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Project Glowworm: Testing Laser Sail Propulsion in LEO

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Abstract

Laser sail propulsion is a promising concept for accelerating spacecraft to great velocities without the need for any propellant. However, despite the fact that this concept has been discussed for a long time, it has never been demonstrated in space. The Initiative for Interstellar Studies (i4is) is developing the Glowworm mission which aims to conduct the first in-orbit demonstration of laser sail propulsion. Glowworm will consist of a CubeSat that deploys a small chipsat attached to a sail; the CubeSat will then use an onboard laser to push the sail and raise the orbit of the chipsat; the mission is targeting a semi-major axis increase of 10 km. This paper describes two concepts for how to achieve this. The first concept has the CubeSat maintain its position relative to with the sail using an electric propulsion system, while the second has the CubeSat remain in its original orbit and use the laser to raise the sail periodically when they pass near each other. A simulation of both concepts is described which uses NASA's General Mission Analysis Tool (GMAT) and a baseline 800 km circular sun-synchronous orbit (selected to minimize the influence of solar pressure which in certain orbits could exceed the thrust from the laser). Results show that the second of these concepts is infeasible. Because the orbit raising achieved by each laser use interval is small, the frequency with which the two spacecraft come close to each other in their orbits is quite low. As the sail experiences drag in the intermediate time period, its orbit decays below the initial level between laser use windows unless a very high laser power is used. In addition, results indicate that, even with a laser power of 500 W focused over a distance of 200 km, the energy imparted to the sail would decay due to drag before the sail passed close enough to the CubeSat to use the laser again. Therefore, only the concept with propulsion included is viable to complete the Glowworm Mission. The paper then describes preliminary analysis on this concept and presents and initial design.

Keywords: Laser, Sail, Interstellar, Lightsail

Nomenclature

a – Acceleration
c – Speed of light
d_{spot} – Laser spot size
D – Diameter of laser optics
M – Sailcraft mass
P – Laser power
r – Distance from laser to sail
t – Time
λ – Laser wavelength
η – Sail reflectance
ΔV – Change in velocity

Acronyms/Abbreviations

ADCS – Attitude Determination and Control System
C&DH – Command and Data Handling
EPS – Electrical Power System
GMAT – General Mission Analysis Tool
i4is – Initiative for Interstellar Studies
ISU – International Space University
LEO – Low Earth Orbit
SMA – Semi-major axis

1. Introduction

Since the earliest days of spaceflight, many have desired to explore beyond the solar system. However, the massive distances between the Sun and even the closest stars has presented an insurmountable obstacle. Existing propulsion technologies are incapable of making the journey in timescales relevant to human beings, if at all. Major limiting factors include the level of thrust that can be provided by current propulsion technologies and the amount of propellant that can be stored for long duration flight. Light sail propulsion is one way that these issues may be overcome.

Light sail propulsion is a broad category of propulsion techniques which use the pressure exerted by photons to produce thrust on a spacecraft. This pressure is very small, but by using large reflective sails operating over long periods of time, it can produce very large changes in velocity. Laser sail propulsion is a variety of light sail propulsion that uses high powered lasers to maximize the thrust generated by a light sail. Laser sails were first proposed by Robert Forward, who imagined using a high energy laser with a massive optical lens of kilometers in diameter to propel spacecraft to the outer planets [1]. This was expanded upon by Marx, who imagined using such a system to reach a rapid interstellar trajectory at relativistic velocities [2]. While this idea showed great promise, the massive size of the lasers and optical systems involved made it impractical to pursue implementation and interest slowly faded.

Recent advances in high energy laser systems and spacecraft miniaturization have started to produce a revival of interest in the laser sail concept. Higher powers and lower masses could enable implementation of a laser sail system without massive optics; this has the potential to make laser sail propulsion feasible on a practical scale [3]. One recent proposal that seeks to leverage this is the Breakthrough Starshot project. This project, initiated by renowned physicist Stephen Hawking and Russian billionaire Yuri Milner, aims to use laser sail propulsion to send a number of extremely small spacecraft called chipsats to the Alpha Centauri star system 4.2 lightyears from Earth [4]. However, many significant barriers remain to its implementation. One of these is the fact that the concept of laser sail propulsion has never been demonstrated in space.

Project Glowworm, under development by the Institute for Interstellar Studies (i4is) is an attempt to advance interstellar laser sail concepts by providing the first in orbit demonstration of a laser sail. Glowworm will be a CubeSat that will deploy a small chipsat attached to a reflective sail. This sailcraft will be pushed by a laser contained within the CubeSat. The project is still in the early phases of development. i4is has identified an 800 km circular sun-synchronous low Earth orbit (LEO) as a likely option for the mission. Currently, no requirements have been defined by i4is, but an increase in the semimajor axis (SMA) of the sailcraft's orbit of 10 km has been identified as a goal.

Two architectures are currently under consideration. In the first, the CubeSat will use propulsion to maintain the same orbit as the sailcraft (the chaser concept). In the second, the CubeSat will stay in its initial orbit and continue to propel the sailcraft periodically when the orbits of the two spacecraft align (the passive concept).

This paper documents the results of an Individual Project completed at the International Space University (ISU). This project aimed to identify the optimal overall design architecture for the Glowworm mission. This was completed by analyzing the feasibility of the two proposed mission concepts then conducting a preliminary design study.

2. Methodology

The first major aim of this analysis of the Glowworm mission was to determine whether the passive concept or the chaser concept should be pursued for further development. To provide an initial indication of the feasibility of these two concepts, an orbital simulation of the mission was created using the General Mission Analysis Tool (GMAT). As the magnitude of the laser sail propulsion effect depends on the basic physics of laser sails and the material selected for the sail itself, these aspects were considered first.

2.1 Acceleration

Laser sizing was conducted based on the equations developed by Forward [5]. Forward’s basic equation for the acceleration of a laser sail is given by Equation 1. This equation was the primary relationship used for modeling the thrust produced by the laser sail effect.

$$a = \frac{2\eta P}{Mc} \tag{1}$$

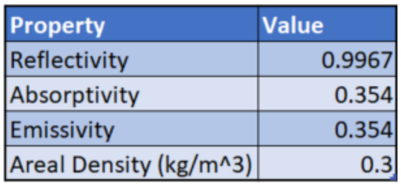
a is the acceleration. η is the reflectance of the sail, P is laser power striking the sail, M is the mass of the sailcraft and c is the speed of light. The variable parameters in this equation are the size of the sail, the material properties and the laser power used. While this equation initially looks simple, the relationship between the variables in it is complex. It is not sufficient to simply select an input power and sail size and calculate acceleration. Indeed, if one were to do so one would find that the optimal sail size is infinitesimally small; the mass of the sail only serves to decrease acceleration. In reality, two factors necessitate the use of a sail with a noticeable size. Firstly, the sail must be sufficiently large to radiate away the energy it absorbs from the laser, the Sun, and other sources. Secondly, the power of the laser will disperse as it crosses space, meaning that the sail must be large enough to capture all of this power for a given distance.

2.2 Sail Material Properties

The material properties of the sail used are a critical parameter of a laser sail system. The reflectivity, absorptivity, and emissivity of the sail determine both the amount of thrust it experiences and its ability to maintain its temperature within acceptable ranges when exposed to the laser. Additionally, the density and size of the sail determine its mass which also has a major effect on performance.

Dielectric mirrors have been identified as a likely material for laser sails in several previous studies and are currently the candidate material for the sail [3,6]. A dielectric mirror consists of multiple thin layers of dielectric materials. By layering these materials, a composite sail can be created that Is optimized for maximum reflectivity at the wavelength of the laser. i4is has developed a Matlab code which outputs the optical properties of a variety of potential dielectric mirrors. This code was used to generate the relevant properties of a 5 layer dielectric mirror consisting of SiO_2, TiO_2, and MgF_2, given in Table 1. These properties have been assumed throughout this report.

Table 1: Dielectric mirror properties



Property	Value
Reflectivity	0.9967
Absorptivity	0.354
Emissivity	0.354
Areal Density (kg/m^3)	0.3

2.3 Laser Beam Divergence

The diameter of a laser beam does not remain constant as it travels across space. This variation is important to the design of a laser sail system because the sail must be large enough to capture the energy emitted by the laser; in other words, it is optimal for the sail diameter to be equal to the diameter of the beam at its operational range. It the sail is larger, it has a higher mass than is needed and thus experiences less acceleration; if it is smaller, it does not capture all of the energy emitted by the laser, creating waste and inefficiency. The relationship for the diameter of a laser beam as a function of distance is given by Equation 2 [7].

$$d_{spot} = \frac{2.44\lambda}{D}\mathrm{r} \tag{2}$$

d_{spot} is the beam diameter. λ is the wavelength of the laser. D is diameter of the laser. r is the distance from the laser emitter to the target. Equation 2 was used in the calculations for the size of the sail and the laser system.

2.4 Orbital Simulations

Informed by the equations, principles, and sail properties given in the previous section, a model of the system was developed using GMAT. GMAT is an open source orbit simulation software developed by NASA Goddard Space Flight Center. It is capable of simulating the effects of atmospheric drag, solar pressure, the oblateness of Earth, and disturbances due to the gravity of other bodies. It also includes built-in optimization and solver functionalities.

To avoid the necessity of developing plugins to add entirely new laser sail analysis functionality to GMAT, the laser propulsion was modeled as an electric propulsion system that does not consume propellant, with thrust applied to the sail perpendicular to the velocity vector. This thrust orientation was a logical assumption to make because this is the optimal configuration to produce an increase in the sail's orbit. Acceleration that is oriented in the same direction as the velocity vector of a spacecraft solely serves to increase the velocity and therefore the orbital energy. As it does not change the direction of the velocity, this only serves to change the SMA and eccentricity of the orbit; the argument of periapsis could potentially also be affected if the periapsis of the orbit changes as the SMA changes. If acceleration occurs in a direction that is not aligned with the velocity vector, some of the energy goes to changing the direction of the velocity vector, which changes all of the orbital elements [8].

For the chaser concept, this is all that was necessary as the distance between the two spacecraft should remain constant. A modified version of this model was developed for the concept with a passive CubeSat. This version of the model was designed to continuously check the distance between the two spacecraft and determine which spacecraft was in front of the other. It then activated the thrust of the laser when the separation distance was appropriate and the sailcraft was in front of the CubeSat.

The chaser concept GMAT model was used to determine the range of laser powers and sailcraft masses that would increase the semimajor axis of the orbit by at least 10 km in a given time. The semimajor axis was considered rather than the apogee altitude as the propulsion effect of the laser is spread out of a long period of time. Therefore, it tends to raise the orbit uniformly rather than only raising the apoapsis. Then, the feasibility of achieving these power levels and sailcraft masses was evaluated.

In the case of the passive concept, the GMAT model was used to simulate the performance of the system for a variety of laser lens sizes and laser powers. In each case, a sail size of a sail size of 0.01 m^2 was assumed and the maximum separation distance was calculated based on Equation 2. For each case, it was first determined whether the targeted orbit raise would be possible within a period of 5 years in the absence of drag. Drag was neglected during this phase of the simulation because its inclusion drastically increased the simulation runtime. Each case that was able to accomplish the mission within 5 years was then analyzed again with drag included.

2.5 Subsystem Allocation

One of the objectives of the project was to determine which subsystems must be developed and included for both the CubeSat and the sailcraft. In order to produce a design with the lowest possible cost and complexity of development, this allocation of subsystems was conducted with the intention of minimizing the number of total subsystems that would be needed on both spacecraft. Therefore, a subsystem was allocated to one of the spacecraft if it was necessary to satisfy a requirement.

A preliminary list of requirements was developed to enable this analysis. Each of these requirements was then matched with a subsystem that would be included to ensure that the system would meet this requirement. These requirements were simplistic initially, then refined further to enable initial design work.

2.6 Spacecraft Design

After the necessary laser and sail parameters were determined, an initial design was created. Requirements were refined and given additional detail based on the subsystems included in the spacecraft. Components were selected to allow Glowworm to fulfill its requirements and execute the mission. An iterative approach was taken to the design process, with each analysis and design decision reevaluated based on subsequent analyses. Where possible, components that are available commercially have been selected in order to minimize the amount of development work needed.

Several aspects of the Glowworm mission have necessitated a slightly unorthodox approach to the design of the spacecraft. While the mission contains two spacecraft, they must be designed in tandem as their performances are interrelated. Ideally, the two vehicles and all of their subsystems would be designed concurrently by a team of engineers who are experts in particular areas, however, this is not possible at this phase of development of the project. Most importantly, a form factor or mass limit for the mission has yet to be defined; this renders the usual systems engineering step of allocating a portion of the total mass to each subsystem impossible, as no fixed upper limit for total mass is known. Instead, an effort has been made to select the components for each subsystem that have the lowest mass while still being capable of achieving the mission. The CubeSat form factor to be used was then selected based on the mass and volume of these components.

3. Results

3.1 Orbital Simulations

The first step in analyzing the two Glowworm mission concepts was to determine whether it would be feasible to implement either concept with a realistically achievable laser power and sail size. Orbital simulations were conducted in GMAT to determine the minimum laser power and optical diameter needed to meet the 10 km orbit raise requirement in each case.

3.1.1 Passive Concept

The simulation for the passive concept was used to determine the time it would take for the 10 km orbit raise to be achieved for a given laser power, sail size, and maximum distance. A simulation of the best conceivable case was conducted to provide an initial indication of feasibility. The following best-case assumptions were used to develop this simulation:

- The best achievable laser diameter achievable with a CubeSat platform is 0.4 m. This corresponds to a CubeSat that is 4 units to a side.
- The minimum sailcraft size that is likely achievable is 0.01 m^2, which is the same as the size of a 1U CubeSat face. It is highly unlikely that a sailcraft much smaller than this is possible as this is only between about one and three times the size of previous chipsat concepts which have not included a sail.
- Using Equation 2, the best case operational distance corresponding to the 0.4 m laser diameter, a circular laser, and the 0.1 m sail size is 10.245 km.
- It was assumed for this phase of the analysis that the CubeSat could be made to be capable of tracking the sail over this distance.
- A best case laser power of 50 W was assumed. This is likely higher than what a CubeSat could sustain for long periods of time.

The results of the GMAT simulation executed with these assumptions showed that, even in a best case scenario, a CubeSat without propulsion would be unable to raise the orbit of the sail by more than 10 km. The laser is able to provide a noticeable increase in the orbit of the sail in its initial operation period, however this is not sufficient to introduce a large deviation between the orbital periods of the two spacecraft. Because the orbital periods remain similar, it takes many days for the sailcraft to pass within 10.54 km of the CubeSat again. Over this long period of time, the influence of atmospheric drag causes the orbit of the sail to decay more than it was raised originally. Therefore, over time, the orbit of the sail decreases rather than increases and will never reach an increase of 10 km. Figure 1 shows the change in the semimajor axis of the sailcraft's orbit over a 50 day period for the best case scenario described. The value of the SMA oscillates because of the oblateness of the Earth and point mass disturbances due to third bodies. The SMA initially increases in the first laser use window then decays to below its initial value before the second window. These are the only two windows to occur within the first 50 day period of the mission.

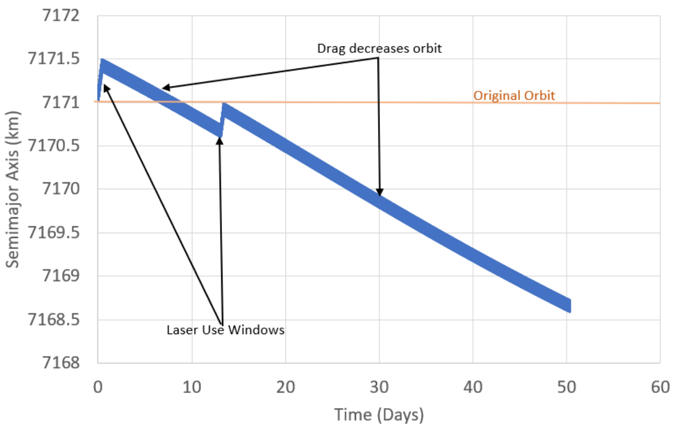


Figure 1: Passive concept change in semimajor axis

Figure 2 shows the separation distance, measured in kilometers, between the two spacecraft over the same 50 day period. The points where separation is less than 10.54 km correspond to the two laser use windows shown in Figure 1. It is interesting to note that the separation distance is still increasing at the end of the 50 day period considered, indicating that the third laser use window would not occur for over 100 days after the second. The stepwise increase in separation visible towards the right of the graph is an artifact of the increased step size between calculations added to the GMAT model when separation is high to decrease the total run time of the simulation.

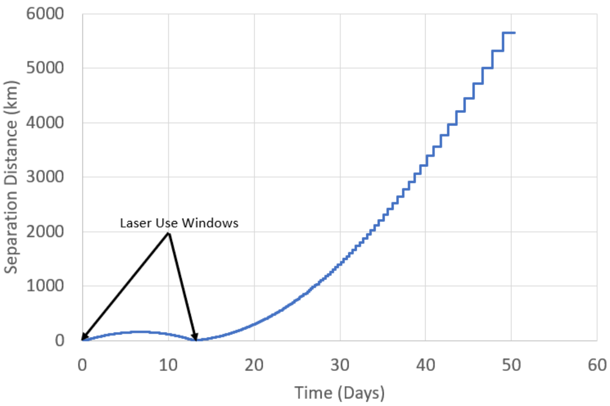


Figure 2: Passive concept separation distance

Atmospheric drag makes the passive concept of operations infeasible for the Glowworm mission. It is impossible for a CubeSat platform to raise the orbit of a laser sailcraft when operating in LEO. It is possible that the concept could be revived by inserting the mission into a much higher orbit, but this is unusual for CubeSats. Moreover, even without the influence of drag, the orbit raise would take five years or more to achieve. It is unlikely the CubeSat would survive in orbit for this long as only about half of CubeSats have survived for more than 600 days [9]. Therefore, achieving a 10 km laser sail orbit increase with a CubeSat that does not contain a propulsion system seems to be generally infeasible. A much larger spacecraft could accomplish the task but would need to be much larger and thusly much more expensive. As a CubeSat form factor is targeted for the Glowworm mission, the passive mission concept is not feasible.

Chaser Concept

In the case of the chaser concept, an approximate estimate of the constraints placed on laser and sail sizes can be achieved without a detailed orbital simulation. Since the CubeSat will be following the sail, it will be able to apply thrust with the laser continuously, creating a continuous acceleration. The ΔV to increase the orbit can be estimated as be 5.7 m/s. This can then be used to find the needed acceleration to achieve the orbit raise in a given time. Because this case involves continuous acceleration, the orbit raise would only be limited by the amount of propellent on the CubeSat. As there is likely to be sufficient propellant for a mission of years in duration, it is logical to select a maximum time for the mission to be completed within. Of CubeSats that successfully deploy and establish communication with the ground, around 90% survive for at least 50 days [9]. As this seems to be an acceptable level of risk, this will be targeted as the maximum time to achieve the needed orbit raise. With this maximum assumed, the acceleration needed to achieve the orbit raise targeted orbit raise can be calculated as seen in Equation 3.

$$a = \frac{\Delta V}{t} = \frac{5.7}{(50 * (3600 * 24))} = 1.319 * 10^{-6}\ \frac{m}{s^2} \quad (3)$$

Using this value with Equation 1 and the properties of dielectric mirrors allows the calculation of sailcraft mass and laser power values that can provide the needed acceleration. As this calculation does not use precise values for ΔV and does not account for the influence of drag and solar pressure, it is an approximation. To generate more precise values, a GMAT simulation was used. The simulation was run for a variety of sailcraft masses. In each case, the simulation was run for 50 days and GMAT's built in solver functionality was used to determine the thrust necessary to archive the required orbit raise at the end of the 50 day period. These thrust values were then used to calculate the laser power.

Figure 3 shows the results of both the simplified calculation and the GMAT simulation. As expected, the influence of atmospheric drag means that more power is required for low sailcraft masses. For higher sailcraft masses, GMAT somewhat counter-intuitively predicted a lower laser power than the constant acceleration estimate. This occurred because the continuous orbital increase modeled in GMAT is actually requires slightly less than the calculated 5.7 m/s. Additionally, the influence of the drag force decreases as the mass of the sailcraft increases.

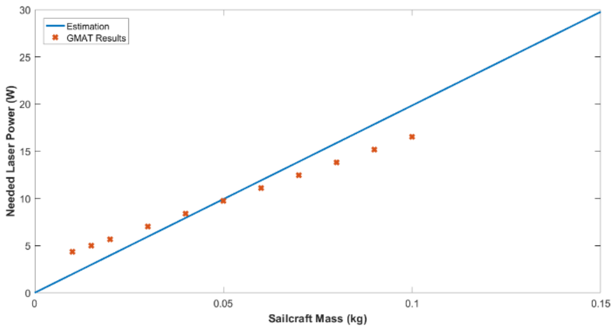


Figure 3: Chaser concept laser power as a function of sailcraft mass

The results shown in Figure 3 show that the needed laser power is within a feasible range for realistic sailcraft masses of between 50 and 100 g. Based on this result, it appears feasible to develop a system that falls within the required sail mass and laser power ranges. Therefore, further design of the Chaser concept was pursued.

Subsystem Allocation

A subsystem allocation was conducted to ensure that only subsystems that are necessary were developed. This was based on matching subsystems to necessary requirements. As no requirements have been defined by i4is, this process began with the development of some proposed requirements. **Error! Reference source not found.** shows the requirements developed and the subsystems that must be developed to satisfy them. It is important to note that careful attention was not paid to grammar and precision of language in this stage of requirements definition. The requirements were later rephrased and refined.

This process resulted in a fairly typical lineup of subsystems for the CubeSat, including all of the usual spacecraft subsystems (attitude determination and control (ADCS), electrical power supply (EPS), thermal protection, structure, communications, command and data handling (C&DH)) and the propulsion system that is inherent to the chaser concept. More importantly, this process indicated that the sailcraft would need to have several subsystems, meaning that it would need to be a more capable femtosatellite than those that have flown before. To fulfill these proposed requirements, the sailcraft will at minimum need an attitude control system to help it maintain a perpendicular orientation with the laser, as well as electrical power and command and data handling systems to support this. Additionally, it may need an accelerometer payload if this is selected of the uses of a laser range finder on the CubeSat. If this payload is included, it will also need a communications system to transmit the accelerometer data to the CubeSat.

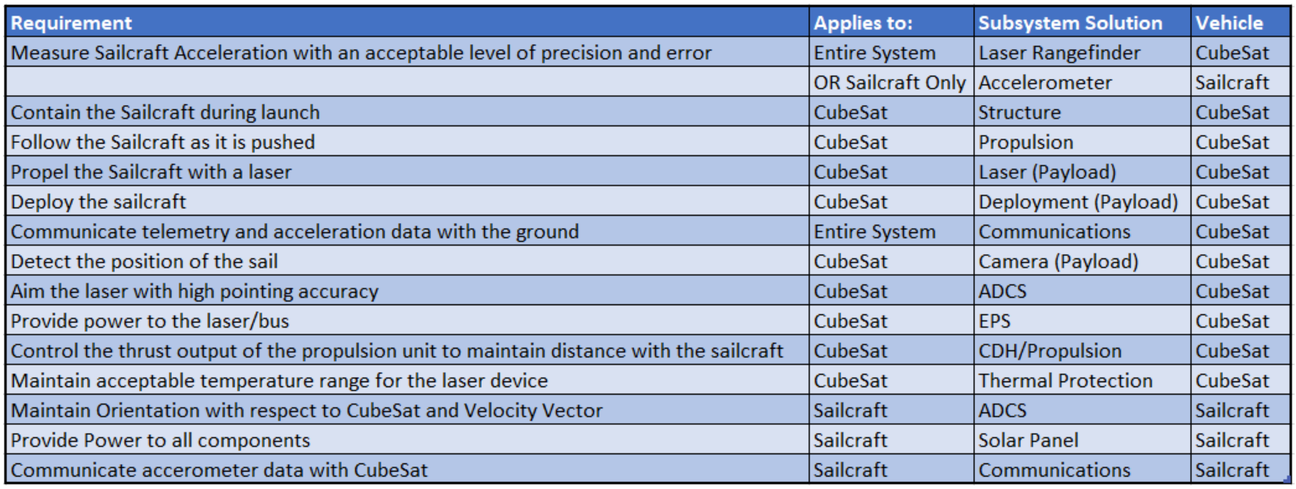
Preliminary Design

Design for the two spacecraft began with the development of more detailed requirements for each of their subsystems. This was necessary to ensure that the selected components were adequate to complete the mission. These requirements were used to guide the selection of components. Each requirement has been classified as a functional, performance or interfacing requirement. These were updated iteratively as the design process progressed; this is especially true for performance requirements that list particular values. The requirements are listed for the sailcraft in Table 3 and for the CubeSat in Table 4.

Sailcraft Design

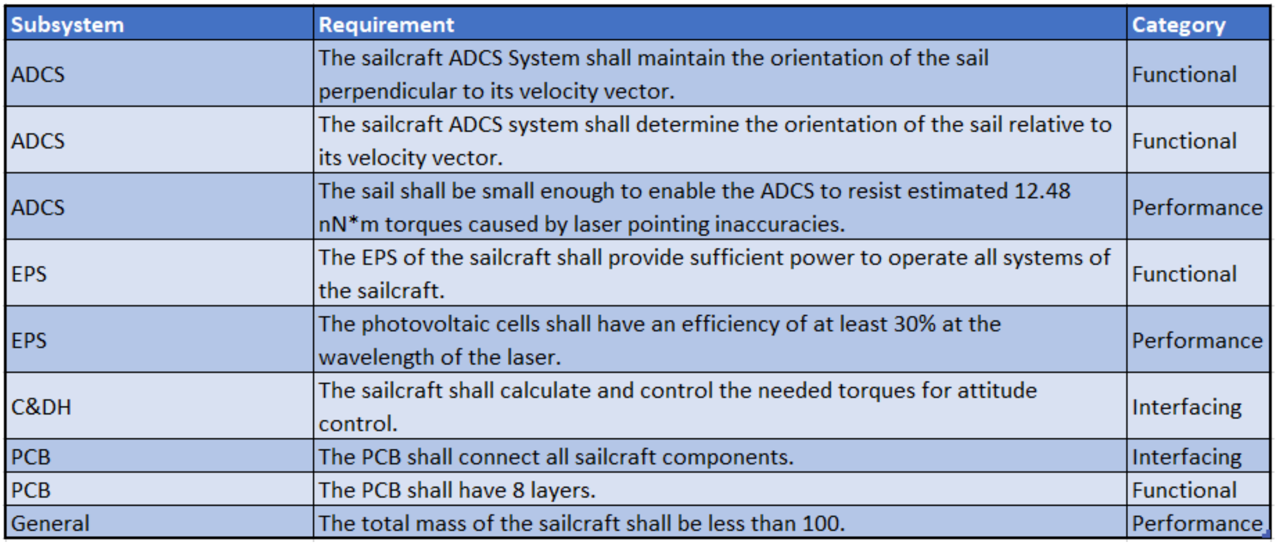
The refined requirements lists were used to begin the creation of a preliminary design. The design of the sailcraft was considered first. As the sailcraft will be contained within the CubeSat initially, it is part of the CubeSats payload. Because of this, the precise parameters of the sailcraft have a significant effect on the design of the CubeSat.

Component selection for the sailcraft was conducted by attempting to identify the lowest mass commercially available solution that would fulfil each subsystem requirement. First, the potential accelerometer component was considered. It was found that there is no currently available accelerometer that is small enough to fit on a chipsat which could meet the needed measurement sensitivity. Instead, the acceleration measurement can be generated by using a laser rangefinder on the CubeSat which would continuously measure the distance to the sailcraft. This measurement could be combined with readings from an accelerometer on the CubeSat to calculate the sailcraft's acceleration. This had the secondary benefit of reducing the overall sailcraft mass by removing the need for a communication system. The sailcraft's ADCS system was then designed. For attitude determination, a three-axis rate gyro and



Requirement	Applies to:	Subsystem Solution	Vehicle
Measure Sailcraft Acceleration with an acceptable level of precision and error	Entire System	Laser Rangefinder	CubeSat
	OR Sailcraft Only	Accelerometer	Sailcraft
Contain the Sailcraft during launch	CubeSat	Structure	CubeSat
Follow the Sailcraft as it is pushed	CubeSat	Propulsion	CubeSat
Propel the Sailcraft with a laser	CubeSat	Laser (Payload)	CubeSat
Deploy the sailcraft	CubeSat	Deployment (Payload)	CubeSat
Communicate telemetry and acceleration data with the ground	Entire System	Communications	CubeSat
Detect the position of the sail	CubeSat	Camera (Payload)	CubeSat
Aim the laser with high pointing accuracy	CubeSat	ADCS	CubeSat
Provide power to the laser/bus	CubeSat	EPS	CubeSat
Control the thrust output of the propulsion unit to maintain distance with the sailcraft	CubeSat	CDH/Propulsion	CubeSat
Maintain acceptable temperature range for the laser device	CubeSat	Thermal Protection	CubeSat
Maintain Orientation with respect to CubeSat and Velocity Vector	Sailcraft	ADCS	Sailcraft
Provide Power to all components	Sailcraft	Solar Panel	Sailcraft
Communicate accerometer data with CubeSat	Sailcraft	Communications	Sailcraft

Table 3: Detailed sailcraft requirements



Subsystem	Requirement	Category
ADCS	The sailcraft ADCS System shall maintain the orientation of the sail perpendicular to its velocity vector.	Functional
ADCS	The sailcraft ADCS system shall determine the orientation of the sail relative to its velocity vector.	Functional
ADCS	The sail shall be small enough to enable the ADCS to resist estimated 12.48 nN*m torques caused by laser pointing inaccuracies.	Performance
EPS	The EPS of the sailcraft shall provide sufficient power to operate all systems of the sailcraft.	Functional
EPS	The photovoltaic cells shall have an efficiency of at least 30% at the wavelength of the laser.	Performance
C&DH	The sailcraft shall calculate and control the needed torques for attitude control.	Interfacing
PCB	The PCB shall connect all sailcraft components.	Interfacing
PCB	The PCB shall have 8 layers.	Functional
General	The total mass of the sailcraft shall be less than 100.	Performance

Table 4: CubeSat requirements

Subsystem or Component	Requirement	Category
Rangefinder	The CubeSat shall determine the separation distance of the sail.	Functional
Laser	The laser shall have an optical output power of at least 16 W.	Performance
Laser Optics	The laser optics shall focus the laser beam such that it occupies the entire area of the sail at a distance of 3 m.	Functional
Laser Optics	The laser optics shall be constructed from a material suited to long term IR exposure.	Functional
Optical Camera	The CubeSat shall incorporate an optical camera to detect the location of the sail.	Functional
Sailcraft Deployment	The deployment mechanism shall deploy the sailcraft without inducing a rotation.	Functional
Sailcraft Deployment	The deployment mechanism for the sailcraft shall have a mass that is less than 90 g.	Performance
Propulsion	The propulsion system shall maintain a separation distance of 3 m between the CubeSat and the sailcraft.	Functional
Propulsion	The thrust of the propulsion system shall be throttleable.	Functional
Propulsion	The propulsion system shall provide sufficient thrust to counter the effect of solar pressure.	Functional
ADCS	The ADCS system shall provide a pointing accuracy of 1.68 degrees or fewer.	Performance
ADCS	The ADCS system shall incorporate a GPS receiver and an accelerometer.	Functional
C&DH	The OBC shall communicate with components via SPI, i^2C, and RS-422 interfaces.	Interfacing
Communications	The CubeSat shall use UHF or VHF for communications.	Functional
EPS	The EPS shall provide 45 W of power continuously.	Performance
EPS	The EPS shall include batteries to power initial operations until solar panel deployment.	Functional
Structure	The CubeSat shall have a 3U structure.	Functional
Structure	The structure shall contain and secure all components.	Interfacing
Structure	The sailcraft deployment mechanism shall be structurally isolated from the rest of the CubeSat.	Functional
Thermal Protection	The thermal protection system shall have a mass that is less than 160 g.	Functional
Thermal Protection	The thermal protection system shall maintain all components within their operational temperature ranges.	Functional

three axis magnetometer were selected; both of these components were low mass and commercially available. Attitude control will be achieved using three magnetic coils to interact with the Earth's magnetic field. A space qualified microprocessor developed by Atmel was selected for C&DH. The electrical power for the sailcraft will be provided using a small solar panel optimized for the wavelength of the laser. This will enable higher efficiencies than typical solar panels [6]. A 6 cm by 6 cm circuit board with 8 layers was selected to contain these components.

Table 5 gives the mass distribution for the current sailcraft design. While the total mass estimated based on the components selected is only 44.5 g, a 100% margin has been applied to account for errors in mass estimation and currently unknown masses, such as that of solder used to attach components to the PCB. With a total mass of 89 g, the chipsat portion of the sailcraft is only slightly less massive than Pocket PUCP which is the most complex chipsat to fly to date. This is not surprising as the design is similar in functionality to Pocket PUCP [10]. Even with a sail of significant mass, the current mass of the sailcraft is low enough to fall within the feasible range shown in Figure 3. While this design would certainly benefit from further optimization, its current status indicates that the sailcraft portion of the Glowworm mission is feasible.

Table 3: Sailcraft mass budget

Subsystem	Mass (g)
C&DH	4.8
ADCS	16
EPS	2.8
Thermal Protection	1.9
Circuit Board	19
100% Margin	44.5
Total	89

The necessary sail area was then estimated. Initially, it was expected that this estimate would be based on determining a target operational distance and using Equation 2. However, it was found that the laser spot size calculated using Equation 2 for operational separation distances suitable for laser range finder measurement was significantly smaller than the likely sail size. Therefore, the sizing of the sail was governed by the need to achieve a sufficiently large reflective surface. As discussed previously, the material properties of dielectric mirrors consisting of SiO_2, TiO_2, and MgF_2 were utilized. The needed sail area was estimated based on the surface area of the femtosatellite portion of the sailcraft. If the femtosatellite were a significant portion of the total surface area, the actual reflectance would significantly lower than the dielectric mirror reflectance. Ideally, the sail would represent 99% or more of the total surface area. However, it was found that sail areas exceeding 95% of the total area produced laser power densities that were too low to provide sufficient electrical power to the sailcraft. Therefore, 95% was used. As the surface area of the femtosatellite portion of the spacecraft is 0.0036 m^2, the total surface area was estimated as 0.072 m^2. This corresponds to a square sail with sides approximately 26.8 cm in length. Using the material properties given in Table 1, this yields a sail mass of 0.25 g and an average reflectance (treating the femtosatellite as completely non-reflecting) of 0.947. This produces a total estimated sailcraft mass of 90 g including both sail and femtosatellite contributions.

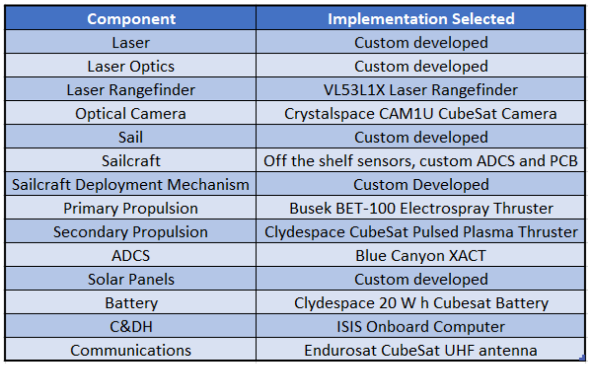
Next, the design of the CubeSat portion of the mission was considered. For the sake of brevity, the detailed logic underlying each design decision made will be omitted. For those interested in more detail, the full report detailing this project is available at the ISU library website. This resulted in the creation of a preliminary design for a 3U CubeSat for the Glowworm mission. The designed CubeSat is theoretically capable of achieving the goals of the mission and meeting all requirements derived from these goals. However, two significant areas of concern have been identified.

Table 6 gives the current mass budget for the CubeSat. 50% of the total mass has been allocated as margin as recommended by Brown, producing a total mass of 6.9 kg [11]. This represents a significant potential issue. The current mass estimate is almost two times the usual 4 kg maximum mass of a 3U CubeSat. It is possible that this usual maximum mass could be waived for the purposes of this mission, but this is not certain. Switching to a 4U volume would potentially alleviate this problem but would in turn result in a mass increase. The current mass estimate is not high enough to prohibit implementation of the mission but could become problematic as design work proceeds.

Table 4: CubeSat mass budget

Subsystem	Mass (kg)
Payload	0.331
Propulsion	0.83
ADCS	0.91
EPS	1.061
C&DH	0.094
Communications	0.085
Thermal	0.138
Margin	3.449
Total	6.898

Table 5: Selected CubeSat components



Component	Implementation Selected
Laser	Custom developed
Laser Optics	Custom developed
Laser Rangefinder	VL53L1X Laser Rangefinder
Optical Camera	Crystalspace CAM1U CubeSat Camera
Sail	Custom developed
Sailcraft	Off the shelf sensors, custom ADCS and PCB
Sailcraft Deployment Mechanism	Custom Developed
Primary Propulsion	Busek BET-100 Electrospray Thruster
Secondary Propulsion	Clydespace CubeSat Pulsed Plasma Thruster
ADCS	Blue Canyon XACT
Solar Panels	Custom developed
Battery	Clydespace 20 W h Cubesat Battery
C&DH	ISIS Onboard Computer
Communications	Endurosat CubeSat UHF antenna

Table 7 shows the selected implementation solutions for key elements of the Glowworm mission. This table succinctly illustrates the second major concern inherent in the current design: a very large number of components will need to be custom developed for the mission. As each of these components will require significant design and testing work, this will likely represent a major driver for the cost and schedule of the mission.

4. Conclusions

Laser sail propulsion is a promising concept that could enable interplanetary missions with rapid travel times or even interstellar missions. While the concept has existed since the 1960s, it was long considered to be technologically infeasible. Recent advances in spacecraft miniaturization could change this. It could be possible to accelerate chip sized spacecraft to relativistic speeds using current or near future laser sail technologies.

Despite this possibility and the promise of the concept, laser sail propulsion has yet to be demonstrated in orbit. The Initiative for Interstellar Studies aims to change this by implementing the Glowworm mission. Glowworm consists of a CubeSat which will deploy a small sailcraft and propel it using an onboard laser. An 800 km sun-synchronous orbit has been identified as a likely option for the mission as this orbit would reduce the influence of solar pressure and drag when compared with lower non-sun-synchronous orbits. i4is has indicated that an increase of 10 km in the semimajor axis of the sailcraft orbit would be sufficient to constitute mission success.

Two mission concepts have been proposed by i4is for Glowworm. The first would have the CubeSat follow the sail and apply propulsion with the laser continuously. The second would have the CubeSat remain in its initial orbit and propel the sail when their orbits aligned. Analysis conducted using GMAT showed that the latter concept is impossible to implement using a CubeSat to carry the laser. The largest CubeSat form factors would enable use of a laser that can propel a sail at a distance of only 10 km. Such a configuration results in infrequent laser use windows. Between these windows, the influence of atmospheric drag, even in an 800 km orbit, far outweighs the thrust of the laser.

The chaser concept, which utilizes a propulsion system onboard the CubeSat shows promise, however. GMAT analysis of this concept indicated that the 10 km orbit increase could be achieved in 50 days of operation using feasible laser power and sail size values. Design work for this concept was conducted.

This process began with the development of proposed requirements and the allocation of subsystems to each spacecraft. Each subsystem was only deemed necessary if it was the only way to fulfill one or more requirements. This process resulted in a relatively standard array of subsystems for the CubeSat; the sailcraft was found to need ADCS, C&DH, and EPS subsystems in addition to a potential accelerometer payload. The need for these subsystems means that the sailcraft will need to be more complex than previous chipsats.

Design for the two spacecraft was then considered. The requirements developed for the subsystem allocation were further refined to provide more guidance to the design process. Then, the sailcraft was designed. This was done first because it is part of the payload of the CubeSat. Then components were selected for the CubeSat. This formed an iterative process; each aspect of the system was reevaluated each time new assumptions were introduced or new components were selected. This process resulted in an initial design for a 3U CubeSat which has a mass of 6.9 kg and a volume of 2100 cm^3. This mass is higher than the usual 3U CubeSat maximum mass and many components, including the solar panels of the CubeSat, will need to be custom developed.

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