Building the future of wafersat spacecraft for relativistic flight

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ABSTRACT

Recently, there has been a dramatic change in the way space missions are viewed. Large spacecraft with massive propellant-filled launch stages have dominated the space industry since the 1960's, but low-mass CubeSats and low-cost rockets have enabled a new approach to space exploration. In recent work, we have built upon the idea of extremely low mass (sub 1 kg), propellant-less spacecraft that are accelerated by photon propulsion from dedicated directed-energy facilities. Advanced photonics on a chip with hybridized electronics can be used to implement a laser-based communication system on board a sub 1U spacecraft that we call a WaferSat. WaferSat spacecraft are equipped with reflective sails suitable for propulsion by directed-energy beams. This low-mass spacecraft design does not require onboard propellant, creating significant new opportunities for deep space exploration at a very low cost. In this paper, we describe the design of a prototype WaferSat spacecraft, constructed on a printed circuit board. The prototype is envisioned as a step toward a design that could be launched on an early mission into Low Earth Orbit (LEO), as a key milestone in the roadmap to interstellar flight. In addition to laser communication, the WaferSat prototype includes subsystems for power source, attitude control, digital image acquisition, and inter-system communications.

Keywords: DE-STAR, Directed Energy, Laser, Phased Array, WaferSats, Relativistic Spacecraft

1. INTRODUCTION

1.1. Background

Recent deep-space missions, such as Voyager, utilize a combination of propellant-driven boosters and gravity assist maneuvers to achieve noteworthy final velocities. Even so, Voyager 1 would still require $O(10^4)$ years to reach the nearest star system. If we want to pursue interstellar missions, it is clear that the propellant-laden spacecraft are insufficient. For interstellar missions, wafer-scale spacecraft have been proposed.[1-14] These spacecraft are equipped with reflective sails for propulsion by directed energy beams. Without the need to carry propellant, very low-mass spacecraft would be capable of reaching relativistic speeds. The small craft would include all mission components imbedded in a wafer, such as power, laser communications, attitude control system, imaging and other sensors. The driving force is provided by radiation pressure from a dedicated directed-energy system, either in Earth orbit or stationed on the ground. The spacecraft includes a reflective sail, converting momentum from photons in the directed-energy beam into thrust.

Prior studies have explored requirements for propelling a wafer-scale spacecraft with a 1 m sail to ~0.26 c; travel time to α-Centauri would be approximately 15 years.[11-14] These studies propose that the entire spacecraft, including the sail, will need to be in the range of a few grams total mass. This paper describes the design of a prototype WaferSat spacecraft, constructed on a printed circuit board (PC board). Images of the prototype board are shown in Fig. 1, with electronics on one side, and photovoltaic power on the back side of the PC board.

1.2. The Roadmap to Interstellar Flight

To start, our goal is to design a spacecraft on a chip that uses only Laser Based Communication for tracking and communication. Initially we want to send our WaferSat into LEO by the end of 2016. We eventually want to turn this satellite that orbits Earth into the first interstellar robotic probe to venture beyond our solar system. To do this we will continue to scale down each and every component on the WaferSat BoardSat and integrate them onto silicon wafers. With this, we will start with our first prototype and continue to scale down along our roadmap[14] to Wafer-based spacecraft.

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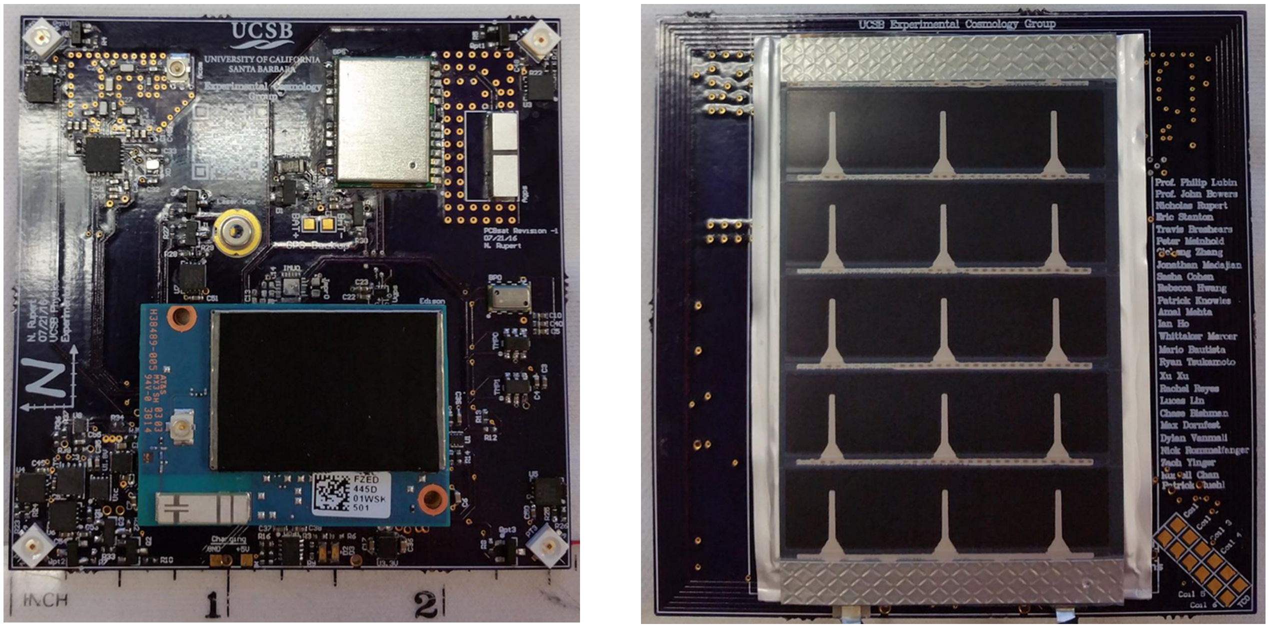

Figure 1. Image of Initial Revision of WaferSat on a PC Board. Top side of the PC board (**left**) includes subsystems for attitude control, digital image acquisition, and inter-system communications. Bottom side (**right**) shows photovoltaic power source.

2. WAFERSAT PROTOTYPE

We propose a small 10 cm by 10 cm foundation that has photonics on a chip, with electronics on one side and photovoltaic solar arrays on the other side. We also have many other great scientific instruments integrated on this first prototype: laser photon thrusters, 9-axis IMU, GPS, Radio, and other components.

2.1. Attitude Control

In order to alleviate the chaotic spin after detachment in LEO, we plan to have a 3-axis pop-up torque coil system to get us stabilized. We then will likely detach these torque coils, and then use photon-thrusters. Many options are being posited and have yet to finalize this issue. In order to align the WaferSat with the ground-based laser, we will need sub-mm alignment ability with a combination of MEMS-mirrors and the attitude control system. This is a problem for our LEO asset, but we will face similar problems moving forward for the interstellar probes, so solving it now would be ideal.

2.2. Communication

There has been a set of CubeSats launched by Aerospace Corp called Aerocube that used lasers for communication. However, we want to go one step further and use lasers for communication and tracking. We are in the process of making a phased array on the ground that will be a two way phased array: transmit and receive. It will be used to track and lock on with the WaferSat and then once locked on it will receive the data via the integrated photonics on board the spacecraft. LEO starts at ~150 km and with a 1 W Peak laser at 1.55 μm and a 3 mm lens, we have about 1 km plane on the earth. Assuming a 1 m telescope on the ground, that gives us $5 \cdot 10^{12}$ ph/s. The data rate is not a problem for us. What will be hard is aligning the WaferSat with the ground-based laser. In order to do this, we propose a laser beacon (pulsed laser) at a separate wavelength that the telescope looks for in the sky, finds it, and locks on. The telescope then transmits a signal to the WaferSat and then the WaferSat aligns itself with the telescope so we then have a "Lock". Torsion coils used for alignment of LEO WaferSat (Fig. 2). The prototype board has been subjected to some environmental tests. The lab setup is shown in Fig. 3, and described in Section 3 below.

Figure 2. Computer generated image of the torsion coils used for alignment of LEO WaferSat.

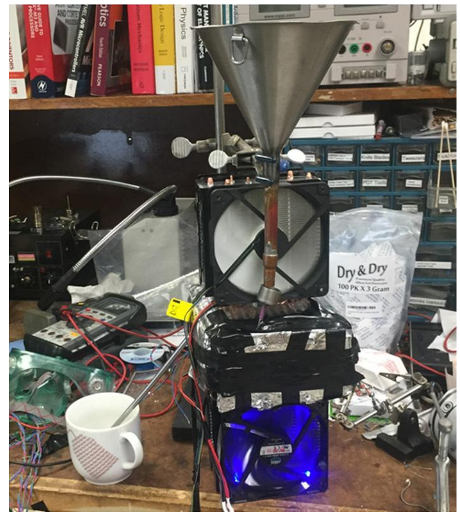

Figure 3. Lab setup of test chamber.

2.3. Power

In order to power the spacecraft, we have solar panels on one side of our spacecraft pointed towards the Sun. With an area of 10 cm by 10 cm, we can achieve about 14 W of power (140 mW/cm^2). With GaAs, we can get ~30% conversion efficiency to electrical power. This gives us ~4 W of electrical power to be stored in a Lithium Ion Cell. This will be used to power the photonics and electronics on board.

2.4. Electronics and Communication

The prototype board includes several subsystem components. Onboard processing via FPGA is being developed for inter-system command and control.

- Laser Thrusters x 4 (one on each corner) – for small attitude control adjustment
- Lithium Ion Battery (assuming 15 W h/g)
- Photo Voltaic (Solar Array) – GaAs/Si 0.3 - 0.2 efficiency
- Imagers, Star/Sun Tracker, Cameras
- Laser Locking System (Beacon)
- Magnetometer
- MEMS accelerometers and Gyros
- Torque Coils

2.5. Goals of WaferSat Prototype

- Provide cost effective and flexible test platform for developing spacecraft and communications technology
- Allow for integration of various sensor systems to support data capture and manipulation
- Utilize readily available materials and integrated circuits to support quick revision turn-around times and system re-designs
- Explore the limits of rigid PCB manufacturing capabilities for future use
- Test and validate early life directed energy technologies
- Test and validate early life propulsion and orientation systems
- Provide a starting point from which future revisions/systems can be based on
- Provide an inexpensive platform to deploy multiple experiments in a single launch
- Produce data, feedback and calculations in order to drive future development

3. ELECTRONICS TESTING

The following figures demonstrate the stress chamber testing results as well as sensor data before and after being acted on by extreme stresses. A thermal stress chamber built from Aluminum, that uses Peltier tiled thermoelectric and Liquid Nitrogen cooling will be constructed for the testing of the electronics. In addition, the interfacing of the microprocessors and sensors was developed in order to test the sensors after a series of cooling and shock testing experiments. Stress conditions on each electronic part include cooling to -60°C with thermal shock testing at temperatures above 125°C.

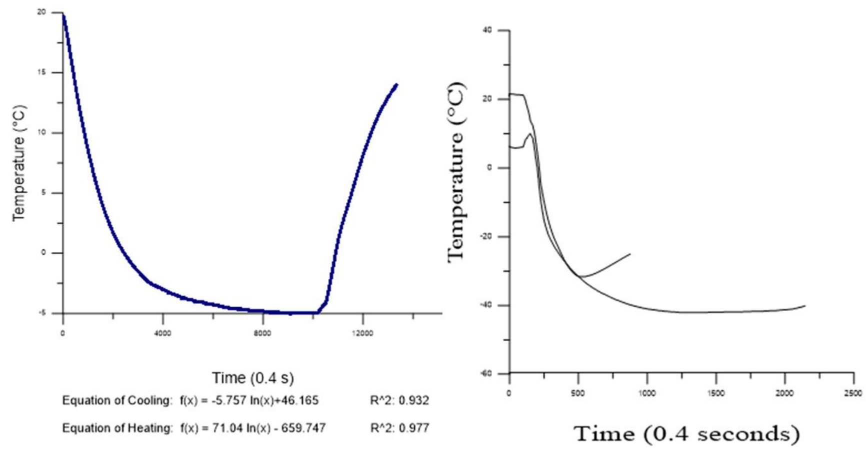

Figure 4. Observing the internal temperature chamber cooling (and ultimately heat dissipation) rate via thermoelectric cooling. (**Left**) Internal stress chamber cooling using Liquid Nitrogen as an aid. (**Right**)

After repeatedly testing the thermoelectric chamber, it was found that solely electrical means of powering the system wouldn't get us close to the goal of -55°C. However, using Liquid Nitrogen and pouring it through metal tubing within the chamber allows for cooling 11 times faster than electrical methods of cooling. Furthermore, when testing the discrepancy between four temperature sensors (Fig. 5), it was found that the sensors only differ (on average) by only 0.0019°C. This result concludes that using the average sensor data of the sensors in space is the best way to find the most accurate results.

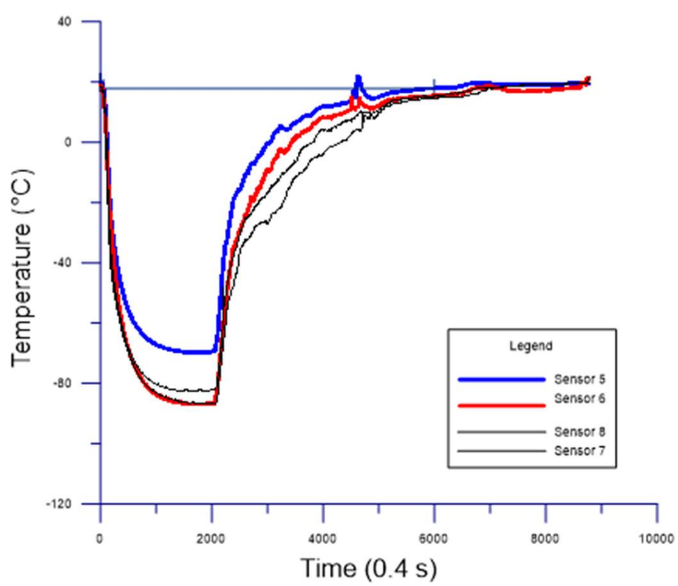

Figure 5. Discrepancies between temperature sensors at low temperatures (-87°C).

Also, when testing the accelerometer (Fig. 6, Fig. 7), and magnetometer (Fig. 8, Fig. 9) under stresses, it was found that temperature and rapid temperature changes (thermal shock) did not affect the sensors electronic and mechanical integrity enough that they would not be able to be used in space. Although the *x*- and *z*-axis's measurements of the magnetometer (2.5 cm. from magnet) showed drastic change, as shown in Fig. 8 and Fig. 9, this was most likely due to a slight human error and the precise (micro tesla) measurements taken by the sensor. The *y*-axis of the magnetometer, which was the direction that was controlled the most by the test, was shown to have little to no discrepancy before and after stress testing. As shown in Fig. 6 and Fig. 7, the magnitude of the accelerometer along the *y*-axis before and after the experiment only deferred by 3 m/s. Given the current control testing circumstances, it can be concluded that the sensors reading ability did not completely breakdown.

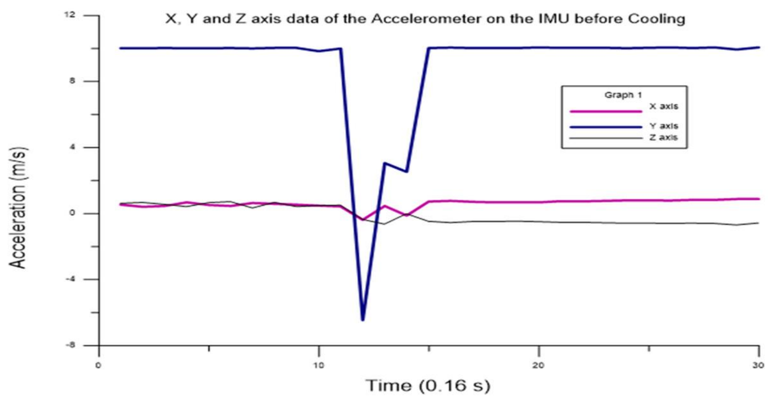

Figure 6. Accelerometer (on the Inertial Measurement Unit) tested from 30.5 cm, before stress was applied.

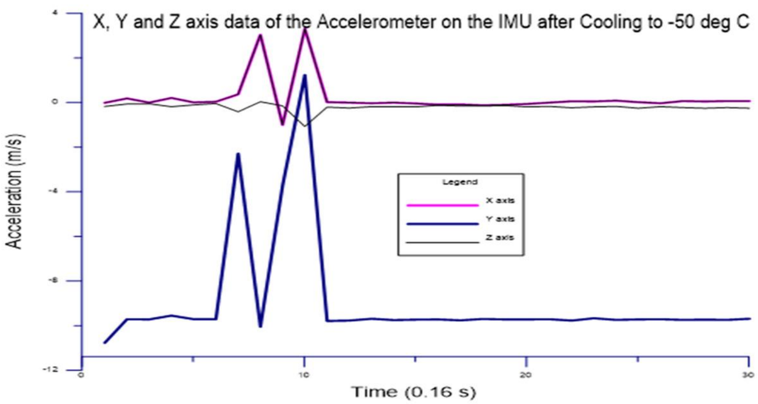

Figure 7. Accelerometer (on the IMU) tested from a height of 30.5 cm, after a stress of -50°C was applied for 5 minutes.

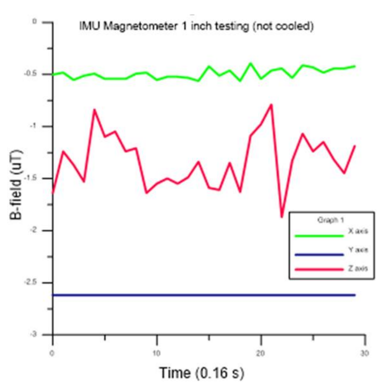

Figure 8. Magnetometer Experimental Testing with the Intel Edison, not cooled.

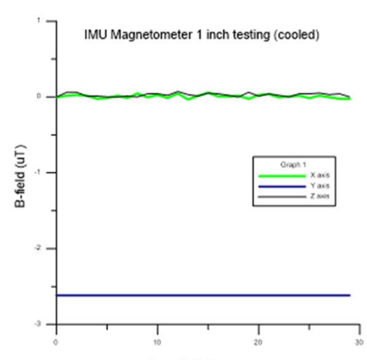

Figure 9. Magnetometer test results change markedly under temperature stress.

4. FUTURE SYSTEM ARCHITECTURE

4.1. Goals of WaferSat Prototype

Once we have developed our multiple revisions of the WaferSat we then begin working on integrating every component onto a single wafer. Here, we will treat the case of the 1 g wafer-scale spacecraft, because it represents the most difficult engineering feat. If we can successfully design an interstellar probe at the wafer level, the scalability of our architecture ensures that a larger craft could also be constructed. As the reverse is not true, the architecture of the wafer-scale probe is considered to be the most essential to the ultimate success of our design. The wafer architecture is centered on the concept of the integrated circuit (IC). An IC is a circuit wherein all of the components are crafted out of the same block of semiconductor material, known as a monolith. The main problem that ICs were developed to solve was that as circuits became smaller and smaller, they required more and more wiring in less and less space, without sacrificing the integrity of the connections. ICs solved this problem by doing away with conventional wires entirely, replacing them with a thin layer of metal printed in the shape of the necessary connections directly onto the monolith which contained all of the circuit components. Our wafer will run cold during the majority of the mission (around 20-50 K) and this will lead to even higher performance (lower leakage currents) especially suitable for GaAs or SiGe or InP based semiconductors we baseline. Normal Si is generally not suitable at these temperatures, though some special doping Si devices have been used in IR arrays for military and space related purposes.

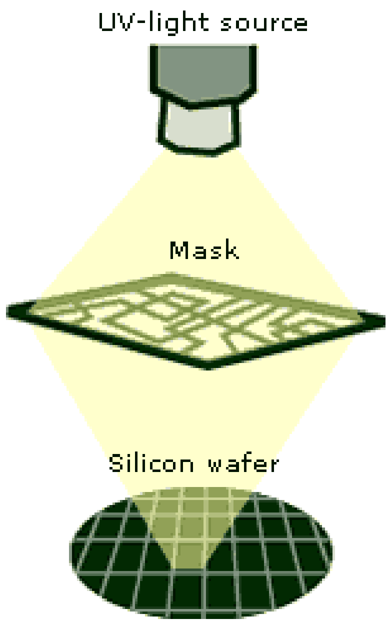

Figure 10. Depiction of UV light source masking Silicon Wafer.

The process of creating an IC begins with growing the semiconductor substrate (Gallium Arsenide, for our purposes) and cutting it into thin wafers with a diamond saw. The wafers are then subjected to a multi-step polishing procedure to ensure a near-perfect finish before the layers of the monolith are added (Fig. 10). The first layer that is added is an insulating layer, followed by a light-sensitive protective coating. The wafer is then exposed to UV light through a kind of stencil, designed on a computer and known as a mask, which blocks certain areas of the wafer from exposure to the UV. Where the UV reaches the wafer, the light-sensitive protective coating is damaged and weakened. The UV-damaged areas of the coating flake away as the wafer is developed, rinsed off, and baked.

The next step is a chemical treatment known as etching, which removes the layer of insulating material no longer protected by the light-sensitive coating. This leaves the bare wafer material exposed in the pattern of the mask. Then, in a process known as doping, a small percentage of foreign atoms are introduced into the wafer's crystal structure, which alters their electrical properties (This “doping” is a defining feature of a semiconductor. The introduction of a few atoms into the lattice of a material which is normally an insulator may give it conductor-like properties, but not to the extent that it becomes a full conductor. This process, beginning with the addition of the insulating layer, is then repeated many more times, until all of the monolithic components have been 'grown,' one layer at a time. When the monolith is complete, a similar process of layering, UV exposure, and etching is performed with metal to create the 'wiring.' Modern ICs may contain up to five layers of metal, separated by insulating layers. The ICs are then ready to tested and shipped.

One of the great advantages of ICs is that once the masks have been created, they can be used over and over, facilitating low-cost mass production. This is a key element of our “shotgun approach” to sending a large number of wafer-scale probes. They can be produced *en masse* at low cost with modern IC wafer printing techniques. Current state-of-the-art wafer IC technology allows for single-functionality systems to be printed (i.e., wafer-level cameras), with multi-function wafer ICs (i.e., wafer-level spacecraft) on the horizon. Research companies such as Fraunhofer are actively working on “heterogeneous integration of different components, such as sensors, processors, memories or antennas”. This is precisely what will be necessary in order to build a wafer-level spacecraft. It has been nearly 60 years since the advent of the integrated circuit, and the technology continues to develop at an incredible rate. Wafer-level MEMS technology is steadily improving as well, which bodes well for the future of wafer IC technology (and printed spacecraft).

4.2. Science Objectives and Instrumentation

For an initial interstellar mission, we propose outfitting our probe with a microspectrometer, a micro-magnetometer, and a MEMS camera. We are creating this now and testing in LEO first and then will go to our interstellar option. This allows for a wide variety of scientific missions. With a spectrometer aboard, we could search for recent or nearby sources of cosmic ray acceleration, determine the relative fraction of cosmic ray electrons and positrons in the interstellar medium, and search for antiprotons produced by Hawking radiation or the decay of the Weakly Interacting Massive Particles (WIMPs) which may account for the missing dark matter. A magnetometer would allow us to measure suprathermal ions and electrons in the solar wind, help characterize the structure of the bow and termination shocks, determine the nature of flows in the heliosheath, discover why the magnetic flux dropped at Voyager 1, help determine why the heliosheath is almost 50% thinner than models indicate it should be, determine the relationship between solar and interstellar magnetic fields, measure the interchange of solar and interstellar ions, determine the nature of instabilities in the heliopause, and the nature of interstellar magnetic fields. And finally, a camera allows us to observe extragalactic background light, zodiacal and Kuiper Belt dust distributions, and zodiacal background. More importantly, however, the camera helps us to feel like we are actually out there, and generates and maintains public interest by providing images of the universe beyond our solar system.

For future missions, some or all of these instruments could be exchanged for others which would allow different tests and discoveries, including, but not limited to, atomic clocks, accelerometers, plasma detectors, dust composition instruments, and small (~3 cm class) telescopes. With these we could test the Equivalence Principle, fundamental constants, local position invariance, the gravitational inverse square law at large distances, the one-way speed of light, search for gravity waves, measure the Edington parameter to a greater precision than ever before, and measure the parallax of distant objects, as well as take plasma measurements of the solar wind, heliopause, heliosheath, and bow and termination shocks.

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