

## SSC18-WKIX-02

**Design and Development of AOBA VELOX-IV nanosatellite for future Lunar Horizon****Glow mission**

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**ABSTRACT**

This paper highlights the mission, design and development of the 2U CubeSat AOBA VELOX-IV by Nanyang Technological University (NTU), Singapore and Kyushu Institute of Technology (Kyutech), Japan. The satellite mission is the precursor for future lunar exploration missions, addressing the challenges in attitude and orbit control of a nanosatellite in Moon's orbit. Innovation includes miniature four-head pulsed plasma thruster for orbit maintenance, attitude control, momentum dumping; low-light camera with horizon sensing capability; and synchronized ground stations to locate the satellite using downlink signals. The satellite design must pass intensive safety reviews by JAXA; some design revisions due to launch requirements, such as hold-down and release mechanism redundancy, power inhibits, and structure, will be discussed. Development of AOBA VELOX-IV follows the proto-flight model (PFM) approach. A flat satellite was built to interface hardware and test firmware. A structural thermal model (STM) was assembled with subsystems QM/EM and went through qualification tests to confirm the design. AOBA VELOX-IV is scheduled to be launched into low Earth's orbit by JAXA in Q1 2019. Integration of the satellite PFM completed in April 2018, followed by acceptance tests in NTU and Kyutech during May - July 2018.

**INTRODUCTION**

AOBA VELOX-IV is a 2U CubeSat for lunar exploration precursor mission, developed by Nanyang Technological University and Kyushu Institute of Technology. The Satellite Research Centre (SaRC) in NTU started its VELOX satellite program in 2010, following its pioneering X-SAT microsatellite, and has successfully launched the VELOX-PII, VELOX-I, VELOX-PIII, VELOX-II nanosatellites and VELOX-CI microsatellite. SaRC has been working with Kyutech on the AOBA VELOX series of nanosatellites for lunar exploration missions. The program starts with the 2U CubeSat AOBA VELOX-III, which was launched from the International Space Station into low Earth's orbit in Jan 2017, and validated the NTU pulsed plasma thruster (PPT). AOBA VELOX-IV will demonstrate a nanosatellite bus capable of operating in Moon's orbit, especially the suit of Attitude and Orbit Control Systems (AOCS) that works for lunar environment. The next AOBA VELOX nanosatellites would perform scientific missions in lunar's orbit, such as Lunar Horizon Glow observation [1].



**Figure 1: AOBA VELOX-IV Nanosatellite**

AOBA VELOX-IV mission was selected for JAXA's Innovative Satellite Technology Demonstration Program, and is scheduled for launch in end 2018 by the Epsilon launch vehicle. In this paper, we will highlight the innovation in AOBA VELOX-IV, discuss its design revisions driven by JAXA's safety reviews, and its development under NTU-Kyutech collaboration.

The success criteria for the AOBA VELOX-IV mission are as follows:

- Momentum dumping of 0.0001 Nms for short axis in 1 hour
- Orbit maneuvering of  $\Delta V=60\text{m/s}$  by PPT in 1 year
- Capturing images of Earth horizon while entering eclipse, and night view images of Earth
- Capturing the Earth-rim image with upper-atmosphere luminous phenomena such as aurora from the eclipse side
- Obtaining new science data from the captured images

## SYSTEM DESIGN

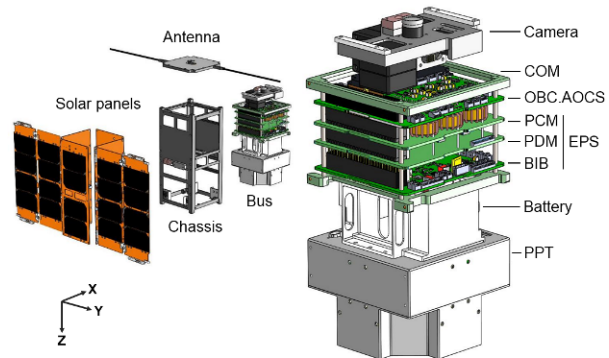
The specifications of AOBA VELOX-IV are shown in Table 1. The satellite follows 2U CubeSat form factor and fits into the launch adapter E-SSOD developed by JAXA. The satellite bus uses flight-proven subsystems from the VELOX satellites and some commercial off-the-shelf (COTS) parts, except for the batter pack, solar panels, and PPT which are custom designed to meet the mission requirements.

**Table 1: Satellite Specifications**

Dimensions	113 mm x 113 mm x 227 mm (stowed) 474 mm x 474 mm x 227 mm (deployed)
Mass	2520 grams
Orbit	Sun-synchronous 500-km orbit
Design lifetime	1 year in low Earth's orbit
AOCS	3-axis gyroscope, 2 fine sun sensors each with 120°-FOV, 6 coarse sun sensors, 3 reaction wheels, 1 PPT
Data handling	OBC with 2GB storage, I <sup>2</sup> C and UART interfaces
Communication	UHF half duplex 4800bps GMSK downlink/uplink, dipole antenna
Power	4 deployable and 2 body-mounted solar panels for 18W peak BOL 5.8 Ah Li-Ion battery at 7.2 V nominal
Structure	Al. 7075-T7351 chassis with stainless steel load bearing parts
Thermal control	Battery heaters
Payloads	Low-light camera, 4-head PPT

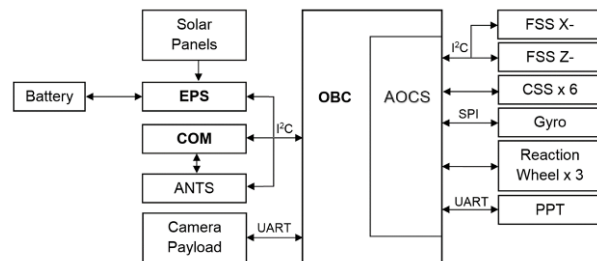
Figure 2 shows the embodiment design of the satellite system. The design is modular to keep integration of the satellite simple: the aluminum alloy chassis houses the satellite bus, the antenna, and solar panels. The bus includes, from top to bottom, an assembly of reaction wheels and camera payload, a stack of Communication System (COM), On-board Computer (OBC), AOCS, Electric Power System (EPS), battery pack, and PPT. The fine sun sensors (FSS) are placed on X- face for

normal operation when the satellite points its solar panels toward the sun; and on Z- face for orbit maintenance when the PPT is pointed to the flight path's trail.



**Figure 2: Satellite System**

Figure 3 shows the architecture of AOBA VELOX-IV. The I<sup>2</sup>C system bus connects the OBC, AOCS, COM, EPS, and the FSSs, while dedicated UART interfaces connect camera and PPT payloads to OBC. 3-axis gyroscope and SD card are interfaced with OBC via SPI. DAC is utilized to control speed of reaction wheels.



**Figure 3: Architecture**

The power budget for AOBA VELOX-IV in shows how the satellite balances its harvested solar energy and used energy. The satellite has a positive power budget for normal operation orbits, when it just does sun tracking and ground passes. It needs 11.81% of the energy stored in the battery for each orbit that it performs orbit maintenance, and 2.67% of battery energy for orbits with imaging mission. The satellite operation will be planned so that the battery's state of charge (SOC) is kept above 75% in order to ensure its life time of 1 year.

**Table 2: Power Budget**

Per Orbit		Sun tracking		Flight path	
		NOP GndPass	NOP w/o GndPass	Orbit Maintenance	Imaging Payload
Energy from SP	Wh	17.82	17.82	5.62	9.60
Energy to Battery (sys. efficiency 64%)	Wh	11.40	11.40	3.60	6.14
COM	Wh	0.97	0.31	0.31	0.31
OBC.AOCS	Wh	3.78	3.78	3.78	3.78
EPS	Wh	2.45	2.45	2.45	2.45
Camera & PPT	Wh	0.00	0.00	1.13	0.04
Energy used	Wh	7.19	6.54	7.66	6.58
Energy gain/loss	Wh	3.54	4.20	-4.93	-1.11
$\Delta$ SOC (BOL)	%	8.84%	10.05%	-11.81%	-2.67%

**INNOVATION**

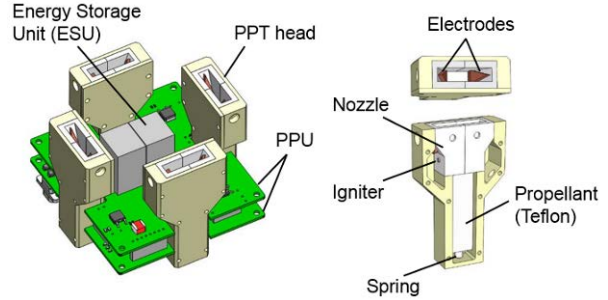
Innovation in Attitude and Orbit Control Systems of AOBA VELOX-IV is highlighted in this section that is designed for lunar orbit operation: a miniature four-head pulsed plasma thruster for orbit maintenance [2], attitude control, momentum dumping; a low-light camera with horizon sensing capability; and synchronized ground stations to locate the satellite using downlink signals.

**Pulsed Plasma Thruster**

The satellite uses reaction wheels for attitude control, and they will saturate eventually. In a lunar mission, the satellite cannot rely on magnetorquers to dump the momentum of the reaction wheels, as there is no usable magnetic field as the one on Earth; it has to use the thruster to support the reaction wheels.

The four-head PPT is based on our dual-axis PPT that has been flight proven on AOBA VELOX-III satellite [3]. The compact design, shown in Figure 4, has four breech-fed heads and a power processing unit (PPU) that fit into 0.5U. The four PPT heads all align with the long axis – and will fire in certain sequences to not only maintain the satellite’s orbit but also dump the momentum for short axes at the same time. Each head carries 5.72 grams of Teflon propellant to meet the 1-year mission’s requirements.

The PPT was tested in our vacuum chamber with thrust stand setup. It consumes 2.25 W to produce an impulse bit of 25.2  $\mu$ Ns, mass bit of 3.8  $\mu$ g, and specific impulse of approximately 676 s.



**Figure 4: PPT (left) and PPT Head (right)**

**Low-light Camera**

As magnetometer cannot be used for satellite in lunar missions, AOCS needs a horizon sensor in addition to the sun sensors for 3-axis stabilization and pointing. AOBA VELOX-IV has a low-light monochrome camera that acts both as an imaging payload for scientific experiment and a horizon sensor. The camera has sensitivity of 3.8 V/lux-sec, average power consumption of 264 mW, and each image is about 30 KB. For this precursor mission, horizon detection will be done by post-processing on ground to evaluate the algorithm safely.

**Synchronized Ground Stations**

Orbit determination using NORAD two-line element (TLE) or Global Positioning System (GPS) is also not applicable for satellites in lunar mission. We have to improvise our own satellite locating method: using three ground stations as different locations to receive signals from the satellite simultaneously, and from that determine the satellite’s location by triangulation. Three ground stations in Singapore, Japan, and Taiwan, all synchronized by GPS clock, will pick up signal from AOBA VELOX-IV as it flies over the area in between the three locations. The signals will be analyzed to determine the satellite location, which will be compared to the orbit information from TLE.

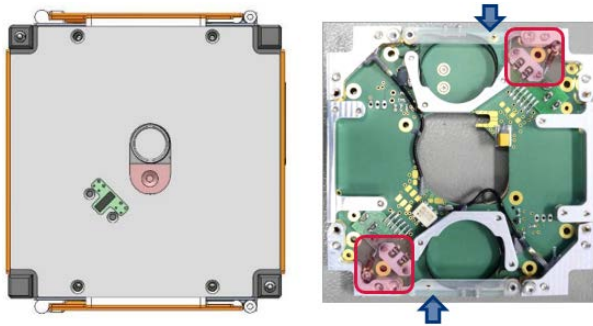
**DESIGN**

In this session, we discuss the design optimization of AOBA VELOX-IV to meet safety requirements by JAXA, i.e. deployment mechanisms, EPS inhibition, and mass reduction. As the satellite would ride on JAXA’s newly developed solid-fuel rocket Epsilon; extra safety consideration is practiced to ensure that it does not cause any problem during launch that jeopardize the main mission. Mechanisms must have two inhibits to prevent premature deployment, power system must have three inhibits to keep the satellite off at all time, and mass is limited at 2660 grams.

### Deployment Mechanism

Redundancy of the hold-down and release mechanism was focus on the ‘hold-down’ part: two inhibits are required for all mechanisms so that no deployment happens accidentally during launch. AOBA VELOX-IV has to stow the solar panels and dipole antenna to fit in the launch adapter, and deploy them in orbit.

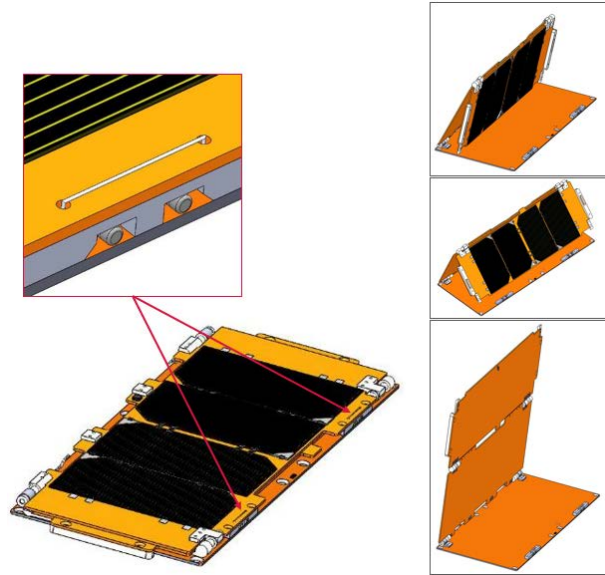
The COTS antenna system has one retaining line holding down the lid of each antenna element. The line runs over two heating resistors, and is stretched by a single spring. In order to have two inhibits, a second line and another spring must be added for each antenna element. As changing the design of the commercial antenna system risks its performance, it was decided to bypass the in-built deployment mechanism. The retaining wires and springs are removed, and the antennas are held down by the deployable solar panels instead, as shown in Figure 5.



**Figure 5: Antenna Hold-down and Release Mechanism**

Figure 6 shows the two-fold deployable solar panel held down by two retaining lines, each runs through two heating resistors. The Dyneema line used has melting temperature of 144 °C and strength of 75.5 N, while the estimated load by the spring hinges and the antenna on each line is 1.33N.

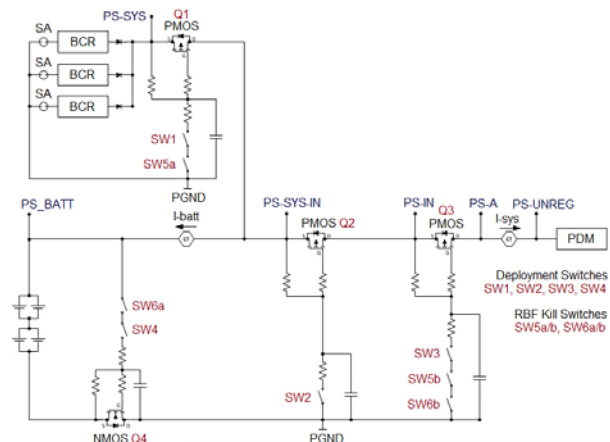
During vibration/shock test of the STM, worst-case scenario was simulated by removing the retaining line closer to the antenna, leaving only one retaining line to hold down the solar panel and the antenna. After all the tests, inspection was done to confirm that the knot is still tight and the deployable solar panels are still within the allowed envelop.



**Figure 6: Deployable Solar Panel Hold-down and Release Mechanism**

### Power Inhibition

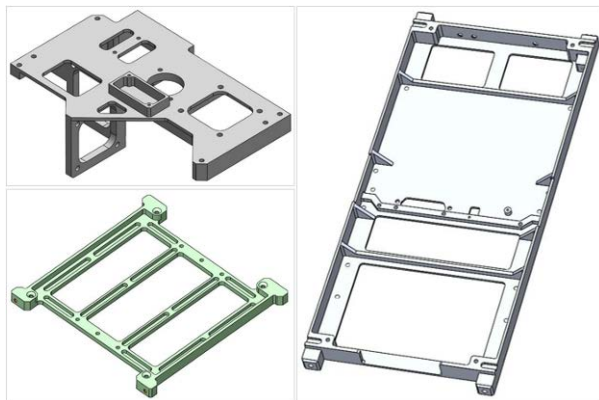
AOBA VELOX-IV must be power off during launch, and there are three inhibits required to ensure that. The EPS inherited from VELOX program was revised to implement that three-inhibition. Instead of its original 2 deployment switches in parallel and 1 remove-before-flight (RBF) kill switch, the EPS has 4 deployment switches and 2 RBF kill switches. As shown in Figure 7, three deployment switches SW2, SW3, and SW4 acts ‘in series’ to insulate the battery pack from the satellite bus. If any of them are pressed, the satellite will be turned off. Another deployment switch SW1 disconnects the solar array from the satellite bus when pressed, as a precaution in case the satellite is accidentally powered on by sunlight while it is inside the launch adapter. The RBF kill switches aim to keep the satellite off during handling, when deployment switches may not be pressed.



**Figure 7: EPS with Three Inhibits Implementation**

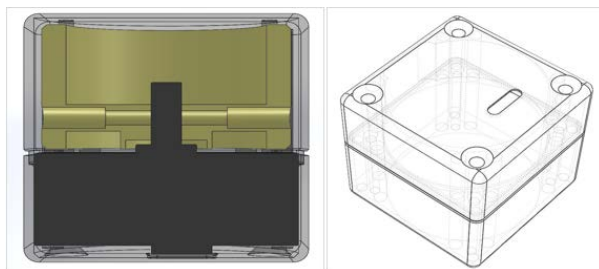
**Mass Reduction**

One challenge in designing AOBA VELOX-IV is the mass constraint of 2660 grams. The battery pack and solar panels are sized according to the mission’s power requirement, and the PPT is heavy with its ceramic capacitor band and 3mm-thick PCBs. Furthermore, the bus’s subsystems are inherited from the VELOX program. So mass reduction is limited to structural parts, as shown in Figure 8 and Figure 9. Mass reduction was achieved by removing areas that are not essential to structure strength: saving 10.1 grams out of 46 grams in the top fixture and 4 grams out of 27.5 grams the BATT frame, and by adding reinforcing features for thinner skin as in the chassis plate.



**Figure 8: Revision of Top Fixture (top left), BATT Frame (bottom left), and Chassis Plate (right)**

The reaction wheel design was also revised, to bring its mass from 80 grams down to 65 grams. With less conservative clearance, the flywheel dimensions was increased to enable better design with mass reduces from 35.2 grams to 27.2 grams, while moment of inertia slightly increases from 26.36 g.mm<sup>2</sup> to 27.66 g.mm<sup>2</sup>. Cut-outs in Aluminum housing of the reaction wheel save 7 grams of mass further.



**Figure 9: Reaction Wheel with Mass Reduction of Flywheel (left) and Housing (right)**

Structural analysis was performed for the design revision, followed by vibration/shock test of the STM to ensure that the satellite structure still meets launch requirements on static loads and stiffness.

**Table 3: Natural Frequencies of the Satellite from Analysis and Vibration Test**

Axis	Requirement [Hz]	Natural freq. from test [Hz]	Natural freq. from FEA [Hz]
X	> 113	380	317
Y	> 113	310	208
Z	> 113	340	318

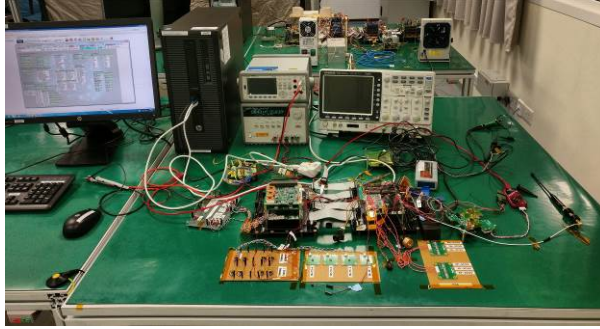
With mass optimization, the AOBA VELOX-IV PFM weighs 2520 grams, of which 330 grams is for battery pack (13%), 460 grams for solar panels (18%), and 520 grams for PPT (20%). The mass constraint is later changed to 3000 grams. However, as mass optimization has been done, we decided to keep the satellite light so that it is better suited for further launch to the Moon.

**DEVELOPMENT**

Development of AOBA VELOX-IV follows the proto-flight model (PFM) approach. A flat satellite was built to interface hardware and test firmware. A structural thermal model (STM) was assembled with subsystems QM/EM and went through qualification tests to confirm the design. And the PFM is assembled with all subsystems FM, and prepared for launched.

**Flat Satellite**

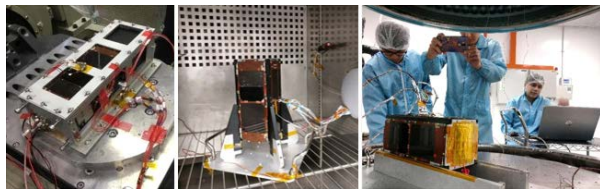
The flat satellite was completed early to ensure that each subsystem, sensor, and actuator interfaces properly with others. The boards are layout on flat on a table, as shown in Figure 10, so that it is easy to probe the signals or access their test points. Firmware of the OBC.AOCS and EPS are tested and troubleshot at the flat satellite, instead of on individual board. The flat satellite is accompanied by a mobile ground station to verify the satellite and ground interface. Till the completion of the PFM, the space and ground segments have been operated and scrutinized almost daily for more than 8 months. When the satellite is in operation in orbit, the flat satellite will be used for test-run of experiments and updates before they are carried out on the satellite.



**Figure 10: AOBA VELOX-IV Flat Satellite**

### *Structural Thermal Model*

The STM was built mainly to validate the structure and thermal design of the satellite. After structural and thermal analysis, we assemble the STM with the chassis, subsystems QM/EM, and some dummy parts. The STM also helps design iterating of newly developed subsystems, i.e. the solar panels and battery pack. The solar panels are EM with the substrates, deployment mechanisms, and only 1-2 real solar cells. It is critical to confirm the panels' integrity and deployment after vibration/shock test, as well as the solar cells installation process with T-VAC and thermal cycling tests. During vibration/shock tests, accelerometers were mounted on the battery pack to record the levels, which will be used for screening the battery packs for PFM. Qualification of the STM is shown in Figure 11.



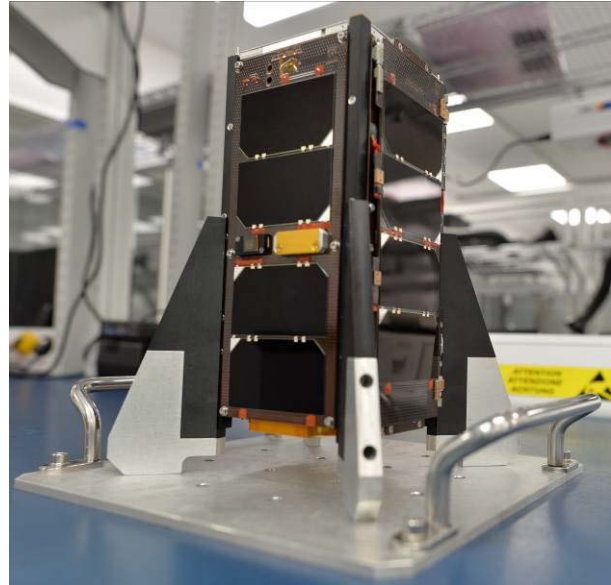
**Figure 11: STM Qualification: Vibration/Shock (left), Thermal Cycling (center), and T-VAC Tests (right)**

### *Proto-Flight Model*

With the design finalized and confirmed with the Flat Satellite and STM, AOBA VELOX-IV PFM was assembled in April 2018 (Figure 12). The PFM then undergoes acceptance tests, including T-VAC, deployment, and end-to-end test in NTU in May 2018, vibration/shock tests and fit check in Kyutech in June 2018. After acceptance tests, the PFM will be kept in Kyutech and will be shipped to the launch site near the launch.

The flight software, esp. AOCS algorithm, is still being validated with the flat satellite and STM. If there is any

critical update, new firmware can be flashed to the OBC.AOCS via its access port. The ground station, satellite tracking, and mission control software – inherited from VELOX-II mission [4] – have also been verified with the flat satellite for several months, and are ready to support the AOBA VELOX-IV mission.



**Figure 12: AOBA VELOX-IV Proto-Flight Model**

### REFERENCE

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2. J.R.C. Alarcon, N.C. Orger, S. Kim, Q.V. Tran, W.S. Lim, T.D.V. Bui, M. Cho, “Moon Mission Lifetime Analysis of a 2U CubeSat Equipped with Pulsed Plasma Thrusters; The AOBA VELOX-IV Mission Case,” 31<sup>st</sup> International Symposium on Space Technology and Science, Jun 2017, Japan.
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