Solar Power for Deep-Space Applications: State of Art and Development

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Solar arrays have been used successfully as the power source for multiple NASA spacecraft, including in deep space as far as the Jupiter orbit at 5.5AU. In this paper, we outline the challenges to solar array performance in deep space environments, and overview the current state of practice. We also highlight recent results from our work on developing solar cells optimized for low irradiance, low temperature (LILT) operating conditions, and the implications on extending the range of solar power out to the Saturn orbit at 9.5AU.

I. Introduction

Solar power is a low-cost, readily available and highly reliable resource for spacecraft, which is why the majority of NASA and ESA planetary-science missions to date have chosen to employ solar arrays over other power sources [1]. Even for missions to deep space, where the solar resource is considerably lower than in Earth orbit, solar power has been used successfully and extensively in recent years. Examples of solar-powered missions to deep space that have either flown or are in advanced stages of development include Stardust (launched 1999, traveled to a maximum sun distance of 2.7AU), Rosetta (2004, 5.3AU), Dawn (2007, 3.0AU), Juno (2011, 5.4AU), Lucy (planned 2021, 5.2AU), Psyche (planned 2022, 3.0AU), JUICE (planned 2022, 5.2AU) and Europa Clipper (planned 2023, 5.5AU).

A downside of solar arrays however is that the power they produce does depend strongly on their operating environment, and most significantly on the available light intensity. Specifically, the power output of a solar array is proportional to the irradiance incident upon it, with the proportionality constant being set to first order by the solar cell device efficiency. For deep-space applications, as the irradiance decreases quadratically with the sun distance, the solar array surface area must increase, also quadratically to first approximation, so as to compensate for the diminished solar resource. This explains why solar arrays have yet to be used at sun distances beyond 5.5AU.

Unlike other spacecraft electronics, solar arrays are typically not actively thermally controlled, so that their temperature is set by balancing the heat input from the sun against the electrical output to the spacecraft plus radiative cooling into free space. From the point of view of solar array operation, the deep-space environment is therefore one of low irradiance and low temperature (LILT). For example, in the Jupiter system at 5-5.5AU, the solar resource is only 3-4% of the 1-sun AM0 irradiance available in Earth orbit, and solar array operating temperatures are typically in the -125 to -140°C range; in the Saturn system at 9-10AU, the irradiance is only ~1% of 1-sun, and the operating temperature is -160 to -170°C. In general, lowering the irradiance has the effect of decreasing the solar cell efficiency; lowering the temperature is beneficial to cell efficiency up to a point, however extremely low temperatures can also degrade the efficiency. Commercial off-the-shelf (COTS) solar cells available for space applications are typically designed and optimized for 1AU environments, and consequently have sub-optimal performance at LILT.

In addition to LILT, other environmental considerations relevant to deep space operation include charged-particle radiation and atmospheric effects. Radiation can be in the form of solar-flare protons or, for planetary bodies with magnetospheres, in the form of trapped radiation belts. In particular, the radiation environment in the Jupiter system is especially severe [2]. Radiation introduces displacement damage into the III-V compound semiconductor materials that the solar cells are made of, and darkening into the coverglass and adhesive materials shielding the sunward side of the cells, leading to reduced power-production performance. For surface operations on planetary bodies that harbor

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atmospheres, such as Mars or Titan, the incident irradiance is reduced by atmospheric absorption and scattering, which also translates into further solar cell performance losses.

From the point of view of solar array operation, the most challenging planetary-science mission targets for sun distances of ≤10AU are arguably the Jupiter system, with its combination of LILT and severe radiation; and the Saturn system, which has relatively milder radiation but an even more severe LILT environment. In this paper, we present an overview of current and near-term deep-space solar power technologies, with a focus on Jupiter and Saturn applications. Section II covers the state of practice and recent developments for Jupiter missions, and section III overviews the state of art and emerging technologies for Saturn missions.

II. Jupiter-System Applications

The state of practice for solar-powered missions to the Jupiter system is Juno, launched in 2011 and currently in polar orbit around Jupiter. The Juno solar arrays [3] are rigid deployable panels populated with 18700 triple-junction UTJ solar cells, which are ~30% efficient under Jupiter BOL conditions. Thanks to the unique mission design, the Juno solar arrays are nearly always illuminated, which keeps their operating temperatures at or above -135°C. Also, the orbit avoids the most intense regions of the Jupiter radiation belts, which results in an end-of-mission dose of 7e14 1MeV e^-/cm^2. The Juno solar array has an end-of-mission specific power (at load) of ~1.2W/kg at 5.44AU.

A representative of the state of art for solar-powered missions to the Jupiter system is Europa Clipper [4], currently under development and planned for launch in 2023. The Clipper solar arrays are, like Juno's, also rigid deployable panels, populated with 28100 triple-junction 3G28 solar cells. The operating temperatures are similar to Juno's; however, Clipper does include significant eclipses in its mission design, leading to solar array survivability temperatures as low as -240°C. Also, the orbit includes multiple fly-bys of the moon Europa, which is of great scientific interest due to its potential for habitability, but which also happens to be located near the peak of Jupiter's radiation belts; this leads to a significantly higher end-of-mission radiation dose than Juno, of 5e15 1MeV e^-/cm^2. The Europa Clipper solar array end-of-mission specific power (at maximum power point) is ~1.4W/kg at 5.46AU.

Ground-based laboratory characterization of solar cells presents a unique challenge to solar array development for missions to Jupiter. Accurate cell data is required in order to predict the array performance in flight. However, non flight-like test artifacts such as room-temperature annealing of radiation damage, which would be negligible under any other conditions, may introduce significant inaccuracies when LILT and high-radiation conditions come into play [5-7]. Compensating for such test artifacts is a non-trivial and active area of investigation, that both the Europa Clipper and the JUICE projects are currently pursuing.

In terms of technology development, NASA's Extreme Environments Solar Power (EESP) project [8] has been pursuing high-efficiency lightweight large-scale solar arrays that would be suitable for solar electric propulsion in the Jupiter system. As part of this project, JPL developed a four-junction inverted metamorphic (IMM4) solar cell which demonstrated 30% average efficiency at 5AU -125°C after exposure to a 4e15 1MeV e^-/cm^2 dose, and 0.91kg/m^2 specific mass at the assembly level with 100μm-thick coverglass [9]. This represents 25% higher end-of-life power production at LILT, and 30% lower specific mass than state-of-art ZTJ cell assemblies, making it an ideal component for integration into high specific power solar arrays for Jupiter missions. If the Jupiter-optimized IMM4 cell is combined with MegaFlex [10] or similar lightweight mechanical structures, the array-level end-of-life specific power will be ~8.6W/kg at 5AU.

III. Saturn-System Applications

To date, solar arrays have powered spacecraft up to sun distances of 5.5AU, but not beyond. Spacecraft traveling to Saturn-orbit or larger sun distances (such as Pioneer 11, Cassini, New Horizons or Voyager 1-2) have all been powered so far by radioisotope thermoelectric generators.

As part of an effort to determine if solar arrays are viable for Saturn missions [11], JPL acquired ground test data on three types of COTS solar cells, under Saturn LILT conditions. As shown in Fig. 1, we found the average cell efficiency at 9.5AU -165°C to be in the 30-34% range, higher than the 28-30% efficiency for the same cell types under standard test conditions of 1AU +28°C. In addition, brief excursions to +150°C temperatures, as could be experienced during Venus fly-by off-nominal events, did not have any measurable impact on subsequent LILT performance. These results show that state-of-art solar cells are viable for use in solar arrays even as far as the Saturn orbit.

Additional corroborating information came in the form of in-flight telemetry data from the Juno spacecraft. During the Jupiter orbit insertion maneuver, the Juno solar array was tilted to large sun angles, causing it to temporarily experience Saturn-like effective irradiances and temperatures. The solar panel telemetry from that time was used to infer a solar cell efficiency of 31.5% at 9.5AU -165°C, in good agreement with and providing independent validation of the ground test data taken under the same conditions.

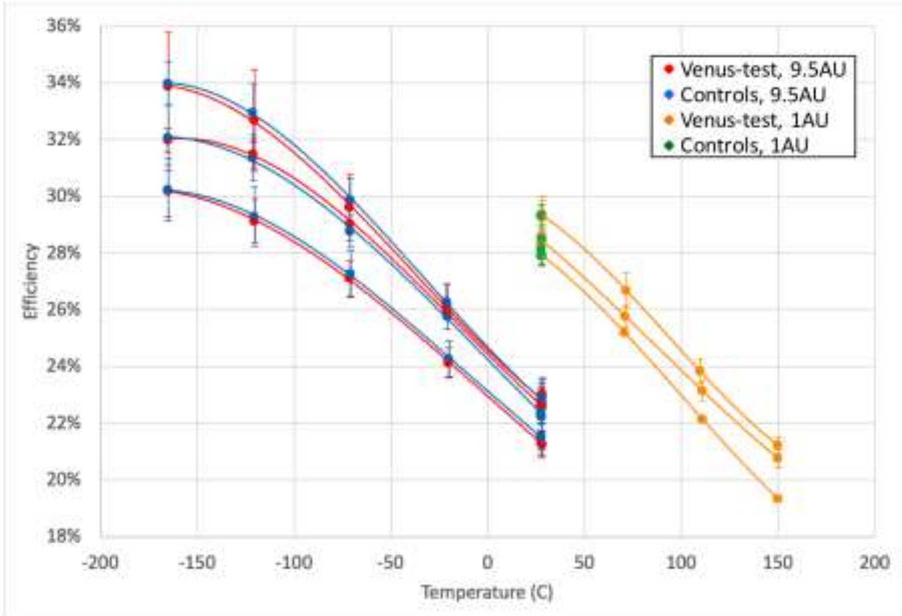

Fig. 1 Efficiency of COTS (ZTJ, UTJ and 3G28) solar cells, as a function of temperature. Under Saturn-orbit conditions (9.5AU -165°C), the measured efficiency is higher than under Earth-orbit conditions (1AU +28°C).

In terms of technology development, we highlight a recently completed JPL project aimed at developing solar cells specifically for operation under Saturn LILT conditions, rather than relying on 1AU-optimized COTS cells. Due to the low irradiance, a future solar-powered Saturn spacecraft would require sizable solar arrays; this means that even small relative gains in cell efficiency will lead to significant absolute savings in mass. The project's objective was to demonstrate ≥36% average efficiency under Saturn beginning of life conditions (9.5AU -165°C BOL, pre-radiation) and ≥33% under Saturn end of life conditions (9.5AU -165°C EOL, after irradiation to a dose of 2e14 1MeV e-/cm^2).

We started out with two different advanced solar cell architectures, Mod-UTJ from Spectrolab and IMM4 from SolAero, both of which had the potential for high efficiency. Then, through an iterative process of design, fabrication and test, we identified and eliminated any performance-limiting features, and optimized these architectures for Saturn LILT operation [12]. Figure 2 summarizes the results demonstrated at this end of this iterative process. Under Saturn conditions, the Mod-UTJ efficiency was 35.8% ± 0.5% at BOL and 33.6% ± 1.1% at EOL; for IMM4, the efficiency was 37.3% ± 0.9% at BOL and 35.5% ± 1.0%. The Mod-UTJ structure is in the process of being qualified to the AIAA-S111 standard by its manufacturer, under the product name XTE-LILT [13].

In particular, we note that the Saturn-optimized IMM4 technology exceeds both the BOL and the EOL Saturn performance objectives, with margin. The same cell also demonstrated an efficiency of 39.4% ± 0.6% under 5.5AU -140°C BOL Jupiter conditions, which represents a 31% improvement over the UTJ state of practice. In other words, if this cell technology had been available at the time, the Juno solar array could have in principle met its power requirement with only two wings' worth of active area instead of three.

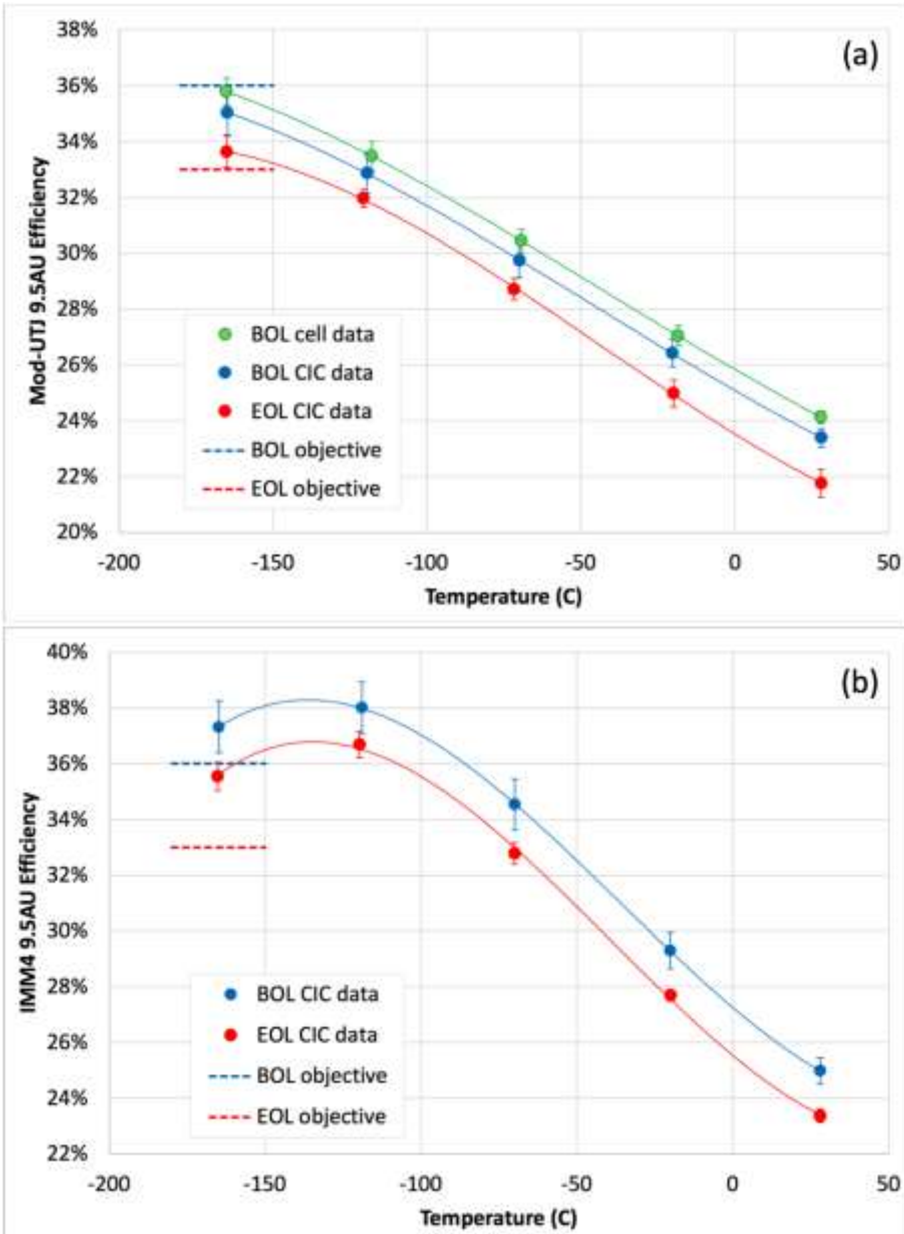

Fig. 2 Efficiency of Mod-UTJ and IMM4 cell technologies at Saturn-orbit (9.5AU) irradiance, as a function of temperature, measured before and after exposure to 2e14 1MeV e^{-}/cm^{2} radiation.

Implications of these recent cell-level developments for the feasibility and performance of future Saturn solar arrays are summarized in Table 1. Using the Juno solution of state-of-practice solar cells combined with rigid panels would lead to a very high mass penalty at Saturn. However, significant mass savings at the array level can be achieved by using the lightweight, high-efficiency Saturn-optimized IMM4 cells. Furthermore, if these cells are combined with lightweight flexible mechanical structures, array-level specific powers of ~3W/kg at Saturn end-of-mission will be attainable in the near future.

Saturn EOM Spec Pwr (W/kg) Mass of 400W array (kg)	Juno Cell UTJ	Saturn-optimized IMM4
Deployable rigid panels (Juno, Europa Clipper)	0.55 726	0.78 516
Flexible roll-out/fold-out (ROSA, UltraFlex)	1.9 211	2.9 139

Table 1 Solar array end-of-mission specific power (black font), and mass at 400W (blue font), if using state of practice versus newly developed cells, and rigid-panel versus lightweight flexible mechanical structures.

IV. Conclusion

Several solar-powered missions to Jupiter now flying or in advanced planning stages are using COTS triple-junction solar cells and rigid solar-array substrates. JPL has recently demonstrated an advanced cell technology which provides significant power and mass advantages over the state of art, for applications in the Jupiter-system environment of LILT and high radiation. Multiple COTS solar cell types have been characterized under Saturn conditions via ground testing; their performance was found to be viable for Saturn LILT operation, a result which was independently validated by Juno in-flight telemetry. In partnership with industry, JPL has developed and demonstrated several LILT-optimized solar cell technologies with Saturn efficiencies of 36-37% BOL and 34-35% EOL. Saturn-optimized solar cells combined with lightweight solar array structures are expected to make end-of-mission specific powers as high as 3W/kg at Saturn attainable in the near-term.

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