The Caltech Space Solar Power Demonstration One Mission

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***Abstract*—This paper describes Caltech's Space Solar Power Demonstration One (SSPD-1) payload and upcoming mission on Momentus Space Vigoride 5. SSPD-1 is comprised of three experiments each of which demonstrates the performance of a key technology piece in the space environment. We describe the goals of SSPD-1. The three experiments - Alba, DOLCE and MAPLE are discussed. The launch of SSPD-1 is scheduled for November 6, 2022 on Space X's Transporter 6 mission.**

***Index Terms*—Space solar power, Photovoltaic devices, wireless power transmission, deployable structures**

I. INTRODUCTION

The Caltech Space Solar Power Project (SSPP) is a multi-year, multi-disciplinary research and development effort on space solar power with the goal of achieving an engineering and economically feasible system to power terrestrial electrical energy from energy gathered in space. A key tenet of SSPP to minimize the mass on-orbit. This tenet leads to a very unique instantiation of the space power station as describe in [1] and [2]. Fig 1 depicts our concept.

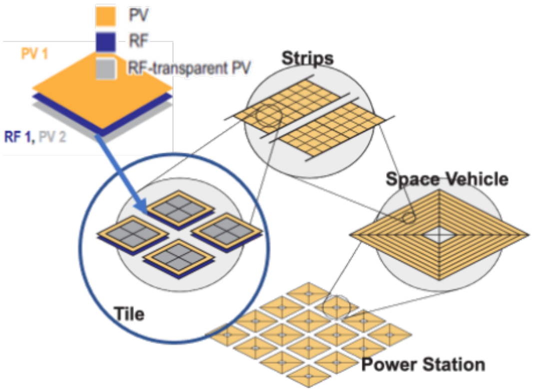

Fig. 1. SSPP employs a modular, scaleable architecture based on an ultra-light weight unit of functionality called a tile.

The tile is a multilayered structure with photovoltaic (PV) material on both surfaces, antennas underneath one of the PV layers and a layer hosting CMOS integrated circuits and routing for reference signals and timing for phase control over the antennas and DC to microwave power conversion. The tile has all the functionality needed to convert solar energy into microwave energy and radiate that energy to a desired location. The tiles are fabricated into strips of lengths ranging from a few meters to 60 meters, and these are laid up into a carbon fiber structure that is attache to a deployment mechanism which, in turn is attached to a spacecraft. The carbon fiber structure enables the strips to be folded and coiled into the deployment mechanism for launch stowage. Our current space vechicle design has a mass of approximately 430 kg. A power station is made up of many space vehicles either mechanically attached by their booms or autonomously formation flying.

One of the intermediate objectives of SSPP is to demonstrate the technologies central to our concept [1] in space. Space demonstrations reduce risk by verifying that the technologies perform in the environment they are designed to operate in and demonstrates that the functional interfaces within the system operate correctly. We envision a series of demonstration of increasing complexity to gain further confidence in the the design and scalability of the technologies. Our first such demonstration is Space Solar Power Demonstration One (SSPD-1). We note that there was recent space demonstration dedicated to space solar power led by P. Jaffe [3]. Jaffe's "sandwich" module was hosted on the U.S. Air Fore X-37B space plane and spent over a year in low earth orbit.

We established several ground rules at the start of SSDP-1. First, the payload consists of three independent experiments so that each technology could be individually tested. By decoupling the dependencies that occur if we were to build and fly a scaled integrated demonstrator, we can verify the performance of the core technologies without potentially confounding factors due to inter-dependencies. Second, we execute the development, assembly, integration and test of SSPD-1 to NASA Class C/D mission standards [4]. Our mission is driven by technical objects (Class C), but we have a higher risk tolerance than other classes (Class D), relatively low complexity (Class D), and have programmatic constraints (Class D). Operating as a Class C/D mission, enables us to speed development by not having to comply with many standards and TORs found in more mission critical payload development programs. We still maintain rigorous testing

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requirements to ensure safety of flight and mission success. Third, the individual payload components are developed in parallel holding to their own internally managed schedules that are anchored to a key milestone schedule taking us from inception to launch. Fourth, SSPD-1 is a hosted payload on a satellite. The hosting option saves us from having to buy a satellite and all the services, including launch, necessary to operate on orbit. This allows us to focus our small team on developing and delivering the key payload components and performance that are relevant to SSPP. This tenet lead us to engage with Momentus Space for a hosted payload on their Vigoride spacecraft.

II. SSPD-1 PAYLOAD DESCRIPTION

SSPD-1, depicted in Fig. 2, is a hosted payload comprised of three experiments and a supporting avionics unit. In keeping with our tenets, we have partnered with Momentus Space to host SSPD-1 on their Vigoride spacecraft scheduled to launch on the Falcon 9 Transporter mission in November 2022. SSPD-1 will spend 7 months in a low Earth, sun synchronous orbit at an altitude of approximately 500 km. Six of the seven months is dedicated to the SSPD-1 mission.

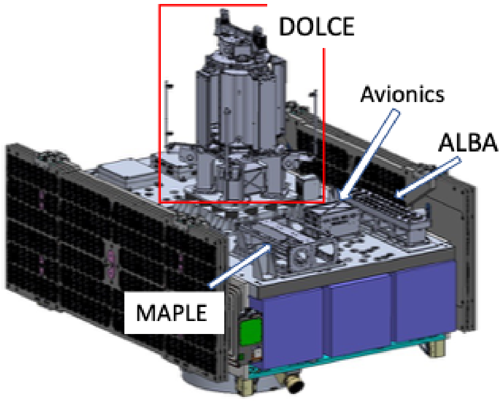

Fig. 2. Rendering of the SSPD-1 payload components on Vigoride 5. (Courtesy of Momentus Space)

Each of the three experiments addresses one of the key technologies being developed in SSPP [5]. Alba is an experiment dedicated to characterizing research and developmental photovoltaic (PV) devices. The Deployable on-Orbit ultraLight Composite Experiment (DOLCE) will demonstrate Caltech's stowage and deployment technology and characterize the structure's flatness and response to disturbances at a 1.7 m x 1.7 m scale. The Microwave Array for Power Transfer LEO Experiment (MAPLE), employs our custom CMOS radio frequency integrated circuits (RFICs) and flexible array technology to perform wireless power transfer (WPT) experiments. The three experiments are supported by an Avionics suite.

A. Alba

Alba's objective is to characterize the performance of research solar cell samples on orbit, with several classes of emerging PV technologies represented among 32 test devices. Alba (see Fig. 3) hosts devices ranging from approximately 3 mm on a side up to 20 mm x 20 mm in size. The manifest of PV devices includes flexible ultralight perovskite cells, rigid perovskite cells, InP and GaAs nanowire cells, diffused-junction III-V cells, luminescent solar concentrator (LSC) cells, CIGS cells, thin Si cells, and a conventional triple-junction III-V cell as a control device. Some cells were sourced from Caltech research efforts, but the majority were provided by a broad range of collaborators at other academic, institutional, or commercial research labs.

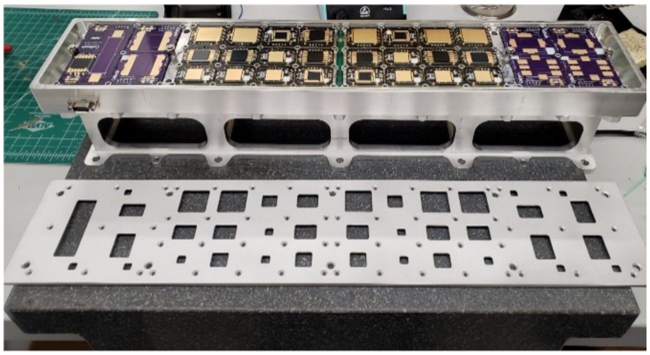

Fig. 3. Alba interior (top) and flight cover (bottom)

Each PV device is mounted on a cell carrier circuit board assembly. The underlying instrumentation circuitry is that of the Aerospace Measurement Unit (AMU) developed by the Aerospace Corporation, which has flight heritage including high-altitude balloon tests and cubesat missions. [6] [7] Each cell carrier comprises an independent AMU circuit, containing a microprocessor, DAC, ADC, and other electronics to enable measurement and recording of the cells' current-voltage (I-V) characteristics (See Fig. 4) To maximize the number of cells that could be included in the experiment, three different form factors of the AMU circuits were fabricated, which work in conjunction with cell-specific interposer PCBs to provide mounting pads for each cell technology. All cell carrier positions include temperature sensors located beneath the cells, and resistive heaters for optional thermostatic regulation of the cells at elevated temperatures. The outermost (8) cell carriers also contain sun angle sensors to enable precise calibration of the results. The circuits are operated over an I2C bus controlled by the the flight computer for data acquisition and down link to the ground. For the purpose of risk diversification, the 32 devices are split into two banks of 16, each with separate I2C and power busses.

Alba is able to collect data once the Vigoride spacecraft has completed its commissioning tasks and is declared operational. There is approximately one month of time that Alba will have to collect data before the DOLCE payload is deployed. During that month, we cannot impose pointing requirements on Vigoride as it is servicing other customers and performing some engineering tests, so any data we collect will be on an opportunistic basis. Alba will essentially free run and collect data during this time. The flight computer will use Alba's sun

Fig. 4. A sample of a characterization circuit board with a PV device installed.

angle sensor data to determine if a given data set should be save for down link or discarded. Once Vigoride is dedicated to SSPD-1, and DOLCE deploys, then Vigoride must make attitude adjustments to ensure that all the PV samples are illuminated every day. Fig. 5 depicts the shadowing caused by the deployed DOLCE structure. In addition, Fig. 5 shows the preferred attitude for the Vigoride deck and the PV samples that receive illumination at each angle. Green indicates near normal incidence for sunlight, red indicates shadowing, and yellow and orange indicate less the desirable incidence angles. Vigoride has a pointing accuracy of less than 5°so Vigoride should provide adequate pointing.

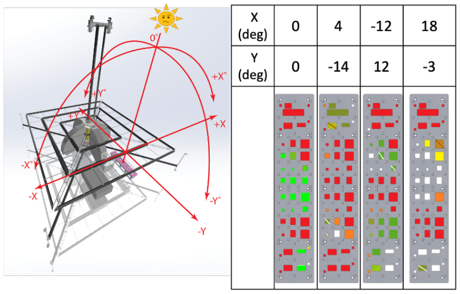

Fig. 5. Preferred Vigoride attitude to mitigate shadowing effects on Alba.

Alba has a mass of approximately 3.6 kg and is housed in a 494 mm long x 110 mm wide x 100 mm tall structure. The experiment will operate throughout most phases of the flight, collecting data opportunistically when the cells are illuminated. During phases when Alba is the primary experiment, the Vigoride spacecraft will adjust its attitude relative to the sun to provide continuous normal-incidence illumination on the test cells.

B. DOLCE

DOLCE's objectives are to demonstrate that the deployment mechanism, which is central to the SSPP packaging concept [8], functions properly in the space environment, and to understand the shape and behavior of the deployed, ultralight weight carbon fiber structure in zero-g after deployment and when subject to disturbances such as spacecraft vibration due to maneuvering or thermal gradients on the structure.

Figure 6 depicts DOLCE in the stowed configuration. The structure is folded and coiled inside of the mechanism. Starting at the top of the mechanism, there is a camera and LED light assembly that is erected vertically on three carbon fiber booms. The cameras provide both video and still imagery for use in characterizing the structure during and after deployment. There is also a camera on the lid of the Avionics Box with a wide angle lens viewing toward the zenith relative to the payload deck. This camera can be used to capture deployment imagery and is the backup camera for the experiment should the camera boom fail to deploy. Below the camera and light assembly is a vertical aluminum plate which is the back side of one of the rollers that enable the structure to uncoil. The rollers are hinged at the bottom and, when deployed, rotate about the hinge permitting the structure to unfold. Kapton sheets (orange film) apply a constraining pressure on the structure as it is uncoiled during deployment to better control the uncoiling and to ensure the structure remains folded until the rollers are deployed. There are four diagonal booms (two are visible in Fig. 6) which deploy prior to uncoiling the structure. These booms support a cord attached to the structure. The cord supplies a constant tension on each corner of the structure to facilitate a smooth uncoiling. Note that the cords do not pull the structure out of the coil, the structure is pushed out by motors driving the rollers.

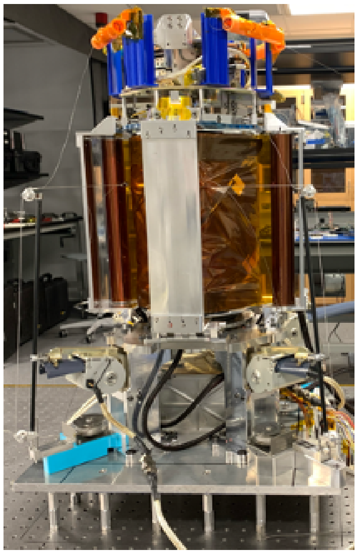

Fig. 6. DOLCE in stowed configuration. Two of the four diagonal booms are visible on the lower portion of DOLCE.

The DOLCE deployment sequence is shown in Figures 7 - yy. The DOLCE flight model is being deployed in the laboratory prior to going into environmental test. Figure 7A shows DOLCE in stow configuration. The camera boom is then deployed (Fig. xx B). Imagery from the four cameras is taken and down linked for verification of the deployment and the next phase of deployment begins. The four diagonal booms are extended to about half of their final length (Figure xy+1 A), and again imagery is captured and down linked. The structure is then unrolled by five motors inside the deployment mechanism (Figure xy+1 B), with imagery being taken and sent to the ground. Once the uncoiling stops, the booms are extended to their full length (Figure yy A). Finally, the rollers on the deployment mechanism are released allowing the 1.7m x 1.7m structure to unfold. The deployment is captured by video for later analysis. This completes the deployment.

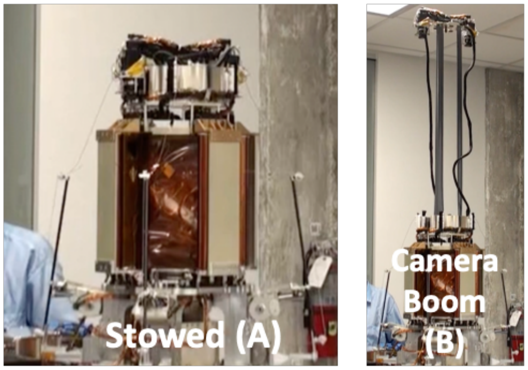

Fig. 7. DOLCE in stowed configuration (A)and with camera boom deployed (B).

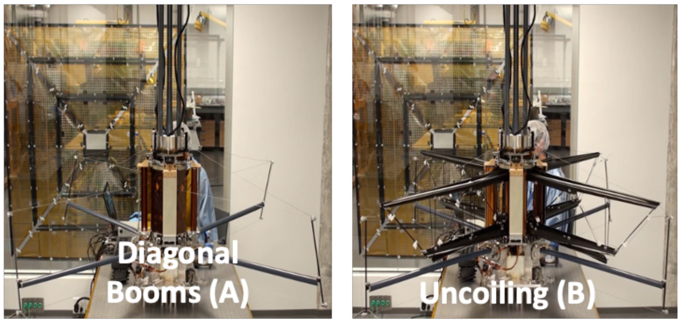

Fig. 8. Diagonal boom extension (A) and structure uncoiling (B).

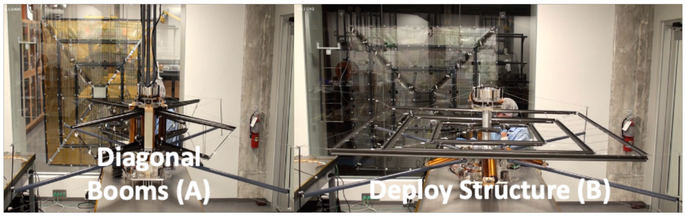

Fig. 9. Full extended booms (A) and structure deployment (B).

DOLCE weighs approximately 33 kg and measures 730 mm in height, 355 mm in length and 355 mm in width in its stowed configuration.

C. *MAPLE*

MAPLE's objectives are to demonstrate beam focusing and steering using the SSPP developed CMOS RFICs and flexible antenna arrays in the space environment [9]. MAPLE is contained in a 6U cubesat frame and weighs approximately 2.6 kg. The payload with its MLI blankets is depicted in Fig. 10). Figure 11 shows the interior of MAPLE. A 32 dipole antenna flexible array, driven by two CMOS RFICs, is located at one end of the 6U frame along with a camera. The array radiates microwave energy at 9.884 GHz. A microprocessor and reference signal generator are co-located with the CMOS RFICs. The microprocessor provides command and control for the experiment and communications with the flight computer for data transfer, telemetry and commanding. At the opposite end of the 6U frame is an aperture covered by a sapphire window and a rectenna array. Along the right side of the frame near the aperture is another rectenna array and camera is mounted on the wall opposite from the rectennas.

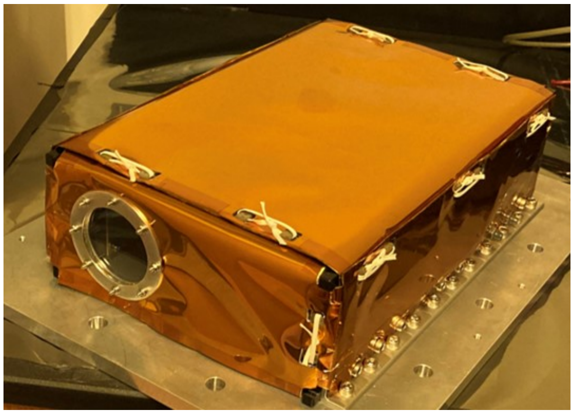

Fig. 10. MAPLE payload with low emissivity covering. Sapphire viewing window is visible.

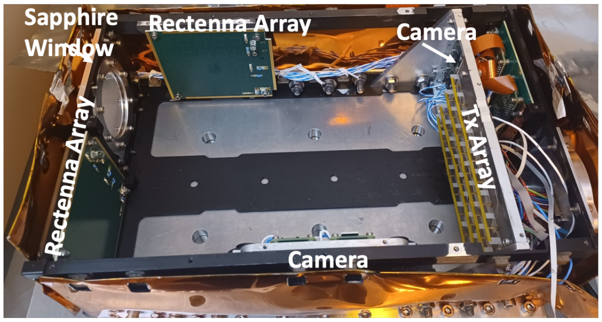

Fig. 11. MAPLE interior showing the Tx array and two rectenna arrays.

The purpose of the rectenna arrays is to demonstrate the beam steering and focusing capabilities of the transmitting array and processor. At various times during the flight, the array will be powered on and the beam focused on one of the rectenna arrays which measures the beam pattern. The cameras are used to record the lighting of an LED attached to the rectennas to offer photographic evidence that power was transmitted. MAPLE has several experimental modes intended to test different attributes of the transmitter hardware. These experimental modes are intended to test sustained operation, repeatability of array focusing, and system aging.

D. Avionics and Software

All the SSPD-1 components are supported by an avionics suite consisting of a Xiphos Q7 single board computer (SBC), three Raspberry Pi for imaging purposes, 5 motor controllers for DOLCE, two custom interface boards, and a GOMSpace electrical power system. The SBC interfaces with Momentus' flight computer to receive commands and pass back telemetry and mission data. The SBC transmits commands to the other SSPD-1 components and receives their telemetry and mission data. The computer also controls the power supply and can selectively power on or off the other three payload components.

Our flight software is based on ASI Inc.'s MAX framework. MAX is hosted on the SBC running on a Linux operating system. Our flight software has approximately 150,000 lines of code. With MAX, we are able to perform fault detection and remediation, command and control, maintain multiple boot images, upload new software from the ground, and perform all the other functions needed to make the payload operate as intended.

E. Status

SSDP-1 has gone through environmental testing and integration to the Vigoride 5 space vehicle. Vigoride 5 has been transported to the Space X processing facility at Kennedy Space Flight Center at Cap Canaveral, Florida, where it will be mounted onto a port on the EPSA (EELV Payload Secondary Adapter) ring of the Falcon 9 for launch on the Transpoter 6 mission scheduled for November 6, 2022. .

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