

On-Orbit Measurement of Next Generation Space Solar Cell Technology on the International Space Station

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I. Abstract

Measurement is essential for the evaluation of new photovoltaic (PV) technology for space solar cells. NASA Glenn Research Center (GRC) is in the process of measuring several solar cells in a supplemental experiment on NASA Goddard Space Flight Center's (GSFC) Robotic Refueling Mission's (RRM) Task Board 4 (TB4). Four industry and government partners have provided advanced PV devices for measurement and orbital environment testing. The experiment will be on-orbit for approximately 18 months. It is completely self-contained and will provide its own power and internal data storage. Several new cell technologies including four-junction (4J) Inverted Metamorphic Multijunction (IMM) cells will be evaluated and the results compared to ground-based measurements.

II. Background

NASA and other aerospace entities use a variety of methods to measure the performance of space solar cells. The main method of measuring air mass zero (AM0) performance is the laboratory solar simulator. Once calibrated with reference standards, the solar simulator can measure large numbers of cells in order to predict on orbit cell performance. Obtaining directly measured AM0 primary reference standards is an on-going challenge for the space PV community. One successful means for accomplishing this has been the Materials International Space Station Experiment (MISSE)1-2. MISSE is an ongoing multi-agency effort to utilize the ISS for materials exposure (including solar cells) to the space environment. All MISSE missions are retrieved and returned to earth for laboratory analysis.

In 2012 center leadership at GSFC and GRC began a dialogue to identify a suitable collaboration objective that would grant additional access to space via the RRM project. RRM is a multi-mission program to demonstrate tools and techniques for robotic satellite servicing. RRM utilizes the Special Purpose Dexterous Manipulator (SPDM). SPDM, also known as Dextre, was a Canadian Space Agency (CSA) contribution to the International Space Station (ISS). The highly versatile SPDM is operated at the end of CSA's Canadarm 2 (SSRMS). Now in its second phase, RRM is managed by GSFC's Satellite Servicing Capabilities Office (SSCO).

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The initial concept for the RRM Solar Cell Experiment (SCE) was for GRC to identify an advanced technology solar cell to provide power for the TB4 Continuity Indicator (COIN). The cell would provide power for continuity checks during RRM activities. Cell performance would be monitored during use. A problem with this approach is that an unproven cell type would add risk to the RRM experiment. Additionally, performance data must be from a known light source, free of reflected light. Even in a known occurrence of full solar illumination, reflection from nearby surfaces will cause unacceptable error. Orbital environmental exposure testing is of value for PV developers; however this test alone for a small number of cells would not justify recovery of the samples and subsequent return to earth.

The experiment that evolved includes both measurement and exposure testing. The best opportunity for measurement is when the task board is located on the robotic arm. This allows for direct pointing of the cells at the sun while avoiding unwanted reflected light. Cells and materials could also be included for full orbital environment exposure. The location of TB4 is shown in figure 4.

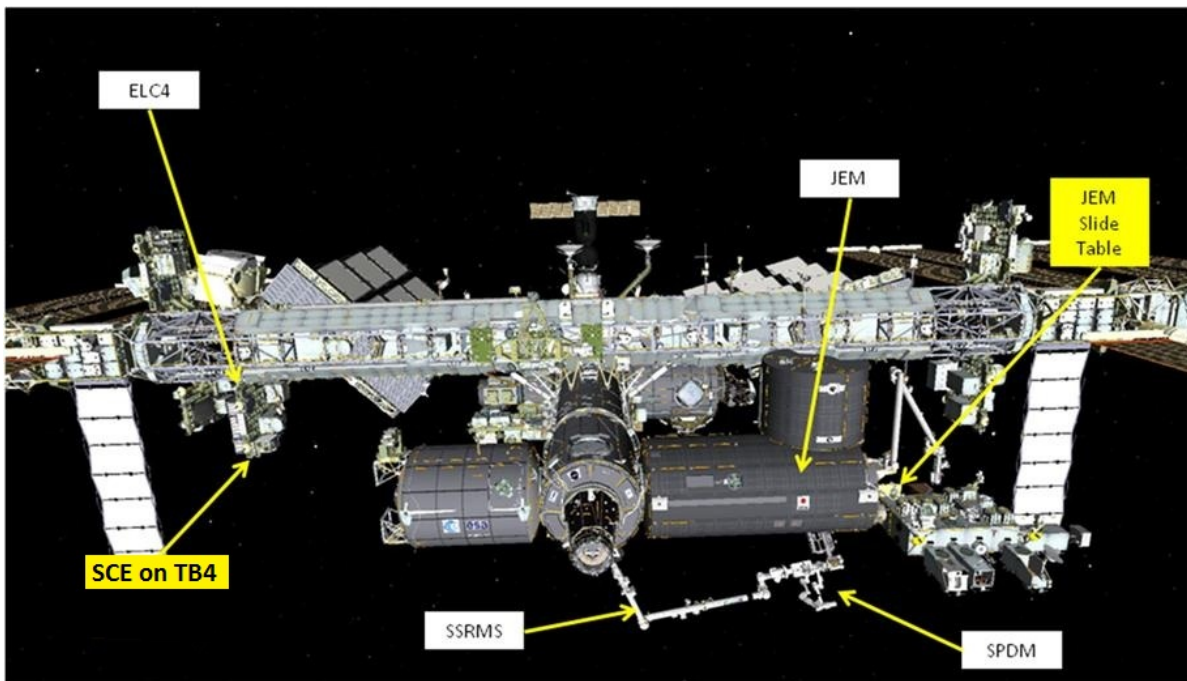


Figure 4. The location of SCE is indicated in the lower left (GSFC).

Crucially, the Mobile and Remote Sensing Laboratory (MARS Lab) team at GRC was identified as an enabling project asset in the fall of 2013. Team members had participated in previous space PV measurement experiments (including MISSE 5, 7 and 8). GRC management’s approval of the project was granted in mid-November with a scheduled delivery of hardware to GSFC February 3, 2014. Beyond that GSFC would undertake preflight qualification tests with GRC participation. Integration with flight hardware and shipment to Johnson Space Center (JSC) would immediately follow.

The opportunity for this experiment comes at an opportune time. The space PV community is in the midst of developing a new generation of space PV. Manufacturers are responding to an industry need for solar arrays of unprecedented size to power Solar Electric Propulsion spacecraft³. The IMM cell will have technology enabling lower mass and stowage volume. The IMM cell4-5 is grown “upside –down” on a substrate. After growth is complete the active cell layers are removed from the substrate for final processing. The result is a lightweight, highly efficient advanced solar cell. The efficiency is enhanced in some cases by the use of additional junctions beyond three, which is the current standard. Although MISSE has been vital in this process, technology has continued to progress since the MISSE 8 May 2011 launch. SCE will help with the ongoing need to verify cells.

III. Experiment Description

The SCE consists of two parts located on opposite sides of TB4. The top side passive area is exposed to the LEO environment for the duration of the flight. These cells are exposed to widely varying solar illumination. The passive experiment samples are not instrumented for measurement during flight. The back side active measurement portion of the experiment is generally shielded from the sun but is designed to power up and record data when illumination is sufficient as directed by SPDM. All solar cells provided by partners were inspected and measured prior to flight. AM0 measurements were made on GRC's three source solar simulator and Large Area Pulsed Solar Simulator. Inspection and measurement will be repeated post-flight. Flight spare plates will also be measured as control specimens.

TB4 was reconfigured in order to make space available for a solar cell experiment. The principal function of TB4 is to serve as a test bed for the Visual Inspection Poseable Invertebrate Robot (VIPIR). VIPIR is an SSCO-built borescope that will allow for internal visual inspection during robotic satellite repair missions. An elevated platform was added over the test bed for VIPIR. This provided an area where the SCE passive experiment samples could be optimally located. The elevated platform also encloses the box that contains the SCE measurement electronics. The cells for active cell measurement are located on the back side of TB4.

GSFC provided three sizes of plates for solar cell samples to be mounted on. The plates are made of 0.2" thick aluminum. Areas on the back of the plates were thinned to reduce the mass of each plate. Each plate has a notch in the middle of one side to allow for wires to pass behind the plates. Each plate was covered with Kapton tape and a SiO₂ coating was applied. The plates were shipped to the various cell providers for cell mounting and electrical connections. Cells were bonded directly to the SiO₂ coated Kapton with CV10-2568 silicone adhesive. Interconnects were soldered to twisted pair wires of 26 gauge wire. One twisted pair was connected to each electrical lead as is required in order to make a four-wire measurement. A conformal coating was used on soldered electrical connections and when the SiO₂ coating was compromised. Wires were staked to the Kapton to direct wires to feed through slots.

The active measurement experiment consists of 5 plates. The large plate contains a string of four Emcore ZTJ cells. These cells are the sole source of power for SCE. The nominal power requirement of both boards during operation is 2.3 W. The power source can produce 4.7 W at 30°C which allows a margin for voltage reduction at high temperature. Two medium sized plates are populated by Emcore Corporation*1 with next generation IMM 4J solar cells. The Emcore test cells are nominally 33% efficient in an AM0 spectrum. One plate contains a string of 3 cells while the other plate has 3 separately measured cells. Spectrolab, Inc.*2 will fly two GaInP component sub-cells. One will be from a current generation XTJ triple junction cell, the other from a next generation 4J IMM cell. MicroLink Inc.*3 has an active measurement plate with 2 next generation 3J IMM cells. MicroLink cells are manufactured using an Epitaxial Lift-Off process which is an innovation particularly well suited to the IMM structure. Figure 1 shows the cells for active measurement on the back of TB4.

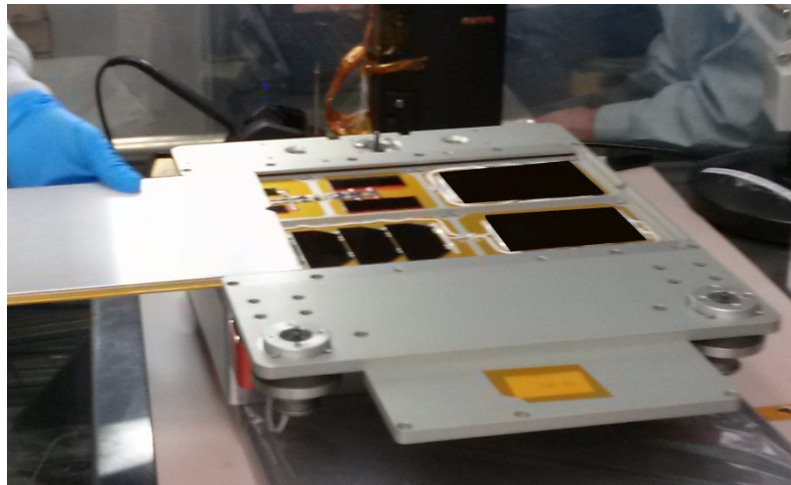


Figure 1. Sample cells located on the back of TB4.
The protective cover is being removed. Detail has been obscured (GRC).

The passive experiment consists of 2 plates. A large plate is populated with four MicroLink 3J IMM cells that are configured in an open circuit with the cathode of each tied to ground. A small plate has 2 novel devices provided by Sandia National Laboratories*4. Each flexible module contains several parallel strings of tiny hexagonal silicon solar cells. Microsystems-Enabled Photovoltaics are highly configurable for different power requirements and shapes. One device contains 750 individual cells and the other contains 500 cells. The Sandia devices each have a 3k Ω , 50 mW resistor across the power leads as a load. Their cathodes are tied to ground. Sandia has also allowed the Air Force Research Laboratory*5 to add 3 adhesive test samples to the Sandia plate. These samples will be tested for changes in the optical absorption of the adhesive due to the LEO environment. The flight hardware for the passive portion of SCE is shown in figure 2.

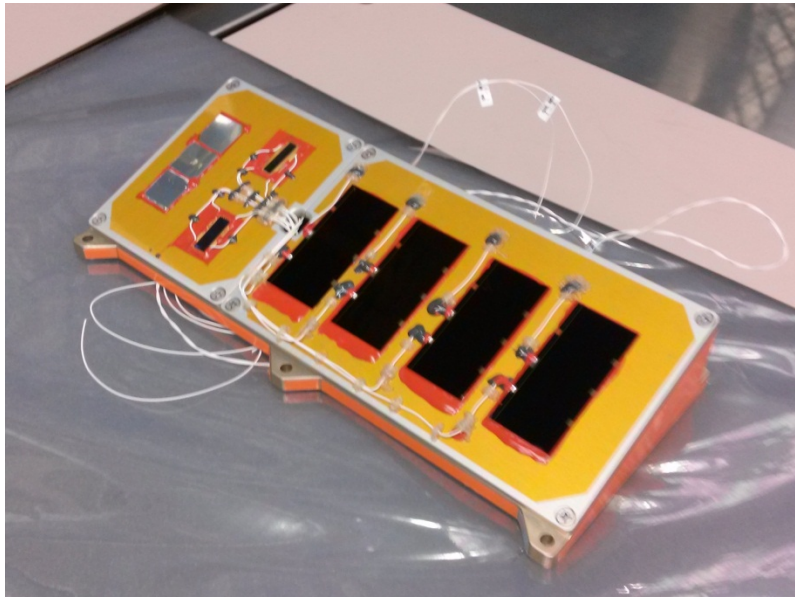


Figure 2. Passive experiment samples on a flight sub assembly.

The measurement electronics were designed and fabricated by the MARS lab at GRC. They consist of 2 printed wiring assemblies (PWA) which can each measure four solar cell circuits and their corresponding temperature sensor. The boards are based on Silicon Labs C8051F121 Microcontrollers. Each board stores data on a Samsung KM29W32000AIT 4M 8 bit NAND Flash memory. The processor becomes active when sufficient power is being generated by the 4 cell power string. Power must be maintained for 1 minute before data is collected. The one minute delay is to minimize false starts and unproductive use of flash memory. Each board will then sequentially scan through its four channels. Current and voltage will be recorded at 128 intervals as the load is varied across the cell or string. The current is stepped from zero, at VOC, through ISC in equal increments. The step size is specific to each channel dependent on the ISC of the cell or string. Each IV scan is preceded by and followed by a temperature reading from an AD590LF integrated circuit temperature sensor. The AD590LF has a tolerance of $\pm 1^{\circ}\text{C}$. Each AD590LF sensor is located on the back of the plate near the center of the corresponding cell or string. Scans will continue at 1 minute intervals while solar illumination is sufficient. The boards will safely power down when input voltage is less than 7 V.

Each PWA has the memory capacity to save 2044 sets of 4 channel scans. The one minute interval between data sets allows for a minimum of 34 hours of continuous data collection. This is enough for a worst case scenario of full time operation for two 12 hour deployments on SPDM (for TB4 placement and retrieval). Additionally, two auxiliary 5 hour deployments would be possible. In practice, the SPDM will be able to keep the solar cells off-sun for a significant portion of that time. When the flash memory is at capacity, the instrument will stop taking data. Recorded data will not be over-written.

Pre-flight qualification testing and integration with TB4 occurred at GSFC from February 7 to April 12, 2014. SSCO conducted the required functional, thermal vacuum (TVAC), EMI and vibration testing. TVAC functional test were done from $+82^{\circ} \pm 2^{\circ}$ to $-37^{\circ} \pm 2^{\circ}$. The hot survival temperature was 88°C . The cold survival temperature was -55°C . Two of the authors (Wolford, Myers) participated on-site during this time. It provided a valued insight to the important disciplines of the space flight community. Figure 5 is a photograph of the fully integrated TB4.



Figure 5. Fully integrated TB4 showing SCE passive samples (GSFC).

IV. Mission Description

Task board 4 was launched on the European Space Agency's Automated Transfer Vehicle "Georges Lemaitre" (ATV-5). The launch took place at Europe's Spaceport in French Guiana on July 29, 2014. Protective covers are in positioned over all solar cells during launch. Once transferred from ATV-5, it will be stowed on the ISS until Fall 2014 when it is scheduled to be moved to the Japanese Experiment Module (JEM/Kibo) air-lock and slide table. The covers will be removed just prior to entering the air lock. Once through the air-lock and transferred to the SPDM, the SCE will be ready to take measurements of the active measurement cells.

Using SSRMS and SPDM, TB4 will be positioned with the active experiment normal to the sun for a period of approximately 20 minutes. This will be done in the portion of the orbit that it is most feasible to maintain orientation without introducing reflection from ISS structures or earth. The sun will be positioned on-sun by robotic ground operators guided by an ISS and SPDM camera feeds. Figure 3 is a graphic that envisions robotic sun pointing during the mission.

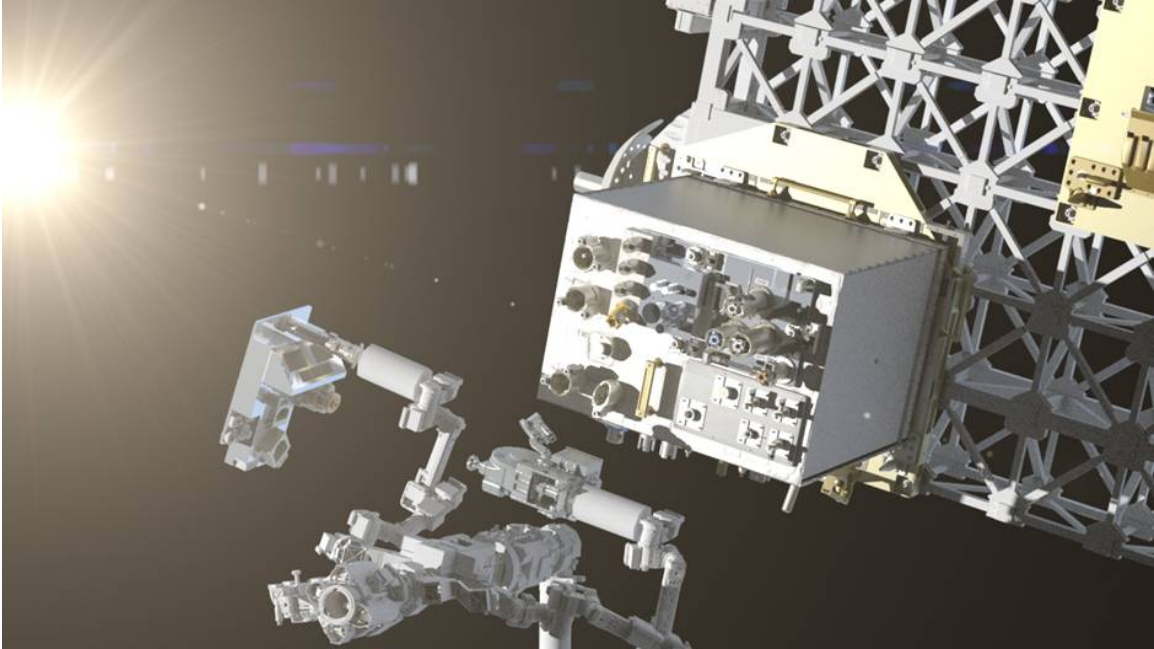


Figure 3. Graphic depicting robotic sun-pointing during the mission (GSFC).

Task board 4 will then be placed on the RRM experiment located on the Express Logistics Carrier 4 (ELC4). The top side of TB4 will be faced in the ram direction of ISS.

If resources are available, an additional set of measurements can be accomplished during the mission by retrieving TB4 and repeating the exposure routine. A last set of measurements will be made when TB4 is retrieved at the end of the 18 month mission. Data and flight samples will returned to GRC for measurement and analysis before being returned to the company of origin.

V. Summary

In collaboration with GSFC, GRC has a solar cell experiment launched to the ISS on July 29, 2014. SCE takes advantage of access to space via SSCO's RRM TB4. Ten advanced AM0 solar cells, from three industry partners, will have their electrical characteristics measured in space. An additional nine samples, from three industry and government partners, will be exposed for eighteen months to the LEO environment. The data from this experiment will provide valuable performance metrics of new technology to manufacturers. NASA will benefit from the opportunity to verify its laboratory measurement accuracy and observe PV technological progress. This type of effort is important for continuing the mutually beneficial collaborative relationship NASA has with the space PV community.

VI. Acknowledgements

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VII. References

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