validated that if one blade can be deployed, the same system should be transferable for as many blades as needed.

In its final production state, information of the deployment and pitch commands will come from personnel on the ground. The mechanical GHOST solar sail deployment mechanism will initiate once the deployment command is made. In the case of a pitch command (i.e. a specific blade pitch angle or pitch profile), the blade pitch control software will govern the actions of the blade pitch control system and actuate the blades to the desired pitch angle(s). Pitch control of undeployed solar sails in a 1G Earth-based environment will be used to simulate the deployed solar sail by using blade equivalent masses at the roots and through the assumption that there will be no drag enacted on the solar sail in space.

4.2 Concept of Operations (ConOps)

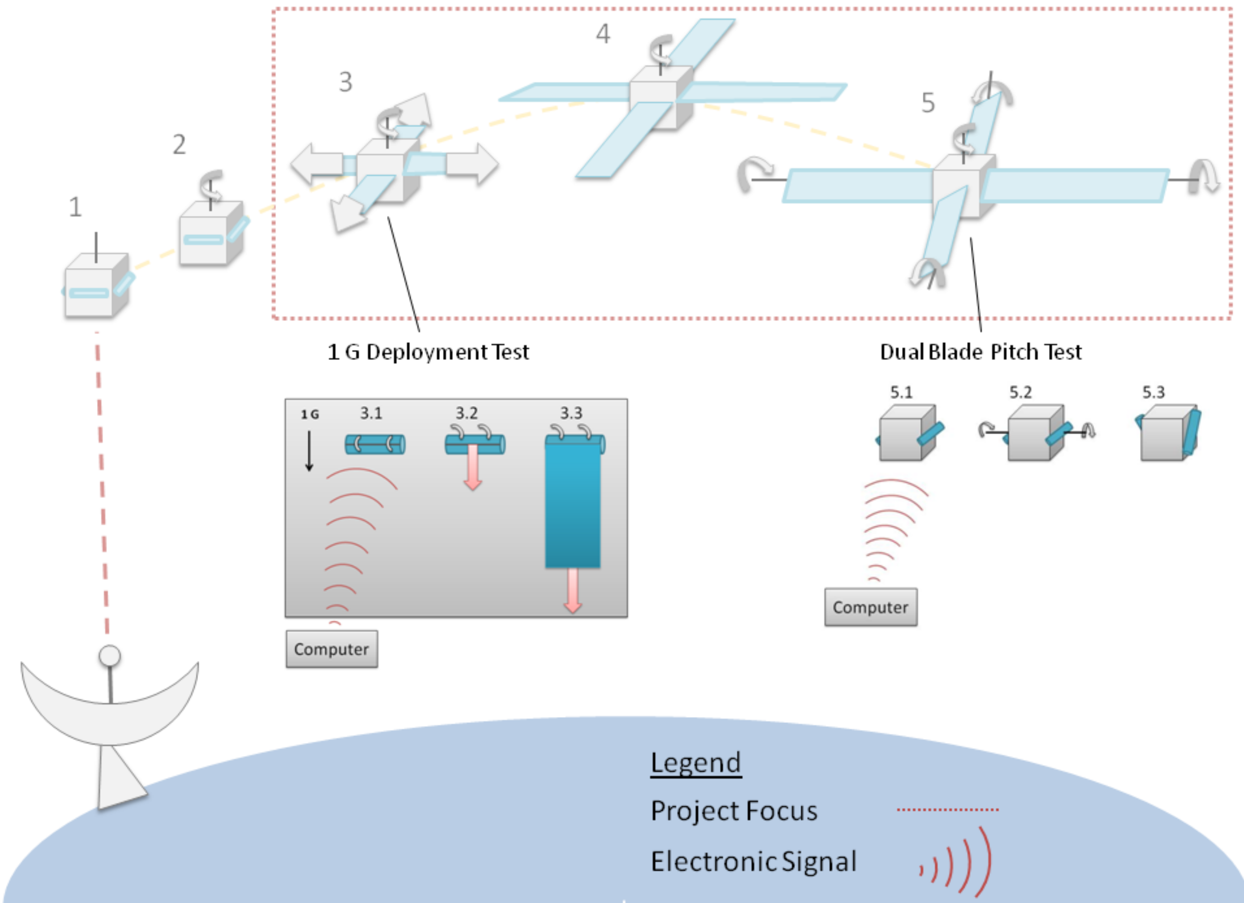

Figure 2. Blade Deployment Pitch Control Concept and Testing

1.0 Establish connection with spacecraft
2.0 Initialize spin when satellite at appropriate altitude
3.0 Controlled deployment sails via motors (SSDM)*
- **3.1 Suspend undeployed blade in 1G**
  - **3.1.1 Establish electronic connection with locking mechanism**
- **3.2 Initiate deployment mechanism**
- **3.3 Sail deployment using motors**

4.0 Spacecraft at full deployment
5.0 Pitch solar sail roots (BPCS)*
- **5.1 Establish remote connection with pitching mechanism**
- **5.2 Send appropriate pitch command**
- **5.3 Measure resulting pitch angle**
  - **5.3.1 Record actual pitch angle and compare to expected pitch angle**
  - **5.3.2 Ensure both actuators are capable of generating static (collective) and periodic (½ P** and 1P*** cyclic) root pitch profiles.**

*The bold sections of the ConOps indicate the two, independent operations tests that will be performed. **Once per two revolutions sine wave pitch profile. ***Once per revolution sine wave pitch profile. [6]

5.0 Critical Project Elements

5.1 Control

5.1.1 In order to maintain orbit, both blades must pitch the same amount at the same time to keep forces balanced, and to avoid toppling of the CubeSat by maintaining a steady spin. This can be validated by recording data of the pitching angles of both blades and that they are equal over time.

5.1.2 Enable orbit transfer capability by offsetting the blade pitch angles, generating a thrust vector that will allow entry and exit from an orbital transfer. Orbit change must be given as a command to the blade pitch control subsystem, and will be validated by software that will send an audible pitch profile to the pitch motors for further actuation. Additional periodic pitch profiles such as ½P and 1P will be utilized for this purpose as needed.

5.1.3 Actuators and sensors can be used to change the pitch angle, which can be supplied by NASA Langley, or purchased. NASA Langley can also provide the CubeSat bus.

5.2 Design and Fabrication

5.2.1 Solar sails, the deployment systems, and pitching systems must be packaged into the small volume of an 8U CubeSat. When given a signal through wireless command to the Cubesat, the deployment system will release and control the deployment rate of the sail. Another wireless command will be given to the CubeSat, which will control the pitching systems.

5.3 Communications

5.3.1 Need to design a COMM subsystem and motor controllers in order to send commands to CubeSat bus.

5.4 Deployment Test

5.4.1 Dr. Frew's 17 m tall lab in the Fleming Building will be used in order to test successful deployment of a single sail blade in a 1G Earth-based environment. If needed, NASA Langley can provide a vacuum chamber. The blade is to be made out of a 2.5 micron aluminum sheet that will be given by NASA Langley.

5.4.2 The finalized system must withstand a vibration test simulating launch conditions and can be validated using a vibration stand test and/or FEM analysis. The vibration stand can be provided by Ball Aerospace in Boulder at cost.

5.5 Integration

5.5.1 The control and mechanics are based on the two main project design elements; deployment mechanics of the blades and solar sails and pitching control of the blades. Together, solar sail must be unpackaged from a CubeSat, release the solar sails, and control pitching, all within the power and size restrictions.

5.4.2 The integration of the different systems will be validated before being manufactured with a Solidworks/CAD model, which will show how the design will fit in a single CubeSat, and deployed from the CubeSat.

6.0 Team Skills and Interests

Team Member	Expertise	Critical Project Elements
Nick Busbey	Test Engineering and Mechanics Lead – has taken Aerospace Software and is passionate about mechanics and materials. He is machine shop certified.	Deployment Test, Design and Fabrication
Mark Dolezal	Project Manager – has had an internship at Sundyne as a project manager and at ULA as a mechanical engineer at the launch pad.	Integration
Casey Myers	Systems Engineering Lead – has worked at LASP for over 2 years as an operations software student, and is experienced in C, Perl, Java and Python. Casey is also currently taking Microavionics.	Integration, Control

Lauren Persons	Electronics Lead – has worked at Space Grant with ground station and communications systems. Lauren is taking Microavionics, and has completed electronics and is great at soldering and electrical systems.	Control, Integration
Emily Proano	Software Lead – has worked at Space@VT as an intern specializing in controls. Knowledgeable at AutoCad.	Control, Deployment Test
Megan Scheele	Materials and Fabrication Lead – has been accepted in the BS/MS program and is currently taking Space Habitat Design. She has taken electronics and is passionate about mechanics.	Design and Fabrication
Taylor Smith	Orbital/Attitude Lead, Financial Lead – has worked at ULA as an intern specializing in payload-fairing separation analysis for the Structural Dynamics Department/LV Loads Group. Taylor is also currently taking Spaceflight Dynamics.	Integration, Design and Fabrication
Karynna Tuan	Structural and Modeling Lead – has previous experience with SolidWorks, simulating lunar environments in a vacuum chamber, and is currently working at Space Grant with 3U/6U CubeSat structures team. Karynna is also machine shop certified.	Design and Fabrication

7.0 Resources

Critical Project Elements	Requirements	Resources
Control	Programming and Hardware	Actuators and sensors purchased using budget and additional aid from LaRC Knowledgeable people: Dr. Dale Lawrence, Dr. Eric Frew
Design and Fabrication	Parts and Materials	Emily Proano can AutoCad up systems and parts Some materials provided by LaRC Purchase materials with budget and machine parts needed in ITLL machine shop Assembly by team Knowledgeable people: Dr. Penina Axelrad & Matt Rhodes
Testing	Facilities	Vibration testing facilities at LASP Knowledgeable Persons: Trudy Schwartz High Bay for deployment: Dr. Eric Frew
Integration	Hardware and Software Integration	Knowledgeable people: Trudy Schwartz, Tim May

8.0 References

[1] Blomquist, Richard, *SOLAR BLADE NANOSATELLITE DEVELOPMENT: HELIOGYRO DEPLOYMENT, DYNAMICS, AND CONTROL*. Carnegie Mellon University. Accessed 4 September 2013.

[2] Blomquist, Richard Stuart, *DESIGN STUDY OF A SOLID-STATE HELIOGYRO SOLAR SAIL.* Massachusetts Institute of Technology. 19 September 1990. Accessed 4 September 2013.

[3] Wilkie, W. K., J. E. Warren, M. W. Thomson, P. D. Lisman, P. E. Walkemeyer, D. V. Guerrant, and D. A. Lawrence, *THE HELIOGYRO RELOADED*. Structural Dynamics Branch at NASA Langley Research Center, Jet Propulsion Laboratory at California Institute of Technology, and Department of Aerospace Engineering Sciences at the University of Colorado. [http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110023680_2011024984.pdf Accessed 3 September 2013.]

[4] Friedman, L., et. al., *SOLAR SAILING – THE CONCEPT MADE REALISTIC*, AIAA paper 78-82, 16th Aerospace Sciences meeting, Jan. 16-18, 1978.

[5] MacNeal, R. H., *STRUCTURAL DYNAMICS OF THE HELIOGYRO*, NASA-CR-1745A, 1971.

[6] Guerrant, D., Lawrence, D., Heaton, A., *EARTH ESCAPE CAPABILITIES OF THE HELIOGYRO SOLAR SAIL*, AAS 13-743 pp. 4, 2013 AAS/AIAA Astrodynamics Specialist Conference, Aug. 11-15, 2013.