A SmallSat Technology Demonstrator for Space-Based Solar Power

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Abstract

Tanabata, a Technology Development mission for Space Solar Power which uses CubeSat architecture is proposed. This mission uses two identical satellites – *Orihime* and *Hikoboshi* – in Low Earth Orbit to conduct satellite-to-satellite X-Band microwave Wireless Power Transmission experiments. An S-Band pilot signal is also used to demonstrate retrodirective beam control. Power will be transmitted at varying distances, with a maximum transmitter output of 1.0kW. Experiments will be conducted to measure power transmission efficiency in orbit, and to test various Space Solar Power enabling technologies. During these experiments, sensors will be used to measure the effect of high-power microwave transmissions on the ionosphere. *Tanabata* is considered the "first step" in a long-term plan to develop commercial Space Solar Power infrastructure.

Introduction

Space Solar Power (SSP) has been proposed as a renewable energy source with the potential to provide reliable "baseload" power. Using a large space station in geostationary orbit, solar power can be collected in space (where there is no cloudy weather or day/night cycle) and transmitted to earth. Japan is at the forefront of SSP research globally, and JAXA is working with multiple stakeholders to realize this technology in the future[1][2].

Several issues associated with the realization of SSP have been identified, such as the high cost of space transportation (leading to high construction costs) and the low technological readiness level of Wireless Power Transmission (WPT) systems[2]. Recent advances in space transportation technology, such as Reusable Launch Vehicles, could lower costs in response to the former issue. This project aims to address the latter issue (WPT technology), by providing a low-cost platform for the development and testing of WPT technology in space.

1. Mission Aims and Purposes

1.1 Aims

The primary aim of this mission is to provide a platform for research, development and testing of SSP technologies in a space environment. Specifically, the mission will test microwave WPT between two satellites in Low Earth Orbit (LEO), using low-cost CubeSat hardware. The technology developed for this mission, and the resulting data it collects, will play an important role in the future development of SSP infrastructure.

1.2 Technical and Social Significance

Japan Space Systems[1] has proposed a 4-step roadmap for commercial SSP development. The first phase in this roadmap is a LEO technology demonstration satellite, for testing SSP systems and technology. This satellite would have a WPT capacity of 100kW.

However, it may be possible to accelerate this development with a smaller technology demonstration mission making use of recent advances in small-scale, low-cost CubeSat architecture. To this end, the *Tanabata* mission is proposed in this paper, as shown in Fig. 1. *Tanabata* will use two identical 27U CubeSats (*Orihime* and *Hikoboshi*) to perform satellite-to-satellite microwave WPT experiments in LEO, with a WPT transmission capacity of approximately 1.0kW. A small-scale mission using standardized CubeSat technology can be achieved with a lower level of funding. It could also lead to larger pilot projects and SSP infrastructure in the future.

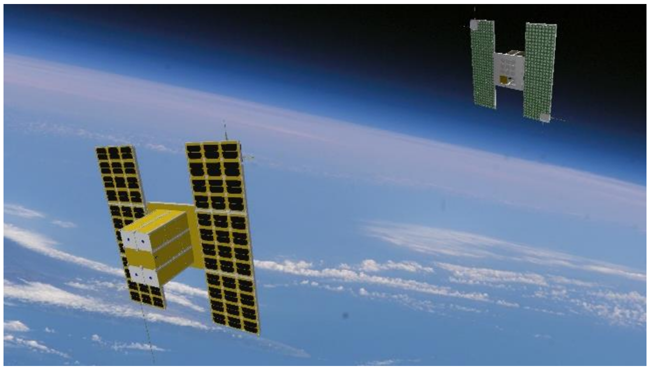

Fig. 1. Artist Concept of *Tanabata* Mission

This mission will measure the efficiency of microwave WPT at various ranges, demonstrate retrodirective beam steering using a pilot signal, and collect data on the effects of high-power microwave transmissions on the ionosphere. Such information will be critical in the future development of larger-scale SSP systems. *Tanabata* would replace the initial phase of the roadmap, making it the first step towards the development of commercial SSP infrastructure. This could deliver environmental and social benefits to Japan and other nations. Refer to Section 4 for more information.

2. Achievement Methods

2.1 Mission Architecture

As described in the previous section, the *Tanabata* mission consists of two 27U CubeSats flying in close formation in LEO. These satellites perform WPT tests, transmitting power to and from each other using microwave frequencies. Data is also collected to measure WPT efficiency. Each satellite also uses its sensors to measure the ionospheric effects of microwave WPT. This section describes the *Tanabata* mission architecture.

2.1.1 Orbit

Several factors were considered in selecting the orbital parameters for Tanabata. First, to reduce launch costs, the orbital altitude should be much lower than Geostationary Orbit (GEO), which has been proposed for full-scale commercial SSP stations. In addition to lower orbital altitude, launching as secondary payload on a larger satellite launch can also save cost, so the satellites should be able to access the chosen orbit flying as a secondary payload. Finally, the orbit should be selected to lower the risk of collision with space debris.

An orbit following the International Space Station (ISS) is an ideal choice for the *Tanabata* mission. This is a low-eccentricity LEO with an altitude of 300 ~ 460km, inclination of 51.6˚ with respect to the equator, and an orbital period of roughly 90 minutes. Due to atmospheric drag, periodic re-boost with thrusters is required to counteract orbital decay and maintain orbital altitude. In comparison to GEO, which has an altitude of approximately 36,000 km, this orbit is roughly 90 times closer to the Earth. This saves significant delta-V, and therefore launch cost. There are frequent resupply missions to the ISS, so there is access to the ISS orbit as a secondary payload on these launches. Sharing an orbit with the ISS also allows the satellite to "borrow" the ISS's debris avoidance system. The US Space Surveillance Network (SSN) tracks objects which pass through an imaginary box around the ISS and warns the ISS to conduct avoidance maneuvers when necessary[3]. By following the ISS and maneuvering along with it, the satellites can also avoid collision with space debris.

To conduct WPT experiments at variable distances, the satellites need to be able to reposition themselves. The repositioning maneuver will be performed in two steps. First, one satellite will use its thrusters to raise its apogee by a small amount, moving into a temporary elliptical orbit. This maneuver will increase the orbital period of the satellite, causing it to fall behind the other satellite. Then, when the satellite completes one orbit and returns to the perigee, it will fire its thrusters again to circularize its orbit. After the maneuver, the two satellites will be in the same orbit, but separated by the desired distance.

Assuming the largest position change will be 150m (a conservative estimate), and a 400 km circular orbit, the delta-V required for a single repositioning maneuver is calculated as 1.803×10^{-2} m/s. Assuming the satellites perform such a maneuver once a day, the total delta-V requirement for repositioning maneuvers is about 6.58 m/s per year.

2.1.2 Ground Station

As described in Section 2.2.5, the *Tanabata* mission uses UHF/VHF communication system for Telemetry, Tracking and Command (TT&C) between satellite and ground stations. This is a typical architecture for a CubeSat, and many CubeSat developers have established ground stations for their own missions. Sharing these resources in a global "ground station network" has also been proposed and tested[4]. *Tanabata* has no unique ground station requirements, thus it should be capable of connecting to existing CubeSat ground stations, without the need for a dedicated ground station of its own. Access to a network of ground stations around the world would also provide more windows for TT&C. However, if this sharing of resources is not an option, a Commercial Off-The-Shelf (COTS) ground station with UHF/VHF capabilities can be procured for approximately ¥6.6 million[7].

2.1.2 Operating Procedures and Data Acquisition

The operations of the Tanabata mission can be categorized into five distinct phases: Deployment (Phase A), Charge/Standby (Phase B), Experiment (Phase C), TT&C (Phase D), Orbit Maintenance (Phase E) and Post-Mission Disposal (PMD, Phase F).

Following launch, Phase (A) (Deployment) begins. During this phase, the satellites are disconnected from the launch vehicle power systems and released through a standardized dispenser. Then, the side panels (which house the WPT arrays and solar panels), UHF/VHF antennas, and the Langmuir Probe are deployed, as shown in Fig. 2. Finally, the Attitude Determination and Control System (ADCS) is used to stabilize satellite rotation, and subsystem functional checks are performed.

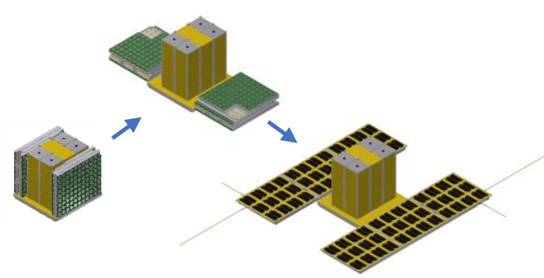

Fig. 2. Satellite Deployment

The satellites spend most of the mission in Phase (B) (Charge/Standby). WPT testing requires high levels of electrical power to be released in a short time. The satellites must spend a significant amount of time charging their battery banks using solar power. The stored energy can then be used for WPT tests. To maximize charging efficiency, prior to Phase (B) the satellites are rotated such that the solar panels constantly face directly toward the sun.

When the batteries are fully charged, Phase (C) (Experiment) commences. First, the distance between the satellites is adjusted as described in Section 2.1.1. Then, the ADCS is used to rotate the two satellite such that their WPT arrays are facing each other, as shown in Fig. 2. The receiving satellite then begins transmitting a pilot signal using its S-Band array, which is used to steer the WPT beam on the transmitting satellite. The transmitting satellite begins "warming up" – increasing the WPT array power from zero to ~1 kW in a period of 2 minutes.

The WPT test is then conducted for 10 seconds. Transmitter input voltage & current, receiver output voltage & current and array temperature data is collected to measure efficiency. Transmission distance is measured with the laser rangefinder. To measure effects on the ionosphere, a Langmuir Probe is used to measure electron temperature & density, while a Retarding Potential Analyzer (RPA) is used to measure ion temperature and composition. Following the completion of the test, WPT power is steadily reduced back to zero over a period of 2 minutes, and data is saved in the Command and Data Handling (C&DH) system memory.

When the satellite next passes in range of a ground station, Phase (D) begins (TT&C). The TT&C system is used to transmit experimental data to the ground and receive new commands for future experiments. In order to prevent orbital decay, the satellite must also spend time performing orbit-raising maneuvers. This is Phase (E) (Orbit Maintenance). The satellites use electric thrusters due to their high specific impulse. However due to the low thrust output, the duration of orbit-raising maneuvers will be longer than that of a chemical propulsion system. The electric thrusters also consume a significant amount of electrical power. However, as the satellites are designed with high-capacity electrical power systems, this is not considered an issue. Phases (B) ~ (E) will repeat over the duration of the mission. At the end of mission life, remaining electrical power and propellant will be used to de-orbit both satellites so they don't become hazardous orbital debris in the future (Phase (F) – PMD).

2.2 Satellite System Architecture

The key design philosophy of the Tanabata mission is reducing cost. As described in Section 1.2, making a low-cost technology demonstration mission may be a key "starting point" which larger-scale pilot projects will follow in the future. The use of COTS hardware and standardized CubeSat technology is crucial to this aim. COTS CubeSat components provide reliability through flight heritage and are cost-effective in comparison to custom-designed systems. While some of the satellites' subsystems are unique and require custom designs, many subsystems can be built from COTS hardware. Making the satellites identical is also a key factor. In comparison to the alternative (i.e. dedicated "transmitter" and "receiver" satellites), this simplifies the design process, increases opportunities for WPT experiments (by recycling received power for another test), and adds redundancy.

2.2.1 Payload

The payload consists of separate WPT transmitter and receiver arrays (with embedded voltage, current and temperature sensors), a Langmuir probe, RPA and a laser rangefinder. The payload is shown in Fig. 3. Separate WPT arrays are mounted on the deployable side panels. The other payload components are mounted on the base of the core structure.

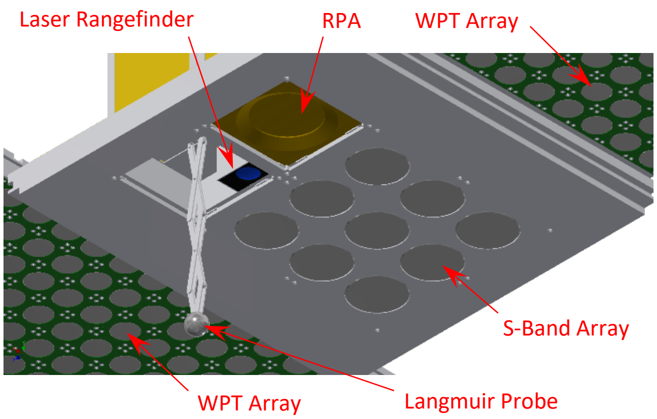

Fig. 3. Payload

The WPT transmitter and receiver arrays are identical in size, and made up of 270 compact active integrated antenna elements arranged in a 992 mm × 288 mm configuration. Maximum transmitted power is 1.08 kW, and the DC-microwave conversion efficiency is assumed to be 40%. The receiver array is a similar design of 270 compact antenna elements arranged in a 992 mm × 288 mm configuration. Both arrays are fitted with temperature sensors, voltmeters and ammeters for measuring WPT efficiency and energy conversion. The WPT arrays will test X-Band (8.5 GHz) microwave power transmission. Unlike other subsystems, the WPT arrays are not standard components. No COTS solution is available, so the arrays will be custom-designed.

An environmental concern associated with SSP is the effect of high-power wireless transmissions on the upper atmosphere. The Langmuir probe and RPA are used to collect ionospheric data, to measure any impacts which high-power microwaves could have on the ionosphere. Finally, the laser rangefinder is used to accurately measure the separation distance between the satellites during WPT tests. Transmission range is an important factor in determining WPT efficiency, so this data is required to compare experimental data to theory. The Jenoptik DLEM 20 laser rangefinder[5] was selected for this application.

2.2.2 Structure

The satellites are designed to comply with the 27U CubeSat standard, which is currently under development[6]. The stowed satellite must fit in a space smaller than 366 mm × 353mm × 339mm, weigh less than 54 kg, and include tabs along the base to interface with the launch vehicle release mechanism. While this is larger than most CubeSats, the increased size and weight allows the satellites to carry the large deployable array panels and heavy battery banks required for an orbital WPT test.

While the structure is compliant with the 27U standard, the payload requirements necessitated a non-traditional approach to a CubeSat structure. The satellite structure consists of a central base plate for the launch vehicle interface. The base plate houses the payload sensors and the S-Band antenna array. Two three-section deployable panels are mounted along the edges of the base plate. The deployable panels house the WPT transmitters as well as the primary and backup UHF/VHF antennas. Solar panels are mounted on the reverse side of the deployable panels. All other subsystems (battery banks, thrusters, transceivers, ADCS, C&DH, etc.) are mounted in an 18U CubeSat standard core structure (show in Fig. 4), which attaches to the base plate. The structure is manufactured from machined 6061 Aluminum alloy, which was selected due to its flight heritage and good machinability. The structure weighs ~23 kg, and total satellite mass is 48 kg.

2.2.3 Propulsion Subsystem

A propulsion system is required for orbital maintenance and maneuvering. Assuming an average orbital altitude of 400 km, it has been determined that a delta-V budget of 86.64 m/s per year will be required to overcome air resistance for orbital maintenance. Also, as described in Section 2.1.1, a delta-V budget of 6.58 m/s per year will be required for maneuvering. Thus, the total delta-V which the propulsion system must provide is 93.22 m/s per year.

An electrical propulsion system is considered ideal due to high specific impulse (low propellant mass), and the high capacity electrical power systems of the satellites. A COTS electrical propulsion system has been selected. The IFM Nano-thruster[7] can provide high specific impulse (5,000s), with a fuel capacity of 250g. This thruster generates a nominal thrust of 350μN while consuming 35W of power. In "hot standby" mode it consumes 3.5W.

A cluster of four of these thrusters are mounted at the top of the core structure, as shown in Fig. 4. Using multiple thrusters extends mission life and adds redundancy. Based on a maximum satellite mass of 48kg, this thruster configuration allows for a mission life of more than 4 years. Assuming a total thrust of 1.4 mN, the satellite will need to spend 17.1 hours per week using the thrusters for orbit maintenance. This represents ~10% of mission time. Assuming the thrusters spend the rest of the time in standby mode, average power consumption for the propulsion system would be 26.8 W, with a maximum consumption of 140W, and a minimum of 14.0W.

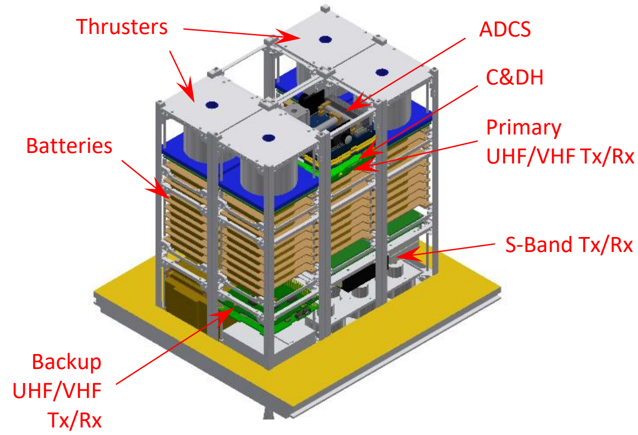

Fig. 4. Core Structure Subsystems (panels not shown)

2.2.4 Attitude Determination and Control Subsystem

The satellites require an Attitude Determination and Control Subsystem (ADCS) to reorient themselves for different mission phases (deployment stabilization, charging, experiments, etc.). Fine attitude control is also required to orient the satellites towards one another for WPT testing. A COTS ADCS solution is available. The CubeSpace CubeADCS[7] provides an integrated ADCS solution with a full suite of attitude sensors (including 3 × MEMS rate gyros, 10 × Sun Sensors, a three-axis magnetometer and a low-power star tracker) and actuators (including 2 × ferrite core torquers, 3 × reaction wheels and an air core coil).

The CubeADCS will be mounted in the top section of the core structure, in between the thrusters, as shown in Fig. 4. The most stringent ADCS requirement on the Tanabata mission is providing pointing accuracy for WPT tests. CubeADCS can provide attitude control accuracy to within 0.1˚. Based on simple trigonometry, this would create a pointing accuracy error of 17cm at a range of 100m, which is anticipated to be the maximum range of a WPT test. However, most tests will be at much closer range, and the S-Band pilot signal will be capable of compensating for this error (refer to section 2.2.5).

2.2.5 Communication Subsystem

The *Tanabata* mission requires 2 separate communication systems: A UHF/VHF system for satellite-ground communications (TT&C), and an S-Band system for satellite-satellite communications (pilot signal for retrodirective beam steering). It has been determined that the UHF/VHF system requires data rate of 2.0 Mbps for downlink, and 19.6 kbps for uplink communication. The data rate for the S-Band system is considered less important as the pilot signal is only required to transmit small amounts of data. The configuration of the communication subsystem is shown in Fig. 5.

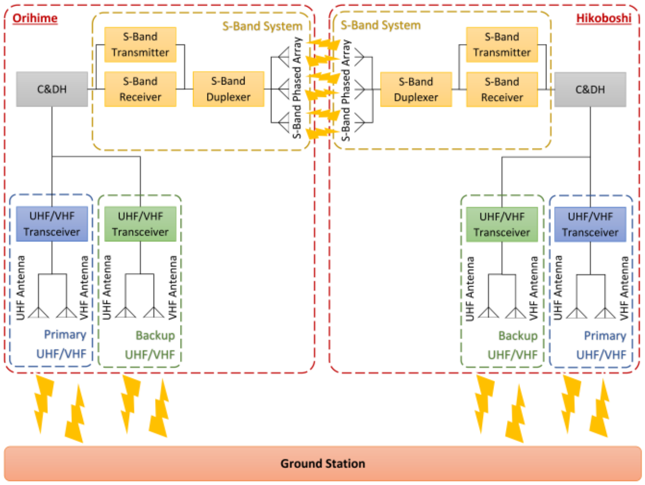

Fig. 5. Communication System

The UHF/VHF system will use UHF (435~438 MHz) for downlink and VHF (145.8~146 MHz) for uplink. As this is a common TT&C configuration for CubeSats, COTS components are used – the ISIS monopole deployable antenna system[7] and VHF uplink/UHF downlink transceiver[7] will be adopted. This system will be fully redundant, with primary and backup transceivers and antennas. S-Band systems for CubeSats are less common, especially those using phased arrays. The S-Band system, which operates at 2.45 GHz, uses a COTS transmitter (ISIS High Data Rate S-Band Transmitter[7]), receiver (SpaceQuest RX-2000 S-Band Receiver[8]) and diplexer (Digital Signal Technology S-Band Diplexer/Coupler[9]). However, the antenna array is a custom design, featuring nine Cobham PSA0218L/1501 antennas[10] mounted on the base plate in a square pattern, spaced at a half-wavelength distance of 61.2mm.

The primary role of the S-Band system is to provide a pilot signal to guide WPT transmissions with greater accuracy than the ADCS alone can achieve. The pilot signal works as follows: the ADCS is used to orient the spacecraft such that they are facing each other. Then, the transmitting satellite sends out a pilot signal using its S-band array. The receiving satellite uses its S-Band array to detect the pilot signal, and to measure the phase difference ($\Delta\phi$) in the signal, which can be used to determine the angle between the receiving array and the source, as shown in Fig. 6. The satellites then switch roles – the receiving satellite uses its S-Band array to transmit $\Delta\phi$ data back to the transmitting satellite. This creates a feedback control loop. The original transmitting satellite can then adjust its S-band array phasing and transmit the pilot signal again. This process continues until the relative attitude between the satellites is well-determined. Prior research[11] indicates that phase difference can be detected with an error of 0.1˚. Based on the pilot signal wavelength and the array spacing, this would translate to a pointing error of 0.03˚ - a three-fold improvement over the ADCS alone.

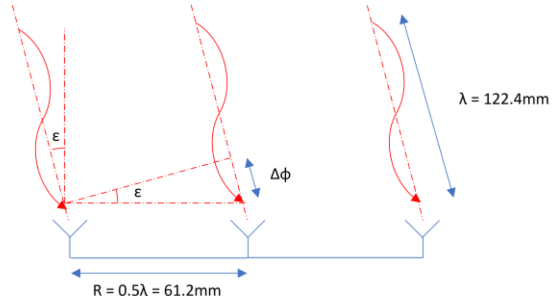

Fig. 6. Pilot Signal Phase Difference

2.2.6 Command and Data Handling Subsystem

For C&DH, interface with all satellite and subsystems is required. Also, as the satellite is only periodically in contact with the ground station, a memory buffer is required to store telemetry and experimental data for later transmission. The ISIS on-board computer[7] satisfies these requirements. This component can be fitted with a daughterboard to customize C&DH interfaces. This can be used to interface the C&DH system to subsystems which are not standard CubeSat components. The ISIS on-board computer can also store up to 4 GB of data. As such, this component has been selected as a C&DH subsystem. The ISIS on-board computer is mounted below the ADCS in the core structure, as shown in Fig. 4.

2.2.7 Electrical Power Subsystem

The electrical power system needs to generate and store power and supply it to all onboard systems. A major difference that sets *Tanabata* apart from other CubeSats is the large power requirement for its WPT payload. In order to operate the WPT payload, the electrical power system has to be capable of both generating and storing a large amount of electrical energy, then very rapidly discharging this energy. Based on a transmitting power of 1.0kW, DC-microwave efficiency of 40%, and a DC-DC voltage conversion efficiency of 80%, the power system needs to supply a maximum of 3.125kW of electrical power during WPT tests. Despite the significantly higher power requirement than usual CubeSats, COTS parts should still be used wherever possible to reduce cost.

72 DHV-CS-10 1U CubeSat solar panels[7] are mounted on the reverse face of the deployable side panels, for electrical power generation. Together, they will produce a maximum power of 173.52W during the charging phase. EXA BA02/S battery[7] banks will be used because of their compact size, light weight, and fast discharge. These batteries have a capacity of 19.9Wh and a maximum discharge rate of 53.28W. Although only six batteries are required to hold enough charge for a single test (0.11kWh), the discharge rate creates a “bottleneck” – 59 batteries will be required to meet the maximum power requirement of 3.125kW. Therefore, 60 battery arrays will be mounted in the core structure, as shown in Fig. 4. Allowing for 50% “eclipse time” (i.e. no solar power) per

orbit, 90% battery charging efficiency and an average power consumption of 28.4W for all non-payload subsystems, the batteries can be fully charged to 1.2kWh in 24 hours (16 orbits), as shown in Fig. 7.

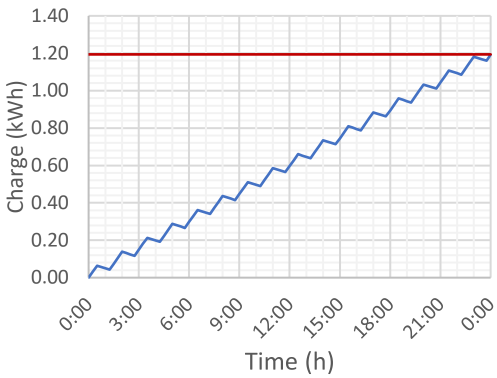

Fig. 7. Charging (Blue) vs. Battery Capacity (Red)

A custom Power Supply System (PSS) will be designed to distribute power. The PSS will have separate busses for low-voltage (3.7V) and high-voltage (12V) subsystems. The WPT arrays will be supplied off a dedicated 14.2V bus. Despite the high power, the PSS uses conventional satellite voltages to reduce the risk of electrical discharge. This results in high-Amperage electrical power, which could lead to wire heating and efficiency issues. Thus, larger wire gauges and parallel circuit wiring will be used to connect the WPT arrays to the bus. The WPT receiver array will also be connected to the PSS charge controller, so power collected during WPT tests can be "recycled".

2.2.8 Thermal Control Subsystem

It is essential to control the heat of the payload, battery and other subsystems. The DC-microwave conversion efficiency of the WPT system is 40%. Thus, there is a 60% energy loss, most of which is emitted as heat. On the other hand, the batteries require heating for efficiency and rapid discharge during WPT tests. An ideal method for thermal control is to use the batteries as a heat sink, and transfer "waste" heat from the WPT arrays and other systems to battery. Heat pipes will be used as a passive system which can transfer heat without requiring electrical power.

The WPT arrays are mounted on panels which unfold as the satellite is deployed. In order to prevent rupture of solid heat pipes during deployment, flexible heat pipes will be used. These experimental heat pipes are constructed from flexible polyurethane tube and a mesh made of strong-base-oxidized super hydrophilic copper[12]. Standard multi-layer insulation will cover the core to protect sensitive subsystems from solar radiation.

2.3 Development Tasks and Issues

COTS components are employed extensively in the design of the satellites to reduce cost and complexity. Although typical COTS components may not meet the strict reliability requirements of a space mission, the components used in this design are primarily CubeSat-standard, with flight heritage on at least one previous mission. This flight heritage, combined with strict acceptance and integration testing, will mitigate reliability risks. There are also components whose requirements cannot be met by COTS parts and require custom design and development. Non-COTS systems include the power supply system, the S-band communication system, 27U CubeSat structure, thermal control system and the payload.

Due to the high power consumption of the payload, COTS power supply systems for CubeSats cannot be used for power distribution. A custom high-capacity system is required. In a similar fashion, while the S-band phased array antenna is not commercially available, the technology has been demonstrated on the ground by JAXA[2], and individual components are COTS. No 27U CubeSat has flown yet, so no COTS structure or deployer are available. However, the proposed standard is available[6], so the parts can be easily manufactured. Regarding the thermal control system, flexible heat pipes have been developed recently[12], but they have not been used outside the laboratory environment.

Regarding the payload, Langmuir probes for CubeSats are not commercially available, but they have been developed and used on the DICE CubeSat recently[13]. By collaborating with the DICE team to reuse this design, the risk and cost of developing a new part can be avoided. Similarly, a COTS RPA is not available, but design and testing are underway[14]. Once again, collaboration can reduce development risk and cost.

Development of the WPT antenna array is the main challenge for this project, because transmitters and receivers need to be both compact and powerful. JAXA has developed and tested prototype WPT arrays on the ground[2], but developing a reliable, space-worthy WPT array which meets mission requirements is still a challenge. This challenge, however, is a necessary step toward commercial SSP, as in-space WPT arrays are also an important technology for future SSP infrastructure.

3. Anticipated Results

As a technology demonstration mission, a key focus of *Tanabata* is the development of prototype technology, and the testing of this technology in the harsh environment of space (hard vacuum, radiation, microgravity, extreme temperatures, etc.), which cannot be easily replicated on Earth. The performance of the technology will be evaluated and issues will be identified. This data will inform design improvements for future missions. The most important outcome of the technology demonstration is the measurement of WPT efficiency. Fig. 8 shows the anticipated efficiency of the *Tanabata* WPT system based on theoretical calculations[15]. It can be seen that efficiency remains high, but starts to decline within the Rayleigh Zone (up to 11.5 m), then remains low in the Fresnel zone and into the far field. While Tanabata only demonstrates short-range satellite-satellite WPT, dimensional analysis of the results data could be used to estimate the efficiency of large scale long-range WPT for a future SSP system.

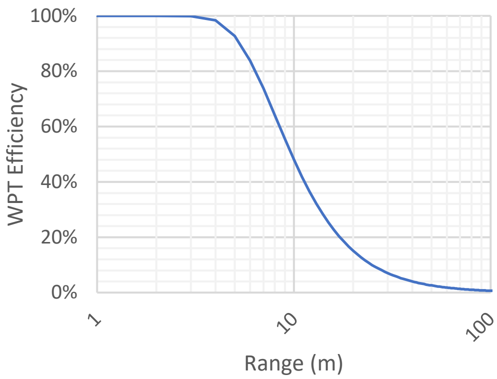

Fig. 8. WPT Range vs. Predicted Efficiency

The satellites will also measure changes in the ionosphere during WPT tests. Specifically, the Langmuir probe measures electron temperature and density, while the RPA measures ion temperature and composition. Previous research[16] indicates that high-power microwave WPT (100~500W/m^2) could increase electron temperature by 200~1000K, increase electron density by 10~40%, Ion temperature increases are less severe, but still possible. Composition changes, such as ozone production, are also possible. Using the above-mentioned instruments during WPT tests, *Tanabata* will measure such effects.

4. Originality and Social Effects

Fossil fuels are unlikely to be able to meet future energy demand. They also create serious social and environmental impacts. In recent years, there has been a significant growth of renewable energy sources, such as wind and solar power. These sources, however, are unlikely to completely replace fossil fuels, especially for baseload power, due to their intermittency and land use. By generating solar power in space and transmitting the power to the Earth, SSP avoids the problems that prevent other renewables from becoming a reliable alternative to fossil fuels. It is not affected by weather conditions or the day-night cycle, and it does not require large land areas.

A successful in-space demonstration of SSP and WPT will pave the way for full-scale commercial SSP stations in GEO in the future. These stations will be able to provide stable and clean power. For countries which lack domestic energy reserves (like Japan), it will also enhance energy security by removing the dependence on imported energy. While SSP Technology Demonstration missions have been proposed in the past, no mission has launched so far. The unique point of *Tanabata* is using a small-scale, low-cost architecture to accelerate development and realize a technology demonstration mission.

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