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Design of the Alpha CubeSat: Technology Demonstration of a ChipSat-Equipped Retroreflective Light Sail

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This paper provides an overview of Alpha, a rapidly developed, low-cost CubeSat mission to verify the performance of a highly retroreflective material for light-sail propulsion. Designed, integrated, and tested by students of the Space Systems Design Studio at Cornell University, this mission demonstrates a number of key technologies that enable next-generation capabilities for space exploration. In particular, this paper focuses on the novel application of ChipSats (gram scale spacecraft-on-a-chip technology) as a means of verifying Alpha's sail orbit and attitude dynamics. Other innovations include an entirely 3D-printed structure to enable quick and inexpensive prototyping, an onboard Iridium modem that bypasses the need for ground-station radio equipment, retroreflective sail material that provides more deterministic thrust from laser illumination, and an attitude-control subsystem that provides full attitude and angular-rate control using magnetorquers only. In addition to these near-term technology demonstrations, Alpha is among the first exhibitions of holography in space, a medium that shows longer-term promise in several roles for interstellar travel.

I. Introduction

A longstanding limitation in space exploration is the amount of propellant a spacecraft carries. Larger Earth satellites, like those used for weather, GNSS, and communications, average lifetimes of 10-15 years before expending all of

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their propellant [1]. Outer-planet missions have similar lifetimes, and typically rely on gravity-assist trajectories for additional energy in order to reach their destinations. Harnessing momentum from photon pressure instead of chemical propulsion, light-sail technology offers a promising alternative that could decrease operational costs and enhance spacecraft capabilities [2].

Light sails, also known as solar sails or photon sails, consist of large sheets of thin reflective material. Photons reflect off the sail, transferring momentum and thereby providing a small push. Spacecraft attitude control orients such a sail relative to this light source; similar to how traditional sails maneuver with the wind. In order to capture as much momentum as possible from solar radiation pressure (SRP), sail designs typically span large surface areas while keeping mass to a minimum. Solar sailing generates relatively low thrust. Unlike short burns of propellant, however, this thrust is continuous and can produce significant delta-V over time. If illuminated by higher-density photon flux, e.g. from lasers, the light sails can be smaller or accelerations higher thanks to higher pressure. Solar sails have flown on a handful of technology-demonstration missions thus far, most notably JAXA's IKAROS mission to Venus, with several more planned for the near future. Laser sail technology is far less mature [3].

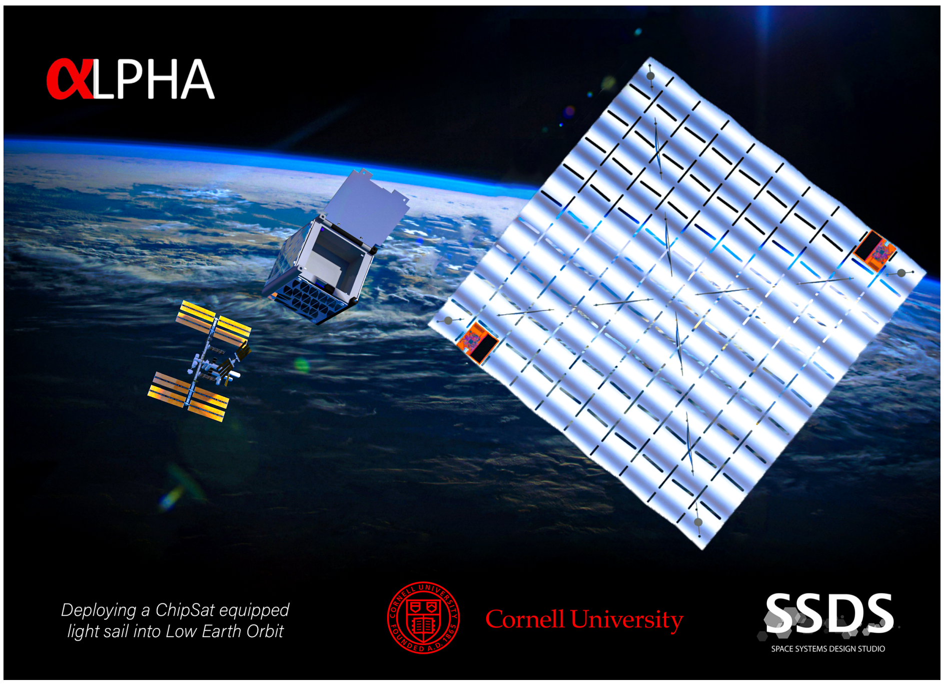


Fig. 1 Artistic representation of the Alpha mission [Image courtesy of Stephanie Young]

This paper provides an overview of the 1U Alpha CubeSat, a novel light-sail mission developed by the Space Systems Design Studio (SSDS) at Cornell University. At 575 mm x 575 mm, Alpha's light sail is smaller than those of similar missions, but features several key advantages. Alpha is the first use of a highly retroreflective material for light-sail propulsion, sending nearly all light back in the direction of its source. The thrust vector is continuously aligned with the light direction, regardless of the orientation of the sail. For this reason, the ability to regulate thrust is built into the physics of the sail material, eliminating the role of attitude control in managing the thrust direction. Alpha's light sail also features a shape-memory alloy frame, enabling near-instantaneous and predictable deployment and rigidization. Lastly, the Alpha sail has a significantly lower areal density, in part because of its small scale, achieving high accelerations on par with the most efficient light sails flown to date. The promise of this architecture in pushing the limits of photon sail technology motivates this flight demonstration.

This high acceleration is made possible by the fact that the Alpha light sail is a free-flying object, untethered from the CubeSat that deploys it into orbit. In spite of this separation, valuable data can still be obtained and downlinked through the novel application of ChipSats (gram scale satellite-on-a-chip technology) as the sail's onboard computer. Developed by SSDS, ChipSats take advantage of the miniaturization of electronics in the smartphone era to produce what has been dubbed "the world's smallest spacecraft" [4]. The newest generation of ChipSats, named Monarch [5], features a flexible

Kapton substrate and more powerful solar cell. The increased power enables GPS capabilities and a 6-DOF inertial measurement unit (IMU). With four Monarchs mounted on the corners of the sail, the enhanced sensor suite allows for tracking of the sail position and verification of attitude dynamics using only a handheld antenna and a software-defined radio (SDR).

Payload aside, a significant portion of this paper is devoted to the design of the Alpha CubeSat itself. In addition to its primary mission as a delivery vehicle for the light sail, the 1U CubeSat has secondary technology-demonstration goals of increasing the capability, responsiveness, and affordability of traditional nanosatellite system architectures. The subsequent sections provide a mission overview, and discuss the innovative aspects of each subsystem:

1) Electrical subsystem is composed entirely from inexpensive commercial off-the-shelf (COTS) components.
2) Structure is 3D printed, enabling rapid and low-cost prototyping, and component compartmentalization.
3) ACS (Attitude Control System) achieves full inertial-body attitude and angular-rate control using magnetorquers only.
4) Communications subsystem uses an Iridium modem that bypasses the need for expensive radio equipment. The Ground Station requires only a web interface for the CubeSat, and a handheld antenna for the light sail.

Lastly, the Alpha CubeSat features a pioneering exhibit of holography in space. Holographic films are mounted on the solar panels of the CubeSat, serving as a message plaque inspired by Pioneer 10 & 11 and the Voyager Golden Records. Despite that they overlay the solar cells, these holograms impede less than 1% of the incident light; so, their effect on the orbit-average power available to Alpha is negligible. Unified by the common code of DNA, the work embodies life-centric themes that contrast the robotic aesthetic of most spacecraft [6]. Each film also contains multi-angle exposures of retroreflective surfaces, providing a means for verifying the behavior of holograms in the space environment. The holograms, like the Alpha mission itself, are inspired by interstellar-travel initiatives such as Breakthrough Starshot. Serving the dual purpose of a message plaque and a method of laser-sail stabilization, holograms have been proposed as a key technology for a successful journey to Alpha Centauri [6].

II. Light Sail Background

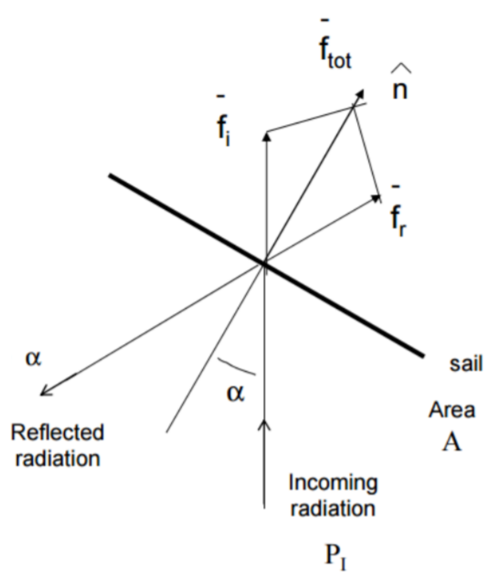


Fig. 2 Light sail vector diagram

The idea of using SRP incident on spacecraft as a means of control or propulsion dates back to the nineteenth century. James Clerk Maxwell's demonstrations proved that sunlight could exert pressure on a reflective surface [7]. While massless, photons carry momentum, ρ, according to

$$\rho = h\nu/c \tag{1}$$

where h is Plank's constant, ν is the light-wave frequency, and c is the speed of light. When light reflects off a surface at an incident angle α, it provides momentum transfer from two effects. The first is from the photons as they impact the surface. This force, denoted by $\boldsymbol{f_i}$ is in the direction of the incoming radiation pressure, P_I. The second is the reaction of the photon reflection. Denoted by $\boldsymbol{f_r}$, this force is opposite the direction of the reflected radiation.

This phenomenon was first applied to the concept of "solar sailing" in the early 1900's, when Konstantin Tsiolkovsky and Fridrikh Tsander speculated that "tremendous mirrors of very thin sheets" could achieve favorable results for flight in interplanetary space [8]. Assuming perfect reflectivity, the resultant force vector, $\boldsymbol{f_{tot}}$, is always in the direction of the normal vector, $\boldsymbol{n}$, of the sail. Therefore, the sails control their trajectories by orienting relative to the source of incident light. The magnitude of the resultant force is dependent on pitch angle α and is described by

$$\boldsymbol{f_{tot}} = 2P_I A(\cos\alpha)^2\boldsymbol{n} \tag{2}$$

Figure 2 shows these vector relationships [9].

The principles of solar sailing have been demonstrated on various spacecraft since 1962, when the technique was first implemented by JPL to save the Mariner 10 mission after significant propellant loss [7]. However, there are few examples as notable and groundbreaking as the Japan Aerospace Exploration Agency's (JAXA) IKAROS mission. This spacecraft is the first to use light sailing as the primary method of propulsion. IKAROS exhibited a 14 m x 14 m light sail with 80 Reflectivity Controlled Devices (RCDs), thin films with adjustable liquid-crystal components that rotate the sail in a controlled manner [10]. Since the mission's success in 2010, several other light-sail missions have been proposed and deployed, such as LightSail 1, LightSail 2, and NanoSail-D2. All of them are designed to demonstrate and collect data for solar sailing in Low Earth Orbit instead of deep space [8].

Future missions to employ light sail technologies build upon these legacy technologies, addressing science objectives that include near-Earth objects such as NEA Scout, or combining with ion propulsion as in JAXA's proposed OKEANOS. Other light-sail missions are testing novel applications of solar sails. Examples include the CubeSail project, which seeks to adapt light sails as a drag-augmentation device for deorbiting [11]. A "pole-sitter" mission has also been proposed for continuous and propellent-less coverage of the polar regions [7]. Lastly, a long-term goal for light sails is beamed-energy propulsion. One such application is the Breakthrough Starshot initiative, which aims to accelerate a fleet of 1000 laser-sail spacecraft to relativistic speeds in order to explore the Alpha Centauri system within our lifetime [12].

III. The Alpha Payload

The sail developed for the Alpha Mission tests a novel deployment method and seeks to prove the concept of using retroreflective materials in light-sail propulsion. It is cut from a 1.2 mm thin sheet of Avery Dennison® OmniViewTM T-9500 polycarbonate film and carries four Monarch ChipSats as flight computers. Stowed in a Miura-fold configuration, the sail deploys as a free-flyer from the CubeSat and expands via a Nitinol-wire frame. At 0.33 m^2 and 93.5 grams, it is the smallest and lightest sail mission to date. This section provides an overview of each innovative aspect of the payload design, highlighting the distinctions that enable Alpha to achieve a high acceleration on par with the most efficient light sails deployed so far.

A. Retroreflectivity

By reflecting photons back exclusively in the direction they came from, retroreflectivity ensures that the thrust vector remains exactly parallel to the direction of the incident light. With the ability to regulate thrust built into the physics of the sail material, complex (and heavy) attitude-control systems are no longer required. This feature is particularly useful for predictability, reliability, and mission planning because it eliminates the reliance on attitude control or other means to steer the sail. For large sails, attitude control can be challenging because of the system's high moment of inertia and low structural frequencies, both of which demand subtle feedback-control architectures. For JAXA's IKAROS mission, the sail relied on RCDs, whereas previous light-sail CubeSat missions used traditional attitude-control mechanisms onboard the spacecraft (e.g. reaction wheels) to steer the direction of impulse [13]. In the case of Alpha, the sail spins. This momentum stiffness ensures a repeatable orientation of the sail and passive stability throughout the mission.

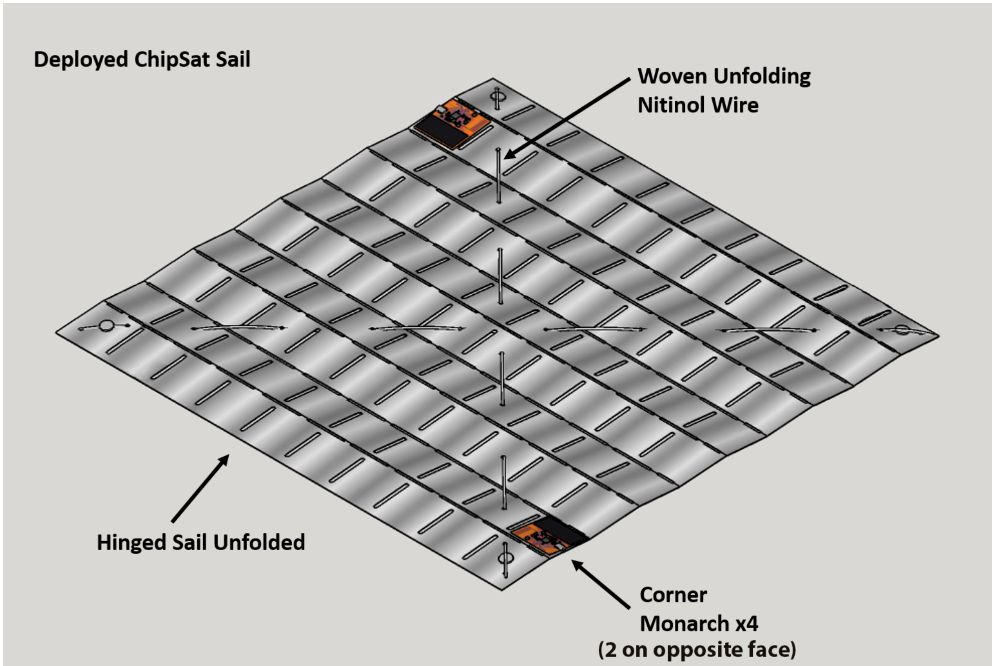


Fig. 3 Rendering of the Alpha light sail assembly

B. ChipSats

In addition to requiring no attitude control from the CubeSat, the sail is independently capable of collecting and downlinking data. Complete independence from the CubeSat's sensors, flight computer, and radio (and therefore significant reduction to light-sail weight), is made possible through the novel application of gram scale satellite-on-a-chip technology (ChipSats) onboard the sail. A technology development program in SSDS since 2006, ChipSats exploit the miniaturization of electronics to fit all the essential components of a satellite on a single PCB [14]. The first prototypes were launched in 2011 as part of the MISSE-8 experiment and demonstrated survival in the LEO environment over a three-year exposure outside the International Space Station [15]. Since then, there have been a handful of free-flying ChipSat missions, notably KickSat 1 & 2 as well as a launch funded by Breakthrough Starshot [16]. Research is currently underway to increase their capabilities.

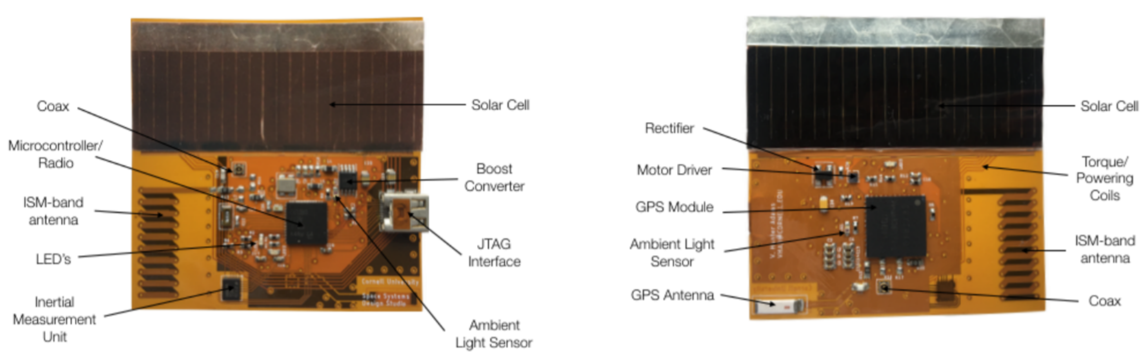


Fig. 4 Monarch ChipSat with consumer-market electronics components labeled

Alpha's ChipSats are slightly wider, although thinner and lighter, than those previously flown (5 cm x 5 cm instead of 3.5 cm x 3.5 cm) in order to accommodate a high-efficiency flexible solar cell [17]. Capable of 300 mW, the flexible thin-film cells produce about triple the power of the 40 mW cells onboard the prior "Sprite" ChipSat [18]. This power permits Monarchs to operate a GPS receiver, a radio, and an IMU continuously in illumination, enabling the sail to telemeter its orbit and attitude dynamics. To reduce mass further, and to take advantage of the solar cell's flexibility, the Monarchs are printed on a lightweight Kapton substrate. The flexible PCB allows for easy folding of the sail with little risk to the ChipSats. The larger surface area accommodates a PCB helical antenna in place of the previous Sprite's hand-soldered dipole antenna, which had been a bottleneck in the manufacturing process. Despite their increased size, Monarchs still weigh under 3 grams each [5], more than a 1/3 reduction in mass from the Sprites. A full outline of the Monarch capabilities is shown in Figure 4 [5].

While capable of networking as a swarm, Monarchs on the Alpha mission operate as four independent flight computers. Two are mounted on each face of the deployed sail in order to ensure continuous power and telemetry outside of Earth eclipse. These design features add redundancy to the mission and augment the quantity and accuracy of the sail data.

C. Passive Deployment

As a third and final aid in the reduction of weight, the Alpha light sail features a passive deployment mechanism through a shape-memory alloy frame. Shown in Figure 3, this cross-frame structure is constructed from two 0.028" Nitinol wires woven through the polycarbonate film. When stowed, the wires provide a restoring spring force to unfold the sail. With the exception of NanoSail-D, the unfurling of every sail flown thus far has been motor driven, and all have used booms or struts [8], which adds significant mass to an otherwise lightweight sail. The deployment process for these missions typically spans several minutes to hours. In contrast, the reduced complexity of the Alpha sail allows for a near-instantaneous unfolding. Rigid structures and controlled-deployment mechanisms are often necessary for larger solar sails. However, what enables Alpha's boomless design is not only its small size, but its retroreflectivity. As incident light reflects back in the same direction regardless of sail orientation, the sail can be floppy and exhibit an uneven, deformed surface without altering the thrust direction.

The flexible Nitinol frame is stowed together with the sail in a Miura-fold configuration. Such folds are used by JAXA to simplify the deployment of large solar-panel arrays, as the folded shape only requires forces applied on opposite corners to unravel [19]. This force is exerted by a smaller number of servos than a conventionally-folded solar array. In the case of the Alpha sail, deployment is greatly simplified. The shape-memory alloy frame doubles as the mechanism that pushes on opposing edges of the Miura fold. With no powered actuation needed for deployment, and a less-rigid structure, the Alpha sail can be made even lighter.

D. High Acceleration

By integrating ChipSats, passive deployment, and retroreflectivity, the need to remain attached to the CubeSat is eliminated entirely. As such, the Alpha light sail can be free flying. It is completely untethered from the spacecraft that deploys it into orbit and carries only 12 grams of electronics on board. Upon activation of the payload compartment burn-wire mechanism, the sail ejects from the Alpha CubeSat at a speed of 2 m/s. The free-flying nature of Alpha is perhaps its most significant distinction from existing light-sail missions and one that leads to the greatest reduction in sail mass. As a result of this lower mass, a retroreflective free-flying light sail requires far less thrust to alter its trajectory.

The effectiveness of a light sail is encapsulated in the dimensionless figure of merit known as the lightness number, L. This measure is conventionally defined as a ratio of the force exerted on the sail due to SRP and the gravitational force due to the Sun [2]. The greater the lightness number, the more effective the sail is at accelerating and altering its trajectory. Assuming consistent gravitational forces and solar irradiance (e.g. same distance from the sun), comparison across light sails boils down to the sail loading number, σ. Sail loading number, expressed in g/m^2, is defined as the ratio of total mass, m_{tot} to sail surface area, A [8].

$$\sigma = \frac{m_{tot}}{A} \tag{3}$$

A tabular comparison of light-sail missions launched by the time of publication is shown in Table 1. At 93.5 grams and 0.575 m x 0.575 m, Alpha has a solar loading of 283. This loading is on par with missions such as NASA's NanoSail D and the Planetary Society's LightSail. Given the limitations of Alpha's 0.5U payload compartment, this figure is a significant accomplishment. It enables notably high accelerations for a sailing spacecraft of this scale. At a larger scale, this architecture would likely outperform all current solutions.

Table 1 Comparison of Alpha sail loading number to all missions flown (as of Jan. 2021)

	IKAROS (2010)	NanoSail D-2 (2010)	LightSail-1,-2 (2015, 2019)	CanX-7 (2016)	InflateSail (2017)	CubeSail (2018)	Alpha (2021)
Propelled Mass	315 kg	4 kg	5 kg	3.75 kg	3.2 kg	3.5 kg	93.5 g
Sail Dimensions	14m x 14m	3.05m x 3.05m	5.6m x 5.6m	2m x 2m	3.3m x 3.3m	7.7cm x 250m	0.575m x 0.575m
Sail Area	196 m^2	10 m^2	32 m^2	4 m^2	10 m^2	20 m^2	0.33 m^2
$\sigma\,(\mathbf{g/m^2})$	**1607**	**400**	**156**	**938**	**320**	**175**	**283**

IV. Alpha Mission Overview

This section provides an overview of the Alpha mission, and highlights the many innovations of the CubeSat design that pave the way for increasingly affordable nanosatellite system architectures. The mission was conceived in 2016 as part of an international high-school CubeSat Competition by the Museum of Science Fiction. A STEAM (Science, Technology, Engineering, Art & Math) education initiative, the competition sought to reward innovation that leveraged off-the-shelf technologies and other agile approaches to creating next-generation spacecraft, with a total budget under $10,000 [20]. University partners would then help make the spacecraft concepts a reality, for a possible launch through the NASA CubeSat Launch Initiative (CSLI). Ithaca High School's winning "CayugaSat" submission evolved into a partnership with Cornell University's Space Systems Design Studio, and their design was adapted into what has become the Alpha CubeSat.

Consistent with the goals of the competition, Alpha was developed with simplicity and affordability in mind. Over summer 2016, the CubeSat was brought from concept to a fully assembled unit in just 10 weeks by maximizing the use of low-cost rapid prototyping techniques such as 3D printing, and COTS components from hobbyist companies such as Adafruit and SparkFun. After additional testing and design modifications, Alpha applied for CSLI in 2017, was selected by NASA the following year [21], and is slated for launch in 2021.

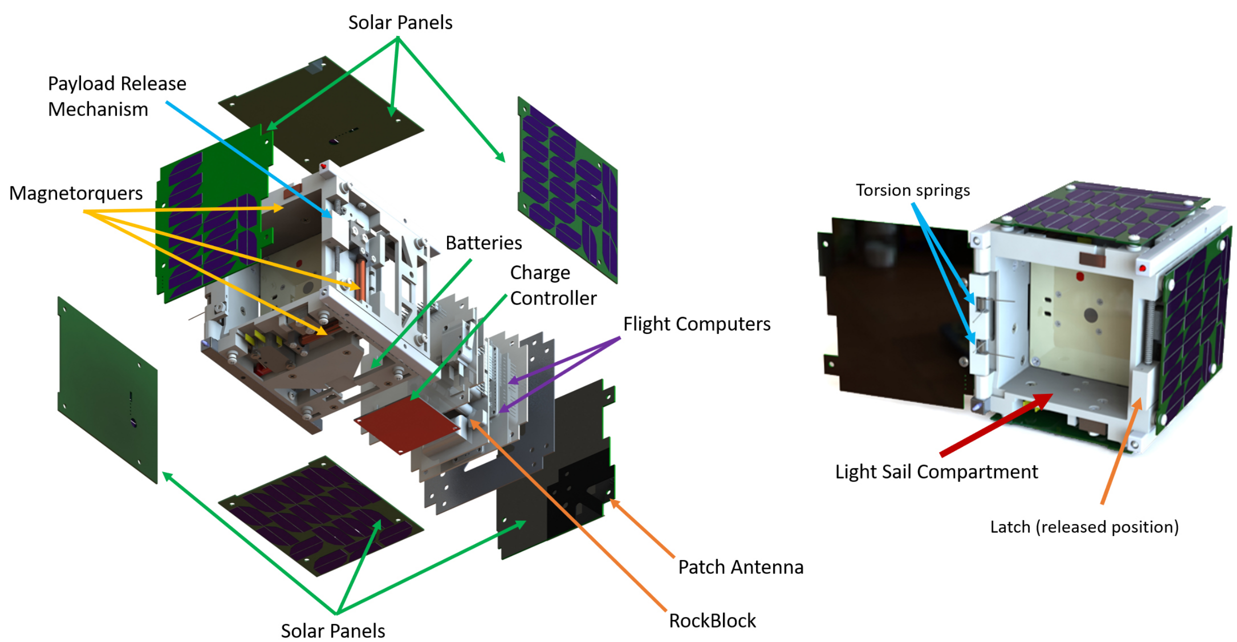


Fig. 5 Exploded view of the Alpha CubeSat (left); Open light sail compartment (right)

A. Introduction to the Alpha CubeSat

Alpha is a 1U CubeSat (10 cm x 10 cm x 11.35 cm) with a total mass of 1.5 kg. The spacecraft is divided into two primary compartments, 0.5U each, that respectively house the light sail and main electronics stack.

As shown in Figure 5, the top solar panel is mounted on a hinge, serving as a hatch for the payload compartment. The hatch is held shut by a spring-loaded latch, which is in turn held in place by two nylon fishing lines. When it is time to release the light sail into orbit, two Nichrome burn wires cut the nylon lines. The force from the Nitinol frame of the compressed sail, as well as the torsion springs mounted in the hinge, swing open the hatch and allow the light sail to deploy.

B. Mission ConOps

The Alpha mission follows a short and straightforward Concept of Operations (ConOps), outlined in Figure 6. Upon deployment from the ISS, the CubeSat powers up, initializes detumbling, and begins a two-hour countdown to start transmissions. After a period of three weeks—a safe distance from the space station when normal-mode operations have been established—Alpha begins its primary mission. With frequent transmissions and spin stabilization achieved, the ground commands the CubeSat to release the light sail as it flies over North America (ITU Region 2, due to ISM band communications). The burn-wire mechanism then releases the payload hatch, ejecting the sail in a spin motion to facilitate unfolding and free-flying stability. Lastly, powered-on upon release, the Monarch flight computers continuously relay GPS, accelerometer, and gyroscope data, enabling tracking of the sail and telemetry describing its attitude dynamics.

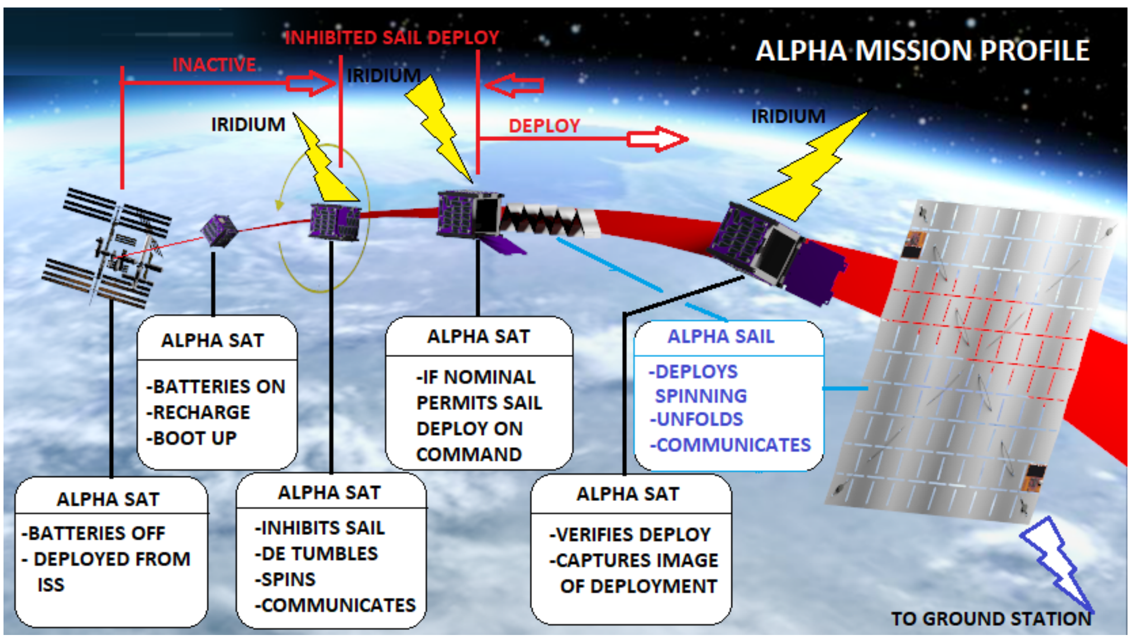


Fig. 6 Alpha Mission Concept of Operations

C. Flight Code

With a Teensy 3.5 as the onboard computer, programming was carried out exclusively in the Arduino IDE. The Alpha flight code follows a simple protocol consisting of an initialization process and five modes of operation. These modes are outlined in Figure 7, and the section succinctly walks through each. What differs between modes is largely the type and content of the data sent back to the Ground Station, as well as the frequency of sensor data capture in order to conserve power. If no faults are detected, the spacecraft remains in Normal Mode.

<u>Initialization</u>
The flight computer powers on upon deployment from the ISS. ACS operations are allowed, as well as transmissions after a two-hour countdown. The spacecraft then detumbles and aligns with the magnetic field. As the antenna mounted to the -z-axis is directional, this maneuver enables a better connection with the Iridium Network.

<u>Normal Mode</u>
After initialization, the spacecraft enters Normal Mode for frequent transmissions. This mode follows a simple

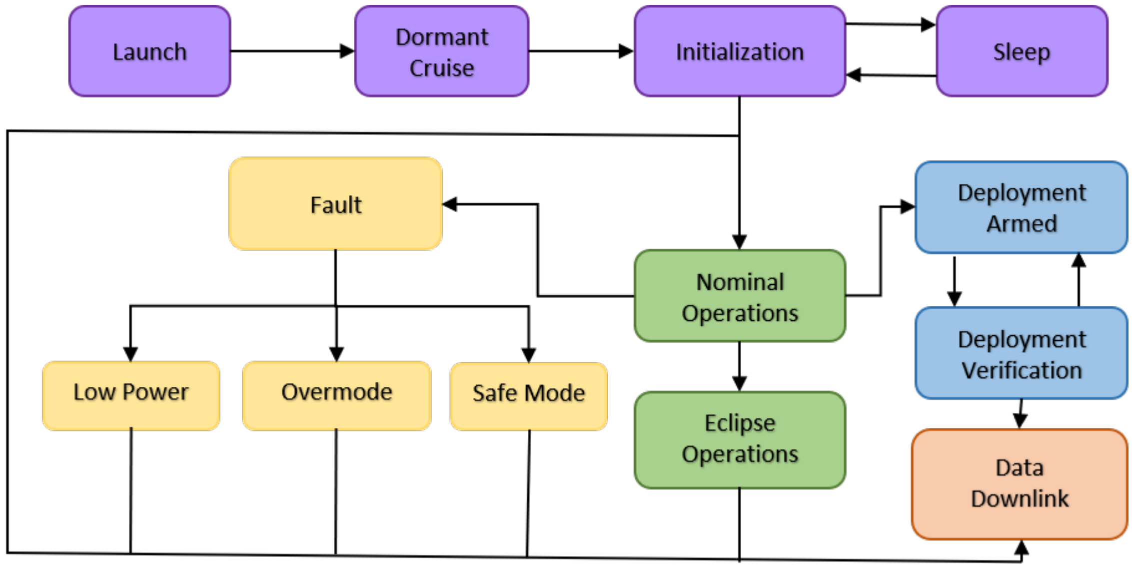


Fig. 7 Modes of operation reflected in the Alpha code structure

routine that updates sensor values, constructs several kinds of messages, and downlinks through the Iridium Network. Occasionally, the ACS shall power on to perform small corrections. During eclipse operations, transmission frequency is decreased to conserve power. The spacecraft remains in Normal Mode until permission is granted for payload release.

The above two modes comprise the sequence of events in the absence of faults. Fault responses are as follows:

Overmode
An override feature, Overmode is not technically a mode of operation, but a means by which the Ground Station may change variable values. Overwriting values can be used to either push the spacecraft to perform certain tasks or to diagnose an issue. It can be implemented during any of the five modes.

Low Power Mode
If on-board fault detection is triggered by low battery voltage, the spacecraft enters low-power mode.The voltage threshold is currently set at 3.75 V, when the power is low enough that successful transmissions become very infrequent. When a sufficient charge level is restored, the spacecraft can enter Normal Mode.

Safe Mode
Autonomous fault detection or ground station command can force the spacecraft to enter Safe Mode.Here, the ACS is completely turned off to preserve power. Transmissions may also have their rate changed, subject to the preferences of the Ground-Station operator via specific Overmode commands.

Deployment of the light sail is subject to approval by NASA and the Air Force, with an expected delay of 1-2 weeks from spacecraft separation. At that point, the ground determines readiness for deployment based on orbit, state of health and other parameters:

Deployment Mode
The deployment code is based on the classic arm-and-fire protocol and contains an operator in the loop: The Ground Station uplinks the first command. Upon receipt, the spacecraft then sets an acknowledgement in telemetry and awaits a second command, serving as a confirmation. This second uplink then triggers the burn-wire mechanism in the absence of faults. Fault protection can inhibit this second command and therefore inhibit sail deployment. In such an event, the ground resolves any anomalies before proceeding. During and after deployment, the spacecraft downlinks data from the deployment-verification sensors to confirm mission success.

Upon release of the sail, the four Monarchs are exposed to sunlight. These ChipSats immediately power on and boot into a simple routine that continually transmits GPS, gyroscope, and accelerometer data for the primary mission.

D. Structure

Maximizing the use of inexpensive and rapid-prototyping techniques, Alpha is among the first CubeSats to have an entirely 3D-printed primary structure. The only exception is the four aluminum rails, a requirement by the CubeSat Design Specification [22]. In addition to the 1U bus panels, 3D printing was employed for the floor of the payload compartment, the hinge for the payload-compartment door, and plungers that compress the rail deployment switches when stowed.

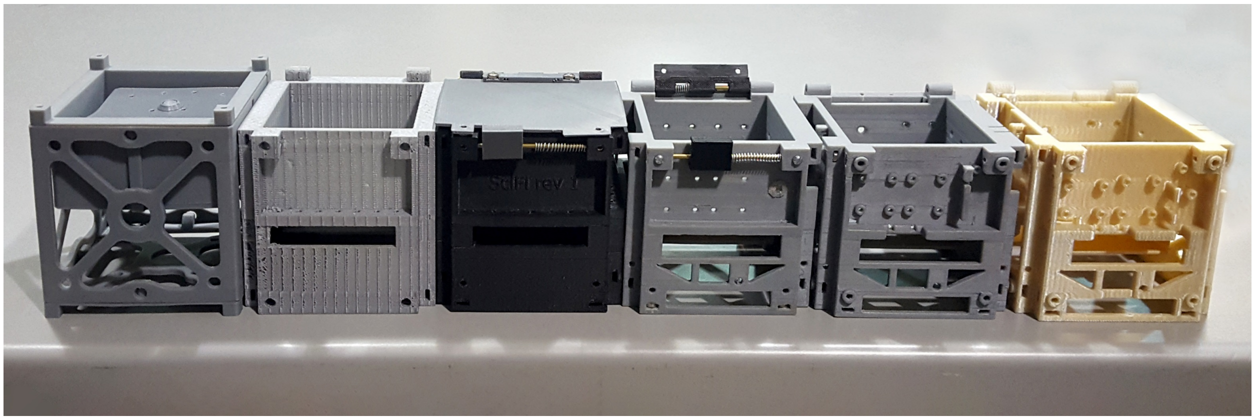


Fig. 8 Rapid prototyping of Alpha chassis made possible through 3D printing. Multiple prototypes shown.

Additive manufacturing enables intricate structure featuring customized compartments for the commercial-off-the-shelf (COTS) components. The quick and low-cost iterations, shown in Figure 8, allowed for varied placement of these components, and was an integral factor to achieving such a short development timeline.

The particular material selected for the Flight version is Accura® Bluestone™, a high-stiffness nanocomposite produced by 3D Systems. It was chosen for its thermal survivability range, with temperature resilience at more than 250° C [23]. Beyond thermal robustness, as an almost non-porous, ceramic-like resin, it exhibits low outgassing [24]. Bluestone™ has flight heritage, having been used successfully in the cold-gas thrusters of UT Austin's Bevo-2 CubeSat in NASA JSC's LONESTAR-2, as well as in the JPL INSPIRE mission [25]. It is also used for the propellant tanks in Cornell's PAN CubeSats. Moreover, Accura® Bluestone™ is included as one of the emerging technologies for SmallSat structures in [26] [27]. These test results confirm that Bluestone™ has more than sufficient material strength for its applications on Alpha and is well suited for the space environment.

E. Electrical

The electrical subsystem, shown in Figure 9, is comprised entirely of commercially available components. It is distributed across eight printed circuit boards (PCBs): six solar panels and an electronics stack that connects the power system to the flight computer, sensors, and actuators. The boards were custom-designed and assembled in-house by SSDS students.

Power

Spacecraft power is generated by solar panels on each face of the CubeSat. The six boards use a total of 136 solar cells, 28% efficient GaAs triple-junction cells from TrisolX [18]. A blocking diode is placed on each branch of cells to prevent current backflow from uneven voltages. Power from these panels feeds into the Sparkfun Sunny Buddy, a solar charge controller for the 3.7 V 4000 mAh lithium-ion battery. This system provides 1.2 W of power to the CubeSat as an orbit average.

Flight Computer

Onboard the electronics stack is a Teensy 3.5, a 2.4 x 0.7 inch microcontroller. It features a 32-bit 120 MHz ARM Cortex-M4 processor, originally designed as the intersection between the versatility of Arduino and the power of ARM-based microcontrollers [28]. The Teensy is also equipped with an microSD card, providing data storage prior to downlink. Serving as the flight computer, the Teensy sends commands to and receives data from the radio transceiver (RockBLOCK Mk2) and all sensors and actuators on board.

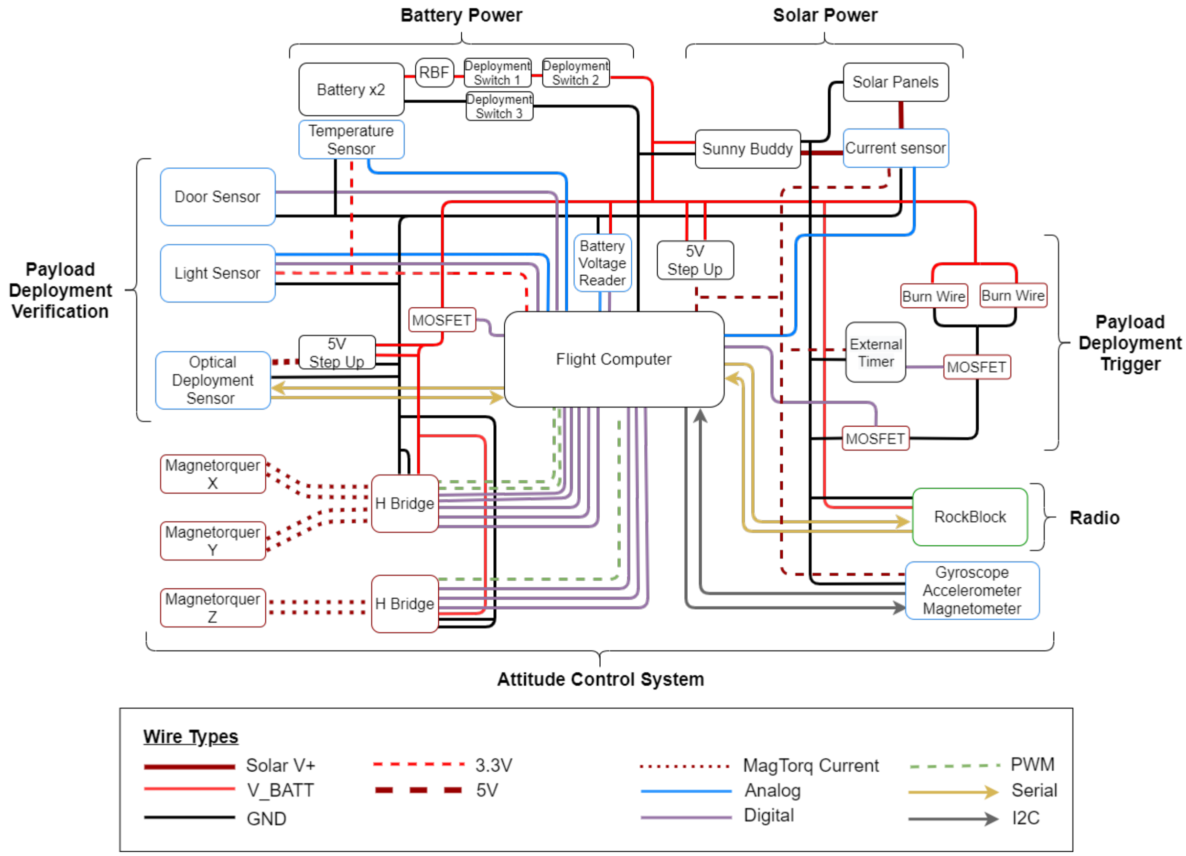


Fig. 9 Electrical schematic of the Alpha CubeSat

Spacecraft Sensors

In line with the goals of the design, all sensors are low-cost COTS components: voltage-divider setups and hobbyist breakout boards. The ACS, for example, uses a Sparkfun LSM9DS1 breakout board. A 9-DOF inertial measurement unit (IMU), it provides 3-axis accelerometer, gyroscope, and magnetometer data to the flight computer via I2C.

An Adafruit INA169 board is used as a high-side current sensor to provide solar-panel telemetry. It sends an analog voltage signal to the Teensy. Consumption is in turn monitored by a simple voltage divider for an analog reading of the battery voltage. To prevent current from constantly running through the resistors, a BJT switch activates the voltage divider only upon command from the Teensy. If the CubeSat enters Low Power Mode, a P-channel MOSFET switch is triggered such that the flight computer and essential sensors remain powered, while the H-Bridges and optical deployment sensor are temporarily shut off.

As a final method to detect system health, a TMP36 temperature sensor monitors the batteries. This analog voltage value is read by the Teensy and is among the default spacecraft bus telemetry. If the batteries are too hot, the spacecraft can decrease the discharge current by entering Low Power Mode and reducing how often telemetry is sent. Conversely, if spacecraft temperatures are too low, the flight computer augments the data rate (subject to available power) to increase the current draw and overall heat dissipation.

Spacecraft Actuators

All attitude maneuvers are performed exclusively through three torque rods assembled in-house from copper wire hand-spun over MuMetal. Their positions on the CubeSat are shown in Figure 10. Controlled by PWM signals from the Teensy, two Sparkfun Motor Driver Dual H-Bridges send current through these magnetorquers in either direction.

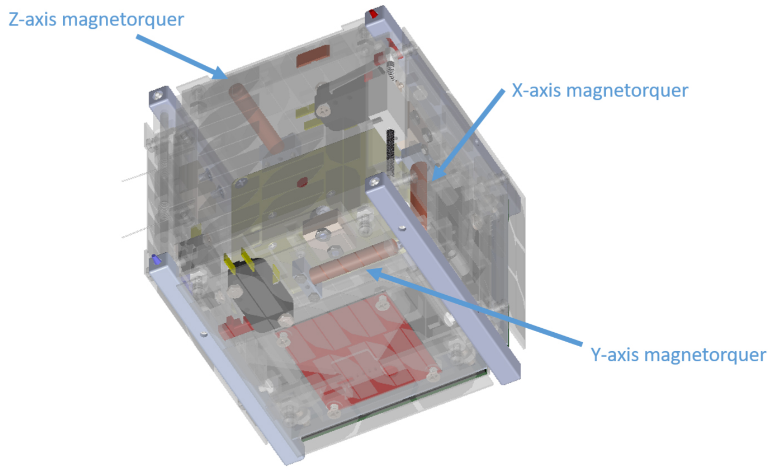


Fig. 10 Magnetorquer placement on the Alpha CubeSat

To deploy the light sail, two Nichrome burn wires release the payload-compartment hatch. These burn wires are activated by N-channel MOSFETs, with several additional inhibits to prevent a premature release.

Electrical Inhibits
Prior to deployment from the ISS, the battery is cut off from the system by four inhibits: three deployment switches and the RBF (remove before flight) pin. The RBF is removed upon integration with the launch vehicle. The three deployment switches, two on the power line and one on the ground line, are connected to 3D-printed plungers on the rails of the CubeSat. The structure of the CubeSat deployer depress these plungers against the walls and the the rails of the adjacent CubeSat in the stack. When Alpha deploys from the ISS, the battery circuit closes, and the power subsystem begins to power the satellite.

The exit velocity of the sail is 2 m/s relative to the CubeSat. The orbit mechanics are such that the sail could be a recontact hazard with the ISS within the first 12 hours of the mission. To prevent an accidental deployment during this period, an independent 24-hour timer module triggers an N-channel MOSFET on the ground leg of the burn wires. The burn-wire mechanism is therefore secured by three MOSFETs in total, in addition to the arm & fire in the code, and the additional nylon filament for structural redundancy.

Deployment Verification
To verify successful deployment of the light sail, Alpha uses three different sensors. The first is a circuit associated with a pressure-sensitive switch in the hatch. A LOW signal sent to the Teensy confirms that the door successfully opens. The second is a photoresistor positioned at the base of the payload compartment. It is used in a voltage divider, with fluctuations in the analog signal indicating sail separation from the CubeSat. Lastly, a 5 V step-up powers an optical deployment sensor, whose illumination provides confirmation that the sail properly unfolds. The three sensors therefore complement each other to enable the ground to assess mission success.

F. Attitude Control System
Initialized at power-up, the ACS stabilizes the CubeSat for improved transmissions and light-sail deployment. Using only magnetorquers, a novel approach is implemented to achieve full inertial-body attitude and angular-rate control, i.e. to detumble the spacecraft, and to align its spin axis in the direction of the Earth's magnetic field. For the detumbling phase, a nonlinear control law based on energy-dissipation principles has been developed, while a simple PD algorithm aligns the CubeSat's spin axis approximately with the Earth's local magnetic field [29].

Additionally, to ensure the spin stability of the spacecraft, passive-stabilization techniques have been adopted and applied through the entire design process of the Alpha CubeSat. In particular, mass distribution was carried out with careful consideration of the major-axis rule. Doing so aligns the axis of maximum inertia as close as possible to the geometrical z-axis along which the solar sail is deployed. The inertia matrix of the CubeSat with the folded sail has been evaluated as:

$$\mathbf{J}_b = \begin{bmatrix} 248252 & -5094 & -1048 \\ -5094 & 244433 & 1099 \\ -1048 & 1099 & 279321 \end{bmatrix} \times 10^{-8}\,\mathrm{k}gm^2 \tag{4}$$

The resulting angle between the axis of maximum inertia and the geometrical z-axis is ~ 2.3 °.

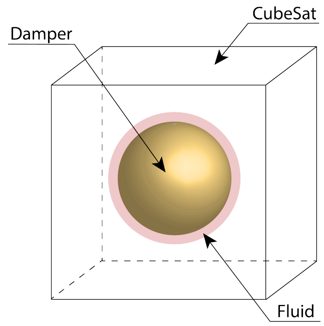
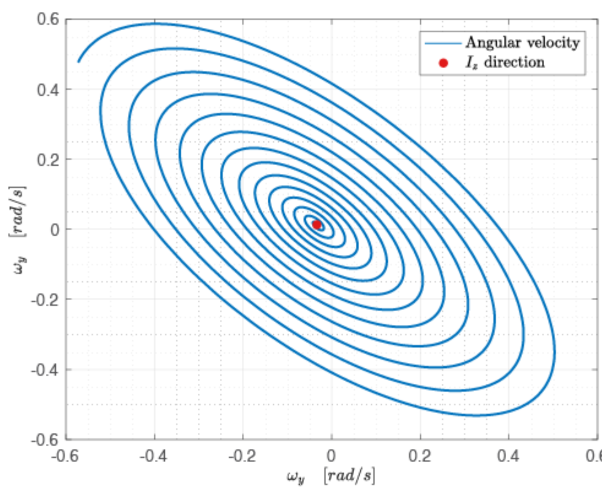
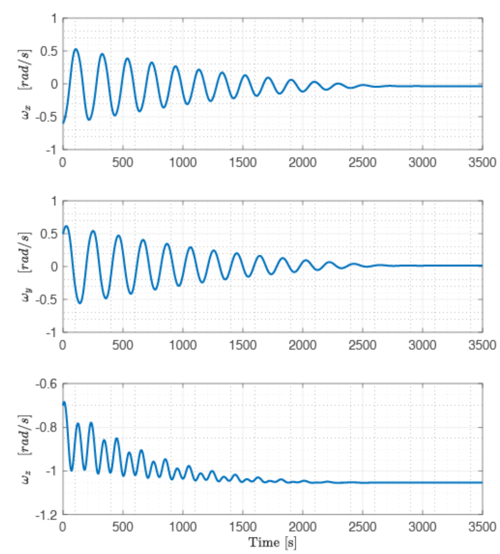


Fig. 11 Kane Damper model

The spacecraft rate-control algorithm closes a loop around the spin rate about the the maximum axis. It drives it to at least ±1 RPM, which is needed to help unfold the sail after deployment and establish the sail's own angular momentum. The rate-control algorithm includes a virtual implementation of a Kane Damper [29], which models torque-free energy dissipation in a rigid body. Damping the transverse rate relative to this spin axis is achieved by simulating the physical phenomenon of energy dissipation as shown in Fig. 11. By simulating the behavior of the damper dynamics and its interaction with the spacecraft through a fictional fluid, the control algorithm asymptotically drives the relative rate of the spacecraft and the damper to zero, dissipating kinetic energy. Thus, the spacecraft quickly decays to spin about its maximum axis of inertia without a need to hard-code this imprecisely known axis *a priori*.



(a) ω_x/ω_y plot for given initial conditions.



(b) $\omega_x, \omega_y, \omega_z$ plot for the selected initial conditions.

Fig. 12 Angular velocity behaviour for the Kane Damper simulation [30]

The entire work is also extensively described in [30] and the main results are highlighted here. The performance of the first algorithm is shown in Fig. 12a-12b. Several simulations with different initial conditions have been performed, leading to the same result. After the desired spin is achieved, the second PD algorithm is used to align the spin axis in the desired direction. [30] presents the control synthesis and the stability proof of the Kane Damper, as well as the gain selection of the PD algorithm.

G. Communications

The Alpha spacecraft houses a RockBLOCK Mk2 and a ceramic patch antenna as its radio hardware. It is sold by Rock Seven, who maintain their own services for communicating with these devices. This third-party infrastructure therefore eliminates the need for Alpha to acquire and maintain costly Ground-Station equipment. If not for security concerns, Alpha could be operated from anywhere in the world using only a web interface.

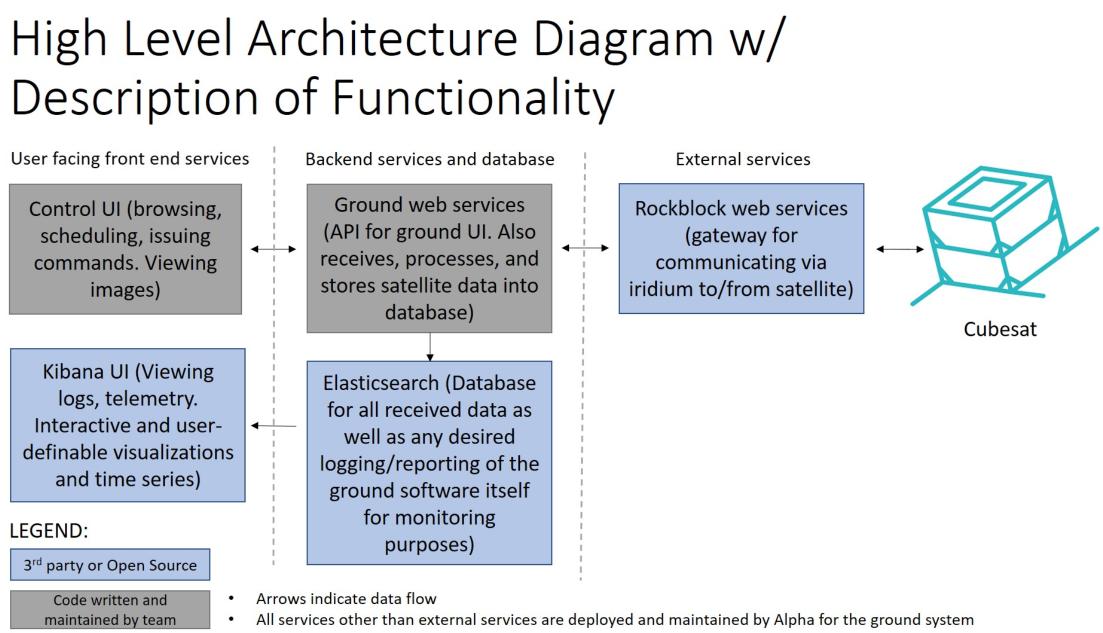


Fig. 13 High-level overview of Alpha communications structure

RockBLOCK

With an Iridium 9602 modem at its core, the RockBLOCK transceiver, shown in Figure 14, communicates via a global constellation of Iridium satellites. The constellation and associated ground network enables uplink and downlink at nearly any point on the CubeSat's orbit. On Earth with a perfect view of the sky, it generally takes around 20 seconds from the power-up of the modem to the successful transmission of a message [31]. Similar performance is anticipated in orbit. Interfaced to the RockBLOCK via serial connection, Alpha's flight computer can either downlink up to 270 bytes of information to Iridium or receive up to 340 bytes roughly every 10 seconds [32]. After extensive vacuum testing during the development phase, Alpha is the first CubeSat to launch with Rock Seven technology.

Ground Station

The Alpha Ground Station is a control system and analytics platform built out of off-the-shelf and open-source components. It demonstrates how a system can be built cheaply, and with hobbyist-communications hardware. This section summarizes the architecture, outlined in Figure 13.

The satellite sends and receives data from RockBLOCK's provided web services, an API. This web service is configured to forward data to and from the Alpha ground system's backend server. This backend server can receive command data from a front-end UI that it serves, forwarding it to the RockBLOCK API. It also receives data sent by the satellite (usually telemetry data such as sensor reading), and stores them in Elasticsearch, an open-source document database that allows for querying and aggregation. Connected to Elasticsearch is Kibana, an open-source data visualization tool that displays incoming telemetry data as time series, creates alerts, tracks metrics, and renders GPS data in user-defined dashboards. An example of this dashboard is shown in Figure 15

Fig. 14 RockBLOCK Mk2 radio featuring an Iridium modem [31]

Together, these software components form a flexible system for controlling and monitoring the CubeSat.

Light Sail Downlink
The four ChipSats on the sail also send gyroscope, accelerometer, and GPS telemetry, this time to ground hardware maintained by SSDS. This data is read immediately and submitted to the ground-system backend for centralized processing along with the CubeSat data. Receiving ChipSat data is still cost effective, requiring only a handheld antenna with an SDR that applies matched filtering and forward error correction (FEC) [14]. The Monarch generation of ChipSats onboard use Gaussian Phase-Shift Keying on a 915 MHz carrier wave (ISM band), with a signal bandwidth of ~64 KHz. This band is unrestricted in ITU Region 2 (the Americas). Elsewhere in orbit, the flight code uses on-board GPS position to inhibit communications in compliance with regulations, despite that the signal has such low signal-to-noise that it is essentially undetectable on the ground except through the computationally intensive matched filtering employed in the ground station.

Overall, the mission-control environment attempts to maximize the use of free and existing products. It forwards data to a central location, the ground-system backend, that is the only place Alpha needs to maintain its own code and services. The result is a maintainable, low-cost, feature-rich, and user-friendly system for mission control.

Fig. 15 Kibana Dashboard for Ground Station User Interface

Fig. 16 Original DNA sculpture by C Bangs (left) and hologram created by Martina Mrongovius (right)

V. A Holographic Message Plaque

Alpha features one of the pioneering exhibitions of holography in space. Holographic films are mounted to the space-facing walls of the CubeSat. They serve as a message plaque, as well as a means to verify the behavior of holograms in the space environment.

The holograms are created from the work of artist C Bangs, who designed clay sculptures and background panels in her home studio in Brooklyn, NY. The original artwork was then brought to the studio of hologram-expert Martina Mrongovius, who set up and executed the holographic exposure. Figure 16 provides an example of both the physical objects and their corresponding hologram. The holographic films are affixed with Arathane to the solar panels of the 1U Alpha CubeSat. Only four of the six sides feature holograms, in order to augment the passive stabilization techniques employed by the ACS.

A. Theme & Inspiration

The theme of the sculptures and panels is the common code for life of DNA. The hereditary material in humans and almost all other organisms, DNA serves as a collective representation of life on earth. The sculptures include male and female human figures, a fish, domestic cat, tiger, moth, and a DNA double-helix structure. The background panels include paintings of images that echo the sculptures. Based in part upon the Pioneer Plaques and the Voyager Golden Records of the 1970s, the holograms onboard Alpha are meant to be a message plaque. They are a reflection of humanity, and of all Earth-based life, as we venture out into the Cosmos.

B. Experimental Aspects

While primarily an art demonstration, the holograms carry the added intention of verifying the behavior of holograms in space. As such, the technicalities of the holographic exposure maximize survivability in the harsh environment, as well as visibility given the spacecraft dynamics. Whereas many holographic materials degrade with exposure to UV light, photopolymer holographic film was chosen for its particular durability [33]. The film is meant to be viewed in white light and UV exposure is the final stage in its development process.

Moreover, all of the sculpture backgrounds feature retroreflective elements or full panels for ground-based observation.

The holographic representation of a retroreflective object, however, is not fully retroreflective. It reflects light back in the direction it comes from, but only at the angle of incidence of the laser light originally used in the hologram exposure. In consideration of the spacecraft's spin about its z-axis, a multi-angle exposure was implemented. Three lasers (red, green, and blue), traditionally combined to reproduce true color, were spaced 120° apart. Photopolymer film physically changes when exposed to light so the three angles were exposed simultaneously. The time lengths of the constituent-laser exposures were varied according to respective power, so that each of the three layers have comparable brightness. While not retroreflective in the true sense, the 12 total viewing angles rotating about the spin-axis greatly increase the likelihood of visibility from the ground with suitable imaging technology.

C. Applications for Space Travel

Holograms affixed to or embossed on thin-sail surfaces have several potential applications to space travel. First, consider the case of a solar-photon sail attempting to depart from low Earth orbit for an interplanetary destination. To accelerate, it is beneficial to have a sail that is reflective to sunlight behind the spacecraft and transmissive to sunlight in front of the spacecraft. Also, a holographic solar sail could orbit Earth with its surface parallel to the orbital path, which would minimize atmospheric drag.

Another application is Earth-based laser acceleration of interstellar pico-probes to relativistic velocities. From experimental work by the Benford brothers and theoretical analysis by Zac Manchester and Avi Loeb [34], it is known that parabolic or spherical sails will self-correct to remain in the beam as Earth's rotation causes the laser beam to move. However, accelerations of 5,000-10,000 Earth gravities are necessary to achieve velocities of 0.1-0.2c within laser collimation distances measured in ~1 million kilometers. A material spherical or parabolic sail would rapidly collapse to a flat sheet under such high accelerations and be ejected from the beam. But a three-dimensional hologram of an appropriately-curved surface embossed or fixed to a flat sail should achieve the same stability.

Finally, holograms are a means of transporting vast amounts of information. With holographic imaging, one can multiplex hundreds of images together and create animations as well as record depth and dynamics [6]. In addition to stabilizing the interstellar probe, a holographic laser sail could therefore double as a message plaque. The sail could be composed of extensive data about humans and life on Earth, including artwork from throughout history. The holograms are thus a medium for the visual representation of ourselves as we begin this journey to Alpha Centauri and beyond.

VI. Conclusion

Combining retroreflectivity, ChipSats, and a shape-memory alloy deployment mechanism, Alpha is the most lightweight sailing spacecraft launched to date. These innovations allow Alpha to achieve an extremely low sail-loading number, resulting in performance on par with the most efficient light sails flown thus far. In addition to its primary purpose of a delivery vehicle for the sail, the CubeSat bus itself features a number of novel design choices. The components selected and prototyping techniques employed successfully achieve the goal of a rapidly-developed low-cost CubeSat platform. Technical advancements, such as the ACS, maximize capabilities despite the space limitations of the 1U form factor. These features can significantly increase the affordability of future nanosatellite system architectures. Lastly, Alpha's holograms serve as a predecessor to the message plaques onboard extrasolar-exploration probes that were once a concept of science fiction. Although the CubeSat trajectory shall remain quite a distance away from Alpha Centauri, the mission represents a small, but meaningful step towards this interstellar journey.

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