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Development of Multifunctional Lightweight Membrane Structure for Antennas and Power Generation on Small Satellites

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ABSTRACT

To enable a broad range of space activities, small satellites demand solutions for lightweight, high-power generation. As a power generation system, Japan Aerospace Exploration Agency (JAXA), Tokyo Institute of Technology, and Sakase Adtech, Co., Ltd. developed "Harvesting Energy with Lightweight Integrated Origami Structure-R" (HELIOS-R) for on-orbit demonstration. HELIOS-R has solar arrays on its surface and demonstrates the technology that enables higher specific power generation capacity than traditional solar array panels. The membrane surface also incorporates 5G antennas and interferometer antennas, conducting communication experiments with the main body of the satellite. This paper introduces the mission outlines, development status, and anticipated outcomes of the HELIOS-R component.

INTRODUCTION

A Lightweight and highly efficient power generation system is needed to enable a broad range of space activities like long-term observation and deep space exploration with ion engines by small spacecraft. One solution involves attaching solar cells to a deployable lightweight membrane structure. Due to their minimal weight, membrane structures can generate more power per mass than conventional solar array panels. Moreover, lightweight membranes can also be used as sun shields[1], phased array antennas[2], solar sails[3], and so on. The on-orbit demonstration is crucial for fully exploring these advantages.

Japan Aerospace Exploration Agency (JAXA), Tokyo Institute of Technology, and Sakase Adtech, Co., Ltd. developed "Harvesting Energy with Lightweight Integrated Origami Structure" (HELIOS) for on-orbit demonstration[4,5]. HELIOS was an onboard component of RAISE-3 (RApid Innovative payload demonstration SatellitE-3). It was scheduled to be launched and demonstrated in fiscal year 2022, but due to the failure of the Epsilon launch vehicle, the on-orbit demonstration was not achieved. Therefore, we are developing HELIOS-R for a second try. HELIOS-R is a component of RAISE-4 and is scheduled for launch in fiscal year 2025. It will demonstrate the technology that potentially achieves power generation of 200 W/kg, exceeding the conventional 150 W/kg.

Many missions aim to increase the efficiency of solar power generation, such as the ROSA (Roll-Out Solar Array) mission by Deployable Space Systems[6,7], and Ultraflex[8] by Northrop Grumman. In Japan, JAXA has made solar panels lighter and more efficient by developing a thin solar array system called TMSAP and demonstrated its performance in orbit in 2019. These missions improved specific power capacity, but at a maximum of about 150 W/kg, solar array membrane has the potential to raise the limits of solar power generation.

In the HELIOS-R mission, fifth generation (5G) and interferometer antennas are attached to the membrane in addition to solar arrays. Communication experiments with antennas on the satellite body will also be conducted to exemplify the potency of the multifunctionality of lightweight membranes.

The mission sequence begins with deploying the membrane structure using a motor to demonstrate deployment technology with booms. A camera records the deployment dynamics for in-depth analysis. Subsequently, the component measures the current-voltage curve to evaluate the performance of solar array characteristics evaluation. Then, a 5G communication experiment will be conducted to demonstrate that membrane array antennas can accommodate non-flatness. Finally, an interferometer experiment will be carried out to measure the shape of the membrane, demonstrating the feasibility of an aperture synthesis on a membrane.

The success of the HELIOS-R mission will validate the deployment of lightweight membrane structures with solar arrays and antennas attached, demonstrating their effectiveness as a future power source for small satellites. In addition, experiments using membrane-attached antennas will illustrate the practicality of multifunctional membrane structures. Such lightweight and multifunctional membrane structures can be used for deep space exploration such as OPENS[9] and have the potential to contribute significantly to expanding the range and diversity of future small satellite activities.

MISSION SEQUENCE

The overview of HELIOS-R is expressed in Figures 1 and 2. The HELIOS-R consists of the EBOX (Electrical BOX) and MS (membrane structure). The EBOX is a 1U-size bus module. The antennas are covered with germanium-deposited polyimide films.

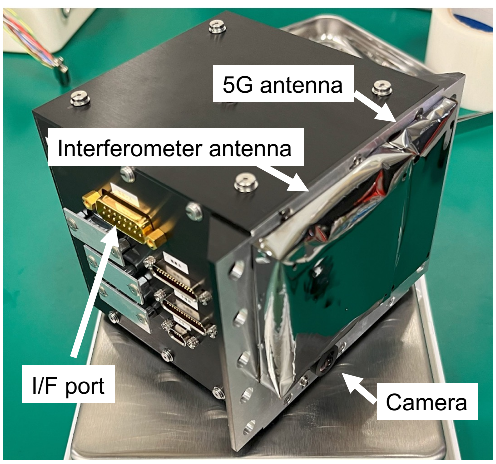

Figure 1: EBOX

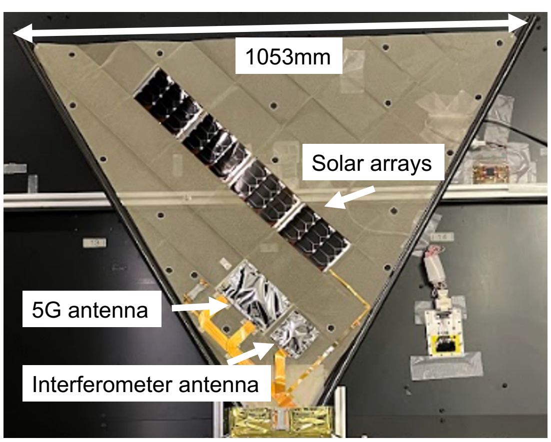

Figure 2: Membrane configuration

The membrane is a 1-meter 1-side triangular membrane supported by CFRP (Carbon Fiber Reinforced Plastic) booms. It is folded and stowed at launch and deployed at the initial operation.

Real-time operation is unavailable due to satellite and ground constraints, so stored commands will be used. The membrane cover will be released by using two burn wire release mechanisms. The release of the membrane is shown in Figure 3.

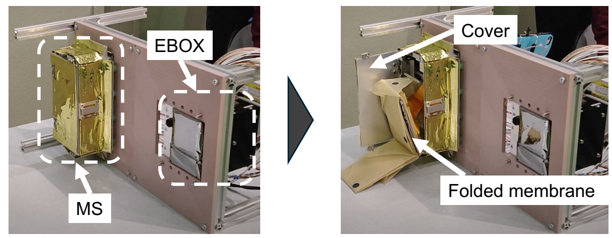

Figure 3: Cover deployment

Figure 4 shows the membrane deployment. Two CFRP booms extend at a constant speed by the motor, and deployment is completed in about 190 seconds. The motor is forced to stop when the deployment detection switch reacts.

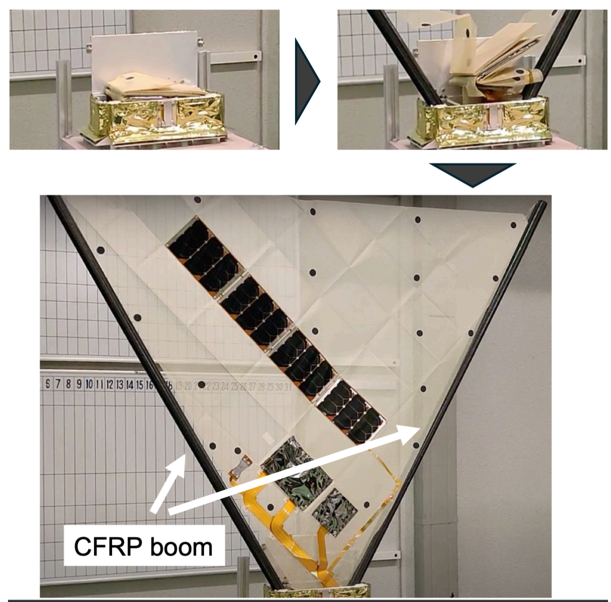

Figure 4: Membrane deployment

After the membrane is deployed, the three missions are carried out in parallel.

HELIOS-R will perform three main missions: 1) solar array membrane mission, 2) beamforming 5G antenna, and 3) interferometer experiment. Figure 5 shows the HELIOS-R mission sequence.

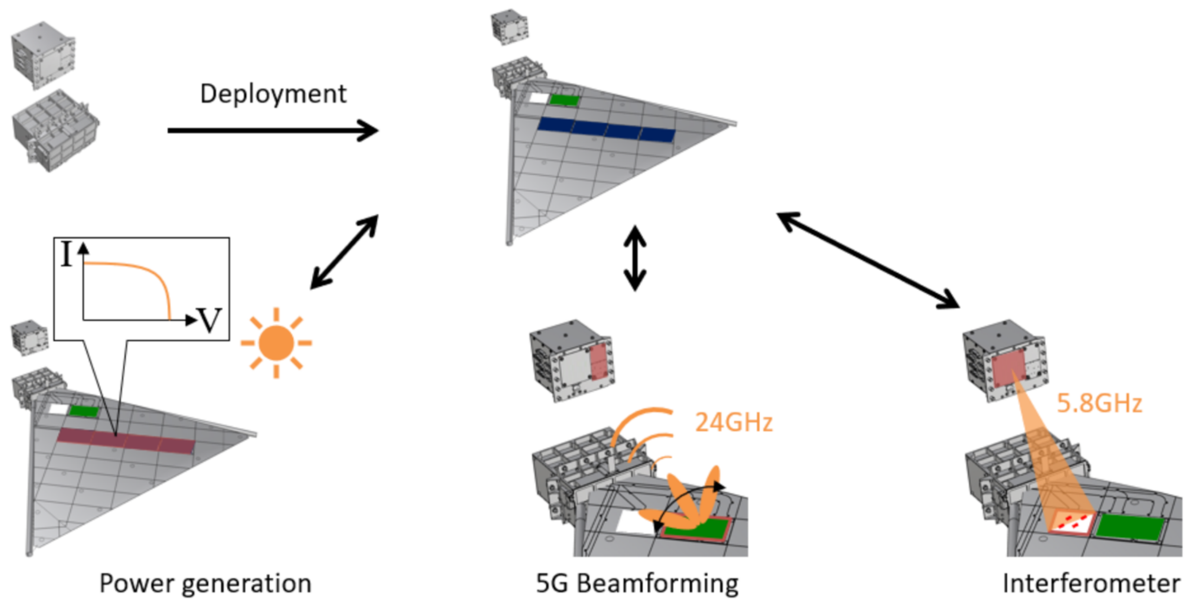

Figure 5: HELIOS-R mission sequence

1) Solar array membrane

HELIOS-R has a solar array membrane with thin-film solar arrays. The main objective of this mission is to demonstrate the technology of potentially achieving 200W/kg power generation by exploiting the advantage of lightweight membranes. HELIOS-R will measure the current-voltage property of the solar array over one year to evaluate the degradation and reliability of the solar array membrane.

2) Beamforming by 5G communication

The transmitting array antenna is mounted on a membrane to demonstrate beamforming that can compensate for the non-flatness of the membrane. The communication uses 24 GHz in the ISM (industry science and medical) band, which is close to the 28 GHz in 5G communications. This technology is expected to enable high-capacity, high-speed communications for small satellites and communications from deep space.

3) Interferometer experiment

To achieve the miniaturization of microwave radiometer technology, we aim to develop an aperture synthesis technique using a lightweight and large membrane. Several thin antennas are used as interferometer elements to transmit radio waves from an antenna on the satellite body to a receiving antenna on the membrane.

The success criteria of the HELIOS-R mission are shown in Table 1.

Table 1: Success criteria

Mission	Minimum success	Full success
1) Solar array membrane	Deployment of a membrane and the power generation	The evaluation of deployment using recorded video
		Evaluation of the current-voltage curve in one orbit
		Evaluation of the current-voltage curve over one year
2) 5G communication experiment		Measurement of transmission power of 5G antenna
		Compensation of antenna's non-flatness using 5G antenna beamforming
3) Interferometer experiment		Demonstration of an interferometer by 5.8GHz membrane antenna
		Membrane shape measurement by 5.8GHz interferometer

SYSTEM DESIGN

Figure 6 shows the system diagram of HELIOS-R. The HELIOS-R system is divided into two major parts, EBOX and MS. The EBOX and the MS are electrically connected by harnesses.

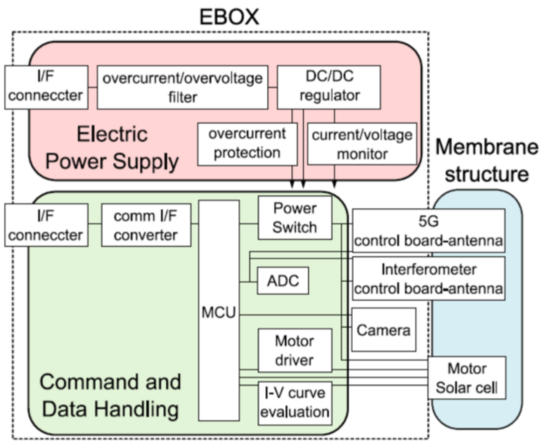

Figure 6: System diagram of HELIOS-R

EBOX

EBOX has five boards as shown in Figure 7. Command & Data Handling (CDH) board, Electrical Power Supply (EPS) board, camera control board, 5G control board, and interferometer control board. Table 2 shows the EBOX specifications.

Figure 7: Cross section of EBOX

Table 2: Specification of EBOX

Mass	0.70 kg
Envelope area	13 x 12 x 11 cm
Electrical power IF	24~33V, 1ch
Power consumption (EBOX & MS)	2 ~ 17 W
Communication IF	RS422 Rx 2ch, Tx 2ch
Others	Camera x 1 5G Rx x 1 Interferometer Tx x 1

Membrane

The membrane specifications are shown in Table 3. In addition to thin-film solar cell sheets and antennas, retroreflective markers are attached to the membrane to estimate membrane shape.

Table 3: Specification of MS

Mass	2.0 kg
Membrane area	0.43 m^2
Thin-film solar cells	Film-type Space Solar Sheet (SHARP) 12 series, 1 parallel solar cell array Voc = 37 V, Isc = 0.43 A @ BOL, Efficiency 31 % @ BOL, Max power 13.7 W @ BOL
Others	5G Tx x 1 Interferometer Rx x 1

SUBSYSTEM DESIGN

This section describes the subsystems of the HELIOS-R.

CDH

The HELIOS-R CDH receives commands from the satellite, executes the commands, and sends telemetry to the satellite CDH. On request, the HELIOS-R CDH communicates with subsystem boards such as the 5G, interferometer, and camera board. The HELIOS-R CDH also outputs the monitored data as housekeeping (HK) data. HK data includes voltage, current, temperature, and power state of subsystems. HELIOS-R CDH monitors them to ensure there are no anomalies.

In addition, CDH manages the motor control for the boom deployment. Real-time operation is not available as mentioned above, so simple control is used. The motor is commanded to drive for a specified number of seconds. During this time, if the switch responds, the motor will stop. In case the motor does not stop for some reason, the drive time management and the motor stop command are prepared in advance.

EPS

EPS provides appropriate voltage to each board using DC/DC converters. It also protects HELIOS-R from overcurrent.

Camera system

A camera system is controlled by Raspberry Pi. The main role of the camera is to record the membrane's behavior during membrane deployment. By analyzing the recorded data on the ground, it is possible to estimate the membrane shape. The camera onboard computer communicates with CDH via UART.

5G, Interferometer control board

5G and Interferometer control boards execute experiments when they receive commands from CDH. In both experiments, radio waves are transmitted and received between the antenna on the membrane and the antenna on the satellite. SPI communication is used for communication with CDH.

Solar array

Space Solar Sheets (SSS) are attached to the membrane as thin-film solar cells. SSS consists of three series and parallel cells. Figure 8 shows the overview of SSS. Because of the cost constraints, only part of the membrane is covered with SSS.

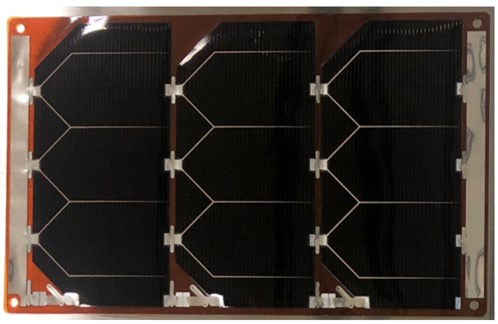

Figure 8: Space Solar Sheet

The on-ground current-voltage evaluation test was carried out by a solar simulator (Figure 9). The current-voltage properties were measured by both the equipment and the EBOX. From this test, it was confirmed that the EBOX was able to measure current-voltage properties, although there are some differences between the measurement result of the equipment and the EBOX (Figure 10).

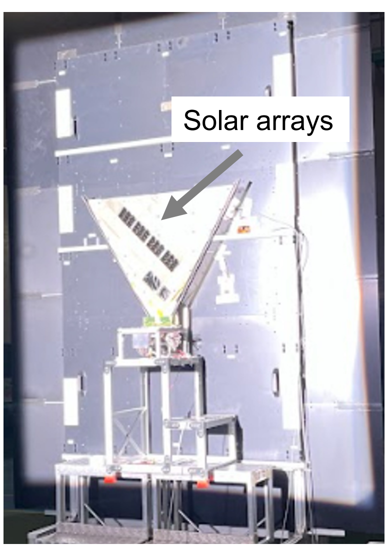

Figure 9: Current-voltage measurement test

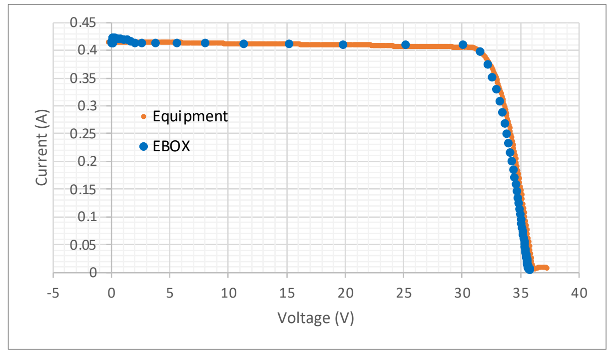

Figure 10: Results of current-voltage measurement

Assuming that SSS is attached to the entire surface of the HELIOS-R membrane, the specific power generation capacity at 0.43 m^2 is estimated to exceed 60 W/kg. Therefore, 2 m^2 class membranes may generate more than 200 W/kg.

DEVELOPMENT STATUS

The development schedule is shown in Figure 11. Development is almost complete and is currently being prepared for operation.

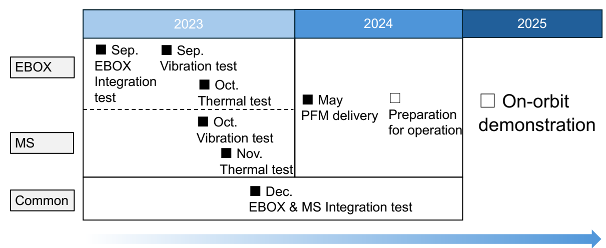

Figure 11: Development schedule of HELIOS-R

Environmental tests

Vibration tests and thermal cycle tests of EBOX and MS are conducted. These conditions are required from the Epsilon rocket and the RAISE-4. Figure 12 shows the vibration test.

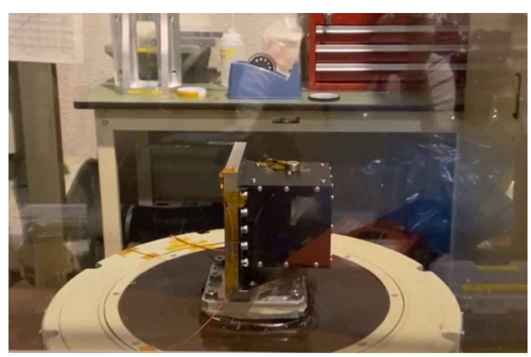

Figure 12: Vibration tests

The thermal cycle test conditions were set to cover the entire temperature range expected in orbit. Table 4 shows the allowable temperature range specification values for each EBOX component, and the on-orbit temperature range estimated from the results of the thermal analysis. The temperature control range of the thermostatic bath was set so that all components are below (at low temperatures) or above (at high temperatures) their respective estimated on-orbit temperatures. The environmental conditions are shown in Figure 13.

Table 4: Thermostatic bath temperature setting ranges for thermal cycle tests

High	60 ℃
Low	-27 ℃

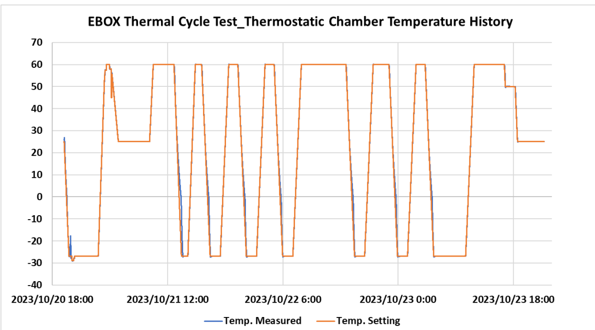

Figure 13: Temperature history of thermostatic chamber for thermal cycle test

Integration tests

After environmental testing, EBOX and MS were tested for proper functionality. Figure 14 shows the HK data of membrane deployment. This indicates that the switch is responding normally due to membrane deployment.

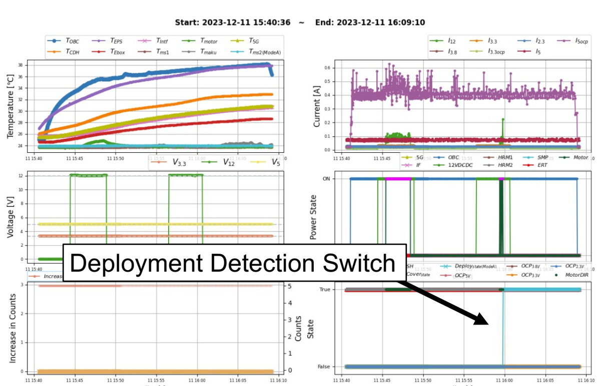

Figure 14: HK data

Integration tests of the 5G and interferometer antennas were also conducted and confirmed to be functioning properly.

CONCLUSION

This paper showed the mission overview and design of the HELIOS-R. HELIOS-R is HELIOS's rechallenge mission to demonstrate one of the highest power generation efficiency solar cell technologies. It also demonstrates the multi-functionality of lightweight membranes through antenna experiments. The HELIOS-R has been delivered and is currently being prepared for operation in fiscal year 2025.

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