SSC21-WKIV-01

Development of Multifunctional Lightweight Membrane with High Specific Power Generation Capacity

Tetsuya Kusumoto
University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan; +81-3-5841-6631
kusumoto.tetsuya@ac.jaxa.jp

Masanori Matsushita, Yuki Takao, Ahmed Kiyoshi Sugihara, Osamu Mori, Yasutaka Sato, Yasuyuki Miyazaki, Nobukatsu. Okuizumi, Shigeo. Kawasaki,
Japan Aerospace Exploration Agency

Akihito Watanabe, Hiroaki Ito, Toshiyuki Hori
Sakase Adtech Corporation

Kazuyuki Nakamura, Chihiro Hatakeyama, Takahiro Kuhara
Technosolver Corporation

Shuhei Yamada, Masahiro Fujita, Yuichiro Nada
University of Tokyo

Genki Ohira, Maiko Yamakawa, Kaoru Namiki,
The Graduate University for Advanced Studies, SOKENDAI

Yudai Kimishima, Kotaro Ikeda, Keiseuke Sugiura,
Aoyama Gakuin University

Hideyuki Takahashi, Ayaka Fujita,
Tokai University

Yuichiro Tsukamoto, Shinji Takeda, Hiraku Sakamoto, Atsushi Shirane, Kenichi Okada
Tokyo Institute of Technology

ABSTRACT

As a lighter power generation system, Japan Aerospace Exploration Agency (JAXA) and Sakase Adtech Corp. are developing a demonstrator component named “Harvesting Energy with Lightweight Integrated Origami Structure” (HELIOS), which is a deployable lightweight membrane structure. HELIOS has solar arrays on its surface and demonstrates the technology which enables higher specific power generation capacity compared to the conventional solar array panels. The membrane also has communication antennas, showing the potency of lightweight membrane’s multifunctionality such as large data transmitting by 5G antennas and high-resolution observation by interferometer antennas. This paper presents the component’s concept and design, and the expected achievements.

INTRODUCTION

Lighter power generation systems are needed for small spacecraft for a wider range of activities in space, including long-term observation and deep space exploration with ion engines. One possible solution that meets this demand is to attach solar arrays to a deployable lightweight membrane structure. Membrane structures are so light that they can generate more power for a given weight compared with conventional solar array panels. Thus, the solar array membrane’s specific power is higher than existing flexible solar arrays and rigid solar panels. As well as efficient power generation, lightweight membranes can be used for a vast variety of applications such as sun shield[1], phased array antenna[2], solar sail[3], and deorbiting sails[4]. To explore these advantages, an on-orbit demonstration is demanded in a space environment.

Towards an on-orbit demonstration, Japan Aerospace Exploration Agency (JAXA) and Sakase Adtech Corp. are developing a demonstrator component named "Harvesting Energy with Lightweight Integrated Origami Structure" (HELIOS), which will be attached to the JAXA's Innovative Satellite Technology Demonstration Program Satellite and will be launched in 2022. This component is a multifunctional membrane structure supported by four deployable booms with solar arrays and phased array antennas on its surface. This component has been developed upon the experience and knowledge of IKAROS[8] (Interplanetary Kite-craft Accelerated by Radiation of the Sun), which is the world's first solar sail developed by JAXA, and OrigamiSat-1[9,10], which is a 3U CubeSat with a multifunctional membrane led by Tokyo Institute of Technology. HELIOS consists of a 1-by-1 m square membrane made of polyimide, diagonal tubular CFRP (carbon fiber reinforced plastic) booms that deploy and support the membrane, and a 1U (1 kg) bus module. HELIOS demonstrates the world's highest specific power by exploiting the advantages of a lightweight membrane structure where 200 W/kg power generation will be possible, while traditional solar array panels can generate at most 150 W/kg.

There have been a lot of solar array paddle missions seeking to achieve higher solar power generation capacity. One example is ROSA (Roll-out Solar Array)[5,6] mission by DSS (Deployable Space Systems) which is a highly modular, elastically deployable, flexible blanket solar array system for lightweight solar array system. Another example is Ultraflex[7] by Northrop Grumman. It is a circular and fan-folded solar array system, which was used in NASA's mission including Cygnus and Insight. In addition, JAXA developed a thin solar array system called TMSAP and demonstrated its performance on-orbit in 2020. Even though these missions advanced specific power capacity greatly, 200 W/kg power generation has not been achieved, and a solar array membrane has the potential to extend the limits of solar power generation technology.

In addition to solar arrays, 5G antennas and interferometer antennas are attached to the membrane, and communication experiments with antennas on the satellite body will be conducted. The antenna missions exemplify the potency of the multifunctionality of the lightweight membrane. This paper presents the component's concept and design, and the expected achievements.

The mission sequence of this component is as follows. The first mission is to deploy the membrane with a motor. This deployment behavior is recorded by a camera and is going to be utilized for the understanding of the deployment dynamics. Subsequently, the component measures the I-V curve to evaluate the performance of solar arrays. Then, the first antenna mission will be performed using 5G communication antennas, demonstrating membrane array antennas that can accommodate non-flatness. Finally, an interferometer experiment will be conducted and the membrane shape is measured, showing the feasibility of an aperture synthesis on a membrane.

The success of the HELIOS mission will demonstrate that the boom-supported membrane can be deployed even with solar arrays and antennas on the surface and can generate more power than conventional solar paddles. This indicates that lightweight solar array membranes are viable options for future small satellites as power generation systems. This mission also opens up the possibilities of lightweight membrane's multifunctionality such as large data transmitting by 5G antennas and high-resolution observation by interferometer antennas on a membrane.

Table 1: Success criteria

mission	Minimum success	Full success
Solar array membrane	Deployment of a membrane and the power generation	The evaluation of a deployment using recorded video
		Evaluation of the I-V characteristic curve Confirmation of power generation for more than one year
5G communication experiment		Measurement of 5G antenna communication power
		Compensation of antennas' non-flatness using 5G antenna beamforming
Interferometer experiment		Demonstration of an interferometer by 5.8 GHz membrane antenna
		Membrane shape measurement of 5.8 GHz interferometer

SUCCESS CRITERIA

HELIOS will perform three missions including solar array membrane mission, beamforming by 5G antenna, and interferometer experiment.

Solar array membrane

The main objective of this mission is to demonstrate the technology which can potentially achieve 200 W/kg by exploiting the advantage of the lightweight membrane. This mission includes the deployment of a membrane using a flange bolt actuator and a motor.

Beamforming by 5G communication

Transmitting array antennas are attached to the HELIOS membrane surface and demonstrate a beamforming technology that can compensate for the non-flatness due to the membrane structure. In the HELIOS mission, 24GHz frequency, which is in the ISM band and close to 28 GHz that is used for 5G communication, is going to be used in the communication between a membrane and a satellite body.

Interferometer experiment

Aiming at the miniaturization of the microwave radiometer, HELIOS demonstrates an aperture synthesis technology using the lightweight membrane structure. In this mission, a few thin antenna elements are used as an interferometer, and an antenna on a satellite body will transmit a radio wave to the receiving antenna on a membrane. The frequency of 5.8 GHz, which is in the ISM band, is going to be used since this frequency can be used for interferometer and the antenna can be on a thin membrane.

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

MISSION SEQUENCE

The overview of HELIOS is expressed in Fig. 1. A box called “Ebox” (Electric box), which receives commands and control the component system, is equipped above the membrane structure in the satellite. Ebox contains circuit boards and the overview of Ebox is shown in Fig. 2. A receive antenna for the 5G communication experiment is attached to the Ebox and communicates with a transmit antenna on the membrane. A transmit antenna for the interferometer is attached to the Ebox and communicates with a receive antenna on the membrane. Four solar arrays are also attached to the membrane. The configuration of the membrane is shown in Fig. 3. Main operations are the four operations listed below and shown in Fig. 7.

- Operation 1 Boom-Supported Membrane Deployment
- Operation 2 Solar array performance evaluation
- Operation 3 5G communication experiment
- Operation 4 Interferometer experiment

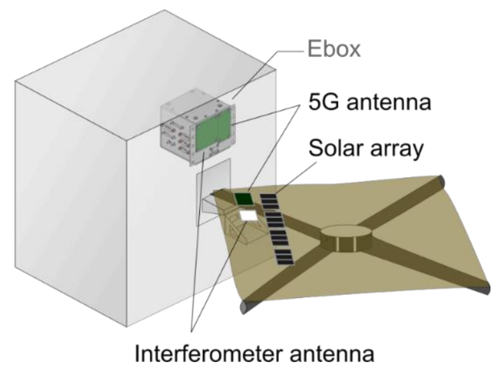

Figure 1: Deployed configuration of HELIOS

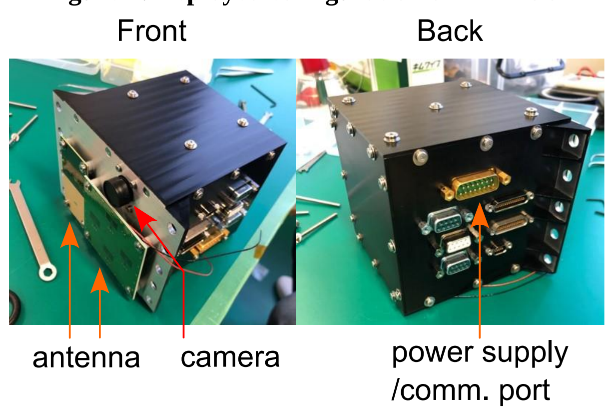

Figure 2: Overview of Ebox

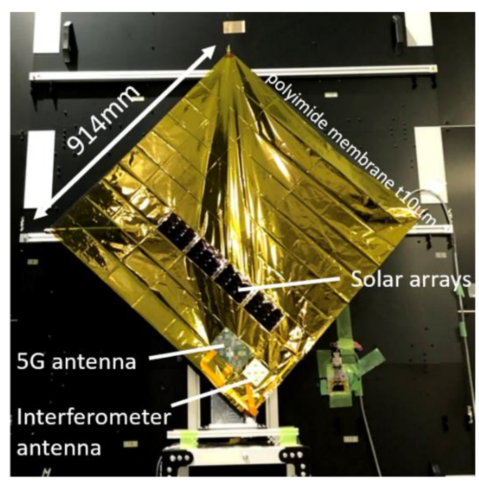

Figure 3: Membrane configuration

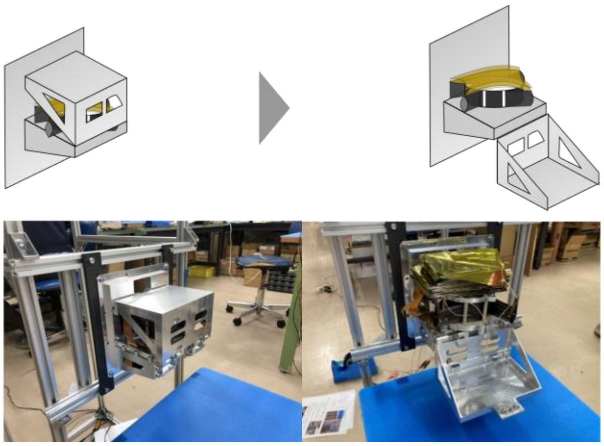

Figure 4: Procedure of the frangibolt actuator release

Operation 1: Boom-Supported Membrane Deployment

A membrane deployment operation consists of two steps: Release of a flange bolt actuator and motor-driven boom deployment.

I. Frangibolt actuator release

A folded membrane and booms are attached to the Ebox and fixed by a frangibolt, which is a shape-memory acutuator. It consists of an electric heater surrounding a hollow cylinder of TiNi and a notched bolt. By applying electric power and heating the TiNi actuator cylinder, it expands and elongates the notched bolt to fracture, releasing membrane and booms as shown in Fig. 4.

II. Motor-driven boom deployment

The deployment sequence of HELIOS is shown in Fig. 5. In this figure, pictures below are taken when an on-ground deployment test are carried out. As shown in the figure, the boom extends gradually according to the motor rotation. This sequence takes about 1 minute and the motor is forced to stop when an encoder pulse becomes a target pulse.

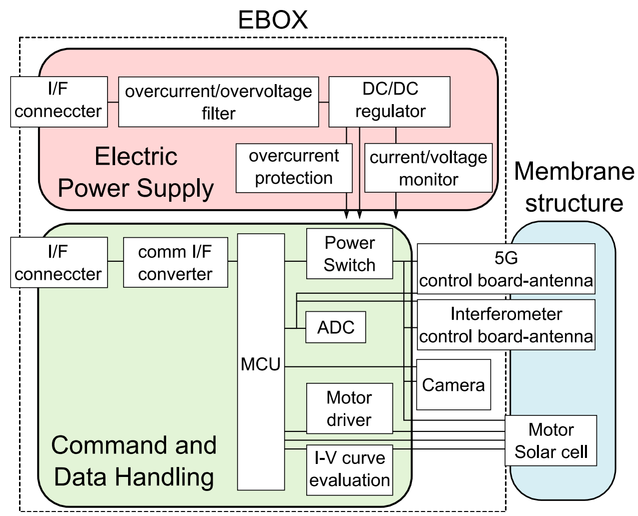

Figure 6: System diagram of HELIOS

Operation 2: Solar array performance evaluation

After the membrane deployment, solar array performance is evaluated by measuring the I-V (current-voltage) curve. The detailed explanation of I-V curve is presented in the section of solar array membrane design.

Operation 3: 5G communication experiment

This experiment demonstrates membrane array antennas that can accommodate non-flatness. Communication is conducted between antennas on a membrane and an antenna on a satellite body. An array IC for 28 GHz is used and 24 GHz which is in ISM (Industry Science and Medical).

Operation 4: Interferometer experiment

This experiment demonstrates a technology that enables interferometer observation by a small satellite. In this mission, the membrane shape after the deployment is measured, exemplifying the potency of the interferometer antennas on a membrane.

SYSTEM DESIGN

A system diagram of HELIOS is shown in Fig. 6. As shown in the figure, the HELIOS system is divided into

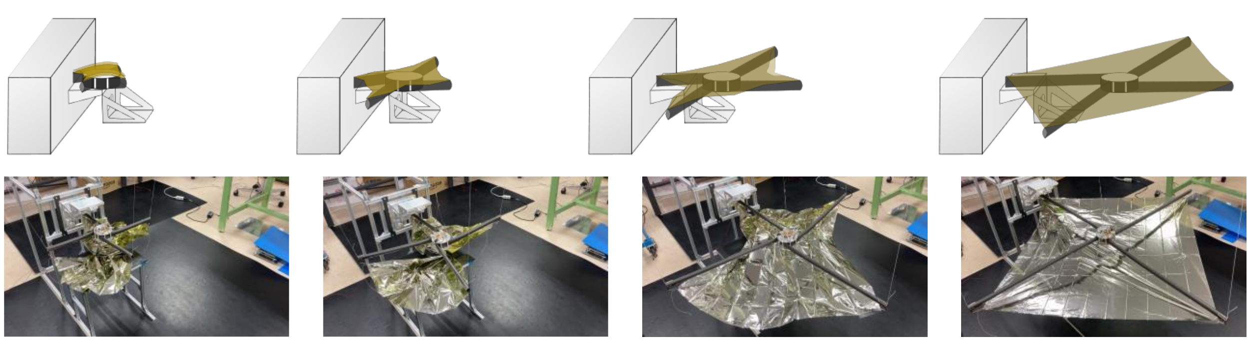

Figure 5: Sequence of a motor-driven membrane deployment

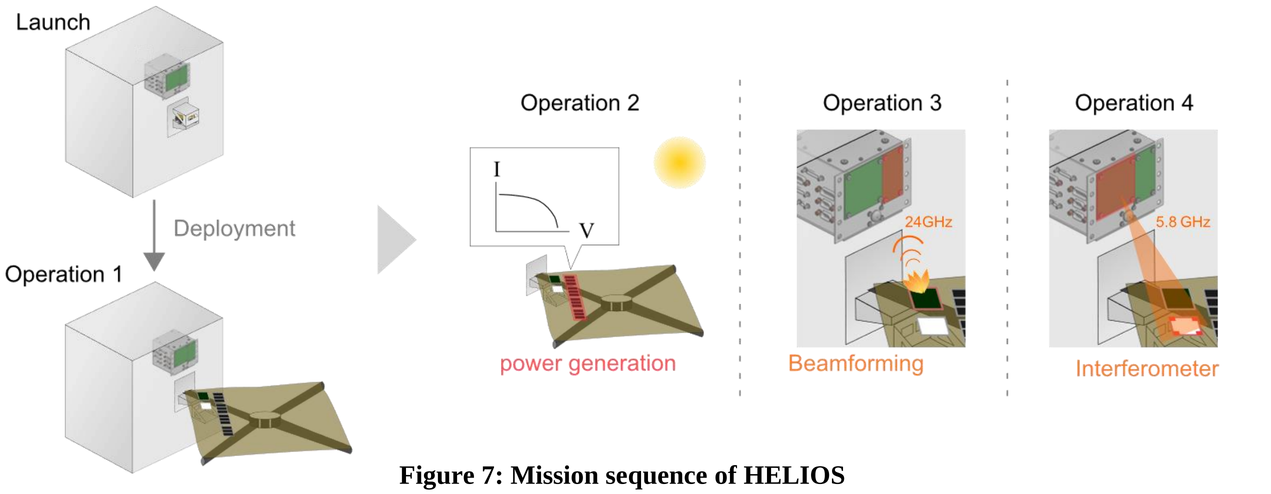

Figure 7: Mission sequence of HELIOS

two parts; Ebox and Membrane structure. Ebox has Electric power supply (EPS) and Command and Data Handling (CDH) boards. In addition to EPS and CDH boards, three boards are included in EBOX; 5G control board, interferometer control board, camera control board. Each subsystem is explained in the next section, and the membrane structure design is explained in the Solar array membrane section.

SUBSYSTEM DESIGN

In this section, the subsystem of HELIOS is described. The HELIOS CDH receives a command from the satellite CDH and executes/distributes the command, then sends telemetry to the satellite CDH. When demanded, HELIOS CDH communicates with the 5G control board, interferometer control board, and Rasberry Pi.

CDH

The component main CDH performs monitoring of each subsystem and processing of command and telemetry. The CDH outputs the monitored data as housekeeping (HK) data. The satellite CDH and the component CDH communicates via RS422 and the component CDH and communicates with a Rasberry Pi via UART. The CDH sends commands and receives telemetries to the 5G control board and the interferometer control board via SPI communication. In addition to the communication with other boards, the CDH manages the motor control for the boom deployment and solar array performance evaluation.

Camera System

A camera system is controlled by Rasberry Pi and utilized for capturing pictures and videos of membrane deployment. Also, the picture of membrane shape after the deployment can be used for the reconstruction of the three-dimensional membrane configuration.

EPS

EPS manages the power of the system. It provides appropriate voltage to each board using DC/DC regulator. It includes overcurrent protection and a current/voltage monitor to ensure safety.

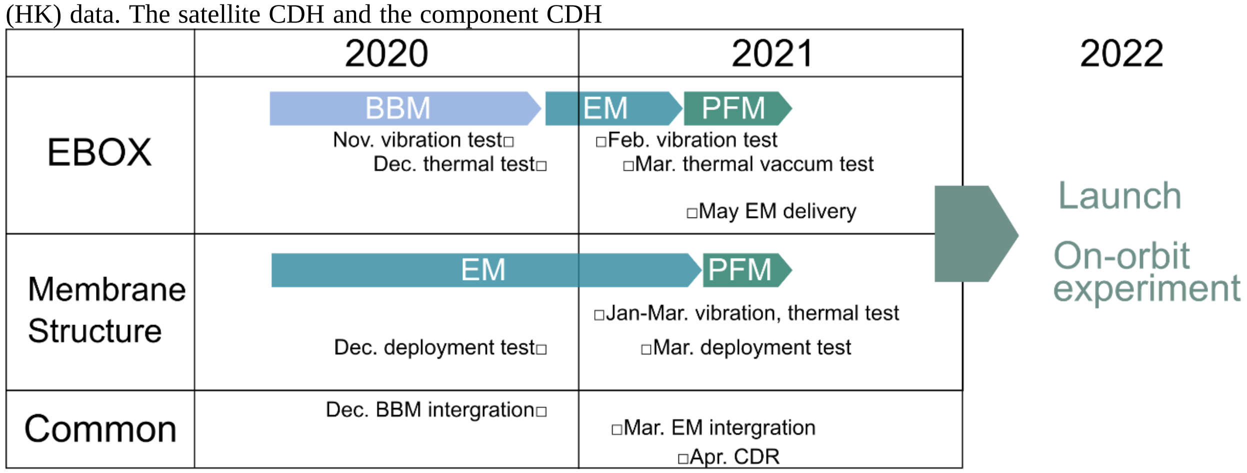

Figure 8: development schedule of HELIOS

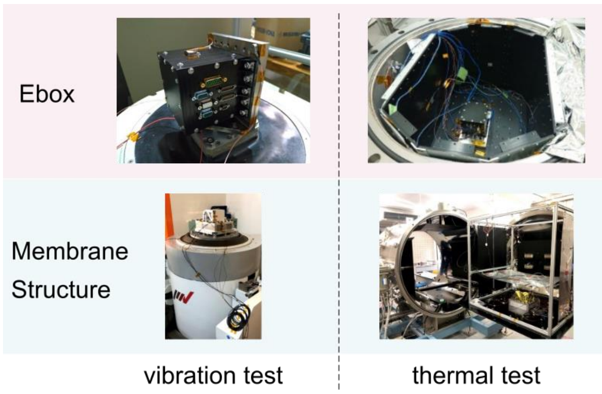

Figure 9: EM test of HELIOS

5G, Interferometer control board

5G and Interferometer control board executes control experiment according to the received command, which is transmitted by CDH. Both of the 5G and Interferometer experiment is the radio wave transmission between the antenna on a satellite body and an antenna on the membrane.

DEVELOPMENT STATUS

The development schedule is shown in Fig. 8. The authors started by developing a Breadboard Model (BBM) and completed developing an Engineering Model (EM) of Ebox in May 2021. Currently, the authors are developing and a Proto-Flight Model (PFM) of Ebox and testing EM of membrane structure. We carried out a thermal test and a vibration test for both Ebox and membrane structure as EM environmental tests as shown in Fig 9.

SOLAR ARRAY MEMBRANE

This section explains solar array membrane design and its performance evaluation. Outside the satellite body, diagonal tubular CFRP (carbon fiber reinforced plastic) booms are attached and they deploy and support a membrane. The membrane is a 1-by-1 m square made of polyimide and has 12 solar array cells, a 5G transmitting antenna, and an interferometer transmitting antenna.

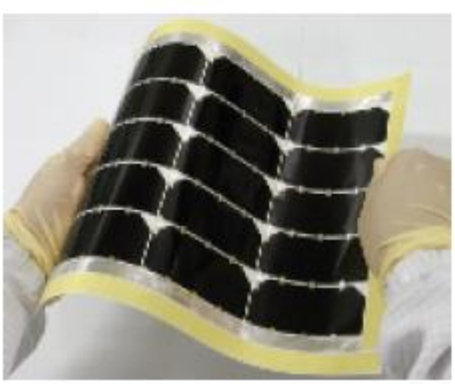

Figure 10: Space Solar Sheet used in HELIOS

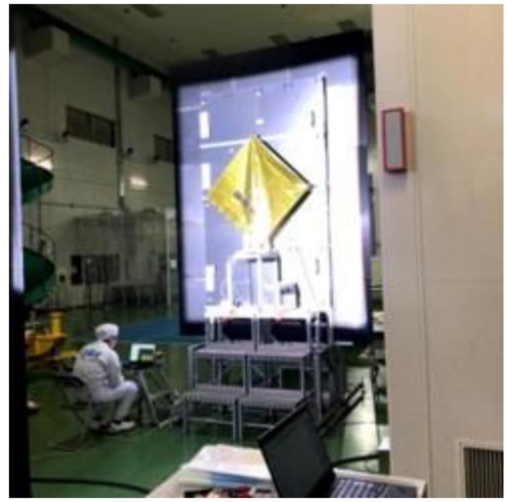

Figure 11: On-ground I-V performance evaluation test

Solar array membrane design

For the design of the solar array membrane, Space Solar Sheet (SSS) was selected as a solar cell (Fig. 10). The cell is a highly efficient and lightweight cell and easy for panel mounting. A typical performance of the cell is shown in Table 2. The SSS is consists of three series connection cells and a parallel connection cell.

Table 2: Typical cell performance of SSS

Parameter	Value
Voc	3.05 V
Isc	0.450 A
Pmax	1.16 W
Imp	0.435 A
Vmp	2.67 V
FF	0.845
Eff	31 %

On-ground current-voltage (I-V) performance evaluation

On-ground I-V performance evaluation is conducted using the engineering model of HELIOS membrane as shown in Fig. 11.

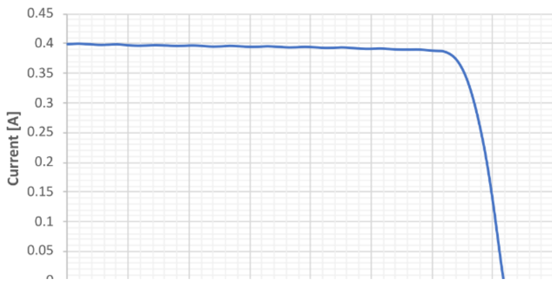

Figure 12: Measured I-V characteristic curve

The I-V characteristic curve is a graph of output voltage versus current for different levels of insolation. From this graph, we can obtain the device's output performance and solar efficiency. Parameters that this graph expresses are short-circuited current (I_{sc}), optimal output current (I_{op}), open-circuit voltage (V_{oc}), optimal output voltage (V_{op}), maximum power (P_{max}), fill factor ($F.F$), and efficiency η. The parameters F.F and η are expressed by the equations below:

$$\eta = \frac{P_{max}}{S_{cell} \times P_{in}} \quad (1)$$

$$F.F = \frac{V_{op} \times I_{op}}{V_{oc} \times I_{sc}} \quad (2)$$

, where S_{cell} indicates the area of a cell and P_{in} denotes the intensity of incident light.

The result of the I-V performance evaluation is shown in Fig. 12 and in Table 3. This result is the standard performance of HELIOS and will be compared to the on-orbit performance. The deterioration of the cells in a space environment and thermal characteristics are going to be measured.

Table 3: Result of I-V performance evaluation

Parameter	Value
Isc [A]	0.3995
Voc [V]	35.88
Pm [W]	12.03
Ipm [A]	0.3832
Vpm[V]	31.40
F.F [%]	83.96

Table 4: Mass parameters for calculating the specific power generation capacity

Component	Parameter	Mass
Membrane	M_{mem}	491 g/m^2
Hub, boom	$M_{hub,boom}$	358 g/m
Launch Lock	M_{ll}	714 g/m

Specific power generation capacity per area and comparisons with the other solar array paddles

As is introduced in the first section, many missions have aimed for achieving higher solar power generation capacity, including ROSA, Ultraflex, and TMSAP. Even though those missions advanced solar array technology greatly, the specific power generation capacity is 150 W/kg at most. However, solar array membranes have a potency of achieving 200 or more W/kg capacity. The estimated solar array membrane's specific power generation capacities per area are shown in Fig. 13. These are calculated with values listed in Table 4 by the following equation:

$$Cp = \frac{N * w}{S * M_{mem} + S^{\frac{1}{2}} * (M_{hub,boom} + M_{ll})} \quad (3)$$

where *Cp* is the specific power generation capacity, *N* is the number of solar arrays on a membrane, *S* is the area of a membrane surface, and *w* is the solar power generated by a single solar array. The power generation *w* is 1.14 W for the solar array used in HELIOS, and when all surface of a 1-by-1 m square membrane is covered with solar arrays, the number of arrays *N* becomes 231. The estimated HELIOS size solar array membrane's *Cp* is 169 W/kg.

In the HELIOS mission, only twelve arrays are attached to the membrane and it does not demonstrate the full capacity of solar array membranes. When all the available membrane surface of HELIOS has solar arrays, the specific power generation capacity becomes 207 W/kg. This can be achieved by just attaching lots of solar cells on a membrane surface and attaching more cells does not interfere with a membrane deployment. Thus, the HELIOS mission demonstrates the solar array membrane technology that enables the highest power generation capacity in solar array systems ever made.

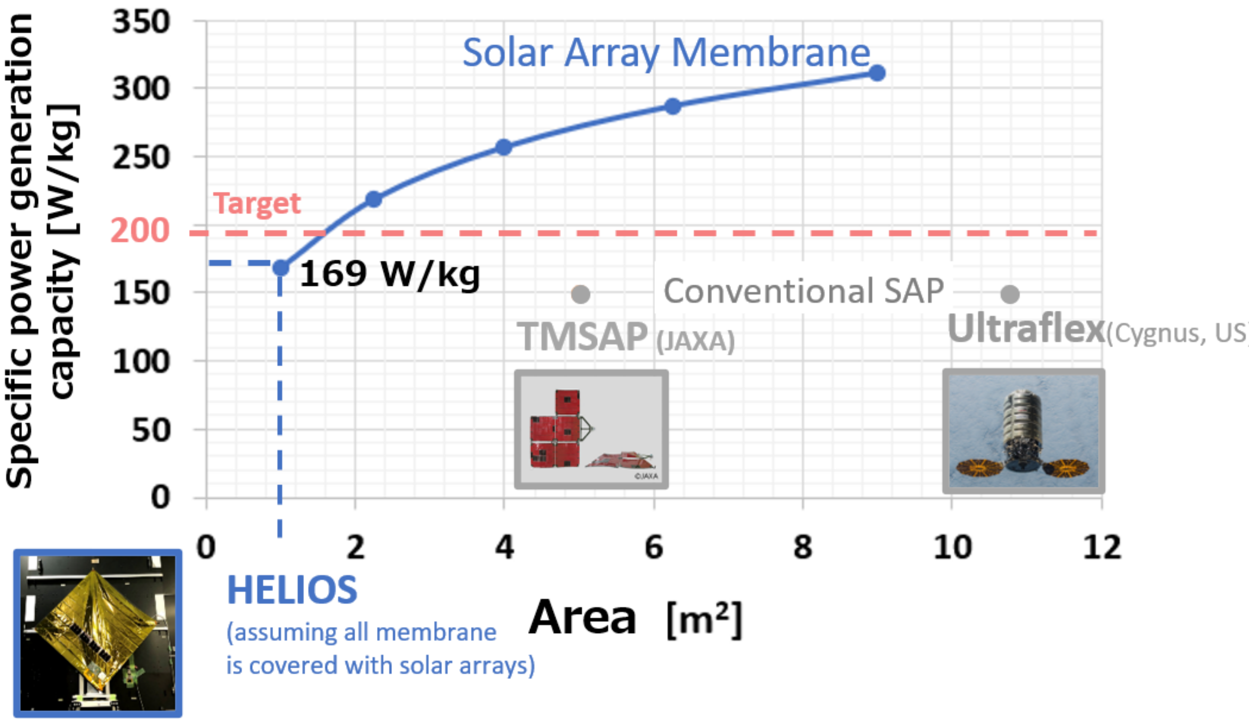

Figure 13: Transition of specific power generation capacity according to membrane area and comparison with other missions

Conclusion

This paper showed the mission overview and the design of HELIOS, which is a lightweight membrane with solar arrays. It also demonstrated the efficacy of a solar array membrane that can achieve high specific capacity. HELIOS is now under FM testing and is to be launched in 2022.

References

1. Ruggiero, Eric J., and Daniel J. Inman. "Gossamer spacecraft: recent trends in design, analysis, experimentation, and control." Journal of Spacecraft and Rockets 43.1 (2006): 10-24.
2. Fan, Liang, et al. "Coupled structural-electromagnetic modeling and analysis of active membrane phased array antenna." Advances in Space Research 66.4 (2020): 760-770.
3. Johnson, Les, et al. "NanoSail-D: A solar sail demonstration mission." Acta astronautica 68.5-6 (2011): 571-575.
4. Lappas, V., et al. "DEORBITSAIL: De-orbiting of satellites using solar sails." 2011 2nd International Conference on Space Technology. IEEE, 2011.
5. Hoang, Bao, et al. "Commercialization of Deployable Space Systems' roll-out solar array (ROSA) technology for Space Systems Loral (SSL) solar arrays." 2016 IEEE Aerospace Conference. IEEE, 2016.
6. Chamberlain, Matthew K., Steven H. Kiefer, and Jeremy Banik. "On-orbit structural dynamics performance of the roll-out solar array." 2018 AIAA Spacecraft Structures Conference. 2018.
7. Murphy, David M., et al. "UltraFlex and MegaFlex-Development of highly scalable solar power." 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC). IEEE, 2015.
8. H. Sawada, Y. Shirasawa, O. Mori, N. Okuizumi, Y. Miyazaki, S. Matunaga, H. Furuya, H. Sakamoto, M. Natori, Y. Tsuda, "On-orbit Result and Analysis of Sail Deployment of World's First Solar Power Sail IKAROS," Journal of Space Technology and Science, Vol. 27, No. 1, 2013, pp. 54-68.
9. K. Ikeya, H. Sakamoto, H. Nakanishi, H. Furuya, T. Tomura, R. Ide, R. Iijima, Y. Iwasaki, K. Ohno, K. Omoto, T. Furuya, T. Hayashi, M. Kato, S. Koide, M. Kurosaki, Y. Nakatsuka, S. Okuyama, R. Kashiyama, J. Nakamura, W. Nio, T. Tsunemitsu, Y. Yamazaki, K. Taga, B. Hohmann,

T. Aamamoto, T. Chubachi, S. Tamura, H. Okada, A. Watanabe, N. Kawabata, T. Hori, H. Ito, T. Kuratomi, Y. Shimoda, N. Hidaka, K. Watanabe, A. Torisaka, M. Yamazaki, "Significance of 3U CubeSat OrigamiSat-1 for space demonstration of multifunctional deployable membrane," Acta Astronautica, Vol. 173, Aug. 2020, pp. 363-377.

10. H. Sakamoto, et al., "On-orbit Demonstration of Innovative Multifunctional Membrane Structure for Ultra-lightweight Solar Arrays and Array Antennas by 3U CubeSat OrigamiSat-1," 35th Small Satellite Conference, SSC21-VIII-06, Aug. 2021.