

Preliminary Test Results for the CellSaver Concentrator in Geosynchronous Earth Orbit

Mike Eskenazi & Alan Jones

Able Engineering, 600 Pine Avenue, Goleta, CA 93117, USA

Raj K. Jain, Bao Hoang, Kenneth MacDonald, Yu Nang Wong, John Kesapradist & Gerrit van Ommering
Space Systems/Loral, 3825 Fabian Way, Palo Alto, CA 94303, USA

Abstract

A flight experiment to evaluate ABLE Engineering's CellSaver concentrator solar array technology was launched into geosynchronous earth Orbit (GEO) in the beginning of 2004 on a Space Systems Loral satellite. This paper presents the experiment design, the ground test qualification program and preliminary on-orbit test results. The on-orbit data includes both temperature and power measurements from the first 9 months of the successful experiment.

Introduction

Concentrator solar cell array technology offers potential for significant cost and mass reduction compared to planar array technology because low-mass inexpensive concentrators replace heavier higher-cost solar cells. This reduces \$/watt and launch costs making concentrators attractive for satellite applications. A new concentrator technology, ABLE Engineering's CellSaver, offers significant potential for spacecraft use based on ground testing. Although detailed analysis and successful qualification testing has been performed there still remain concerns about the fidelity of simulation and the possibility of unforeseen effects and interactions on orbit. Thus, SS/L is flying a CellSaver experiment on a geosynchronous satellite to thoroughly evaluate CellSaver performance and stability in the space environment.

CellSaver Description

As shown in Figure 1, CellSaver is an on-panel reflector that replaces approximately half of the solar cells on a spacecraft solar panel. CellSavers flex to the side and overlap with each other to stow neatly between panels during launch as shown in Figure 2. When the solar panels unfold in space, CellSavers self-deploy under their own spring energy creating rows of nominally 2X reflective concentrators. Cost and weight savings are significant because CellSavers cost and weigh only about 25% of the multi-junction solar cells they replace.

CellSavers are constructed from a single piece of thin ($25\mu\text{m}$), high-strength titanium foil with a space-flight compatible high reflectance coating. No organic materials are used thereby minimizing radiation and thermal cycle induced property changes and degradation. High-strength titanium foil was selected because it can be folded to extremely tight radii between panels ($< 0.5\text{ cm}$) without yielding or creep, it is extremely stable under exposure to space radiation and thermal cycling, and is lightweight. The high reflectance coating is vapor deposited silver with a protective transparent dielectric overcoat. The reflective coating provides high reflectance over the entire response range of the $\text{GaInP}_2/\text{GaAs}/\text{Ge}$ triple-junction cell (350nm to 1800nm). The collapsible CellSaver reflectors are straightforward to implement or retrofit onto conventional

solar array platforms because they are compatible with standard large area multi-junction solar cells, standard composite solar panels and can be stowed in small panel gaps ($<1\text{ cm}$) for long periods of time.

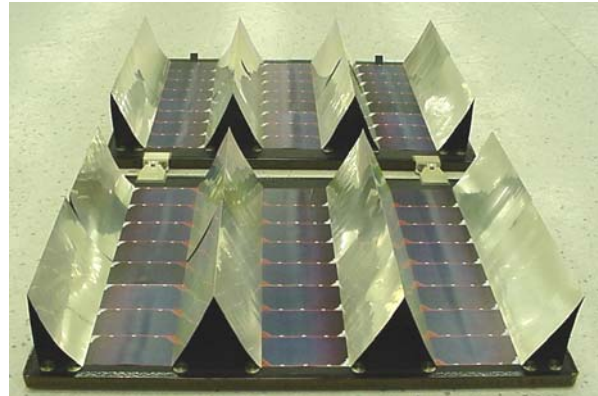


Fig. 1. CellSaver Solar Concentrator Panels.

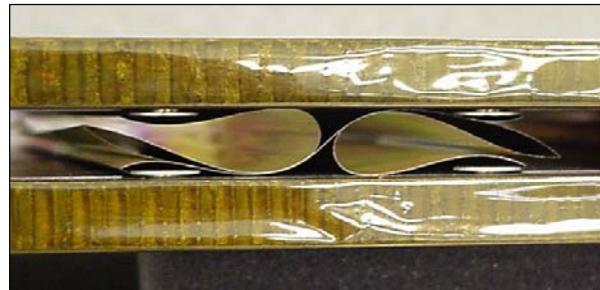


Fig. 2. Stowed CellSaver Reflectors in a 1.1 cm gap.

As shown in Figure 3, the solar heat load per unit area on a CellSaver panel is lower than on a panel with edge reflectors, like those flown on the Boeing 702 satellites [1], resulting in lower cell and panel operating temperatures for CellSaver ($\sim 75^\circ\text{C}$) versus panel edge reflectors ($\sim 125^\circ\text{C}$). This improves cell efficiency and reduces out-gassing of reflector contaminants from the solar panel, which was reported as the cause of anomalous power degradation on several Boeing 702 satellites [2].

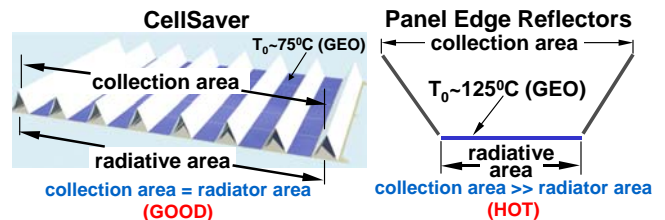


Fig. 3. Reflective Concentrator Thermal Comparisons.

Qualification Test Results

A space-flight qualification program for CellSaver, including ground, launch and on-orbit environmental testing, has been successfully completed [3-5]. The

CellSaver qualification test program is similar in scope to that performed for solar cells by solar cell manufacturers and includes electrical performance measurements before and after random vibration, GEO and LEO thermal cycling, LEO vacuum bake-out, long term stowage, deployment cycling, humidity exposure, and GEO electron, proton and UV radiation. A summary of the CellSaver qualification tests, environments, test hardware and key results are given in Table 1. Thus far, CellSaver has successfully passed all environmental tests.

Table 1. Space Qualification Testing Summary.

Test	Environment	Test Article	Key Results
Electrical	AM0 Large Area Pulsed Solar Simulator (LAPSS)	Multiple CellSaver designs with EMCORE, TECSTAR and Spectrolab multi-junction cell strings	BOL Power Boost 89% to 95% of Concentration Ratio Depending on Specific Design
Off-Pointing	AM0 Large Area Pulsed Solar Simulator (LAPSS)	Multiple CellSaver designs with EMCORE, TECSTAR and Spectrolab multi-junction cell strings	Current roll-off follows cosine law for $\alpha < 10^\circ$ (lateral) & $\beta < 25^\circ$ (series dir)
Random Vibration	x, y & z axes at 52grms, 45grms & 87grms respectively	CellSaver panel pair with four 176 mm long CellSavers and a 4-cell string of TEC3i	No measurable shape change or reduction in power output
GEO Thermal Cycling	-175° to 120°C 2,000 cycles	Two CellSaver panels, one with 4-cell string of TECSTAR TEC3i	Power reduction less than 1% after 2000 cycles (= 20+ years)
LEO Thermal-Vacuum Cycling	-115°C to 135°C 1×10^{-5} Torr 12 cycles	2 panels with 8 CellSavers on each and three 10-cell strings of TEC3i or EMCORE ATJ	No measurable power degradation in any string
LEO Thermal Cycling	-100°C to 120°C 20,000 cycles	2 panels with 8 CellSavers on each and three 10-cell strings of TEC3i or EMCORE ATJ	No measurable reduction of CellSaver performance
Long Term Stowage	Stowed in 11mm gap at ambient for 3 years	Two CellSaver panel pairs with four 176 mm long CellSavers on each	No effect on reflector deployment. 1% power reduction after 16 months
Small Panel Gap	Down to 5 mm panel spacing for 1 minute	Two CellSaver panel pairs with four 176 mm long CellSavers on each	Stowed in 5 mm panel gap without optical or shape degradation
Deployment Cycling	50 stow and deploy cycles	CellSaver panel pair with four 176 mm long CellSavers	No measurable shape change or reduction in power
Deployed Strength	130 g static load applied in x, y & z axes	CellSaver panel pair with four 152 mm long CellSavers	Deployed CellSaver undamaged by 130g static loading in all three axes
Xenon Plume Resistance	Xe ion plume at multiple energies & angles	Reflector material (50mm x 89mm)	Erosion rate of protective coating successfully measured
Humidity	90% RH at 22°C for 60 days	Three CellSaver panels each with two 176 mm CellSavers	No visual defects. P_{mp} degradation approximately 1%
Electrons, Protons & UV Radiation	15 year GEO dose per AE8 and AP8 + 5,973 ESH UV	Reflector material (25mm x 76mm)	Solar reflectance reduced 1.8%. No emittance change.

Flight Experiment Description & Acceptance Testing

The CellSaver flight experiment is designed to provide up to 15 years of electrical and thermal GEO flight data [5]. The test panel (shown in Figure 4) contains two 4-cell strings of large area (27.5 cm²) EMCORE 26% efficient triple-junction solar cells. One string is installed between two CellSaver reflectors and one string is in a standard planar configuration. The experiment is mounted on the anti-earth deck of the spacecraft as shown in Figure 5. The panel orientation results in the sun α -angle changing 15 degrees per hour as the spacecraft orbits the earth and β -angle to vary between ± 23.5 degrees according to the seasonal sun angle. Direct normal illumination only occurs at fall and spring equinoxes during spacecraft local solar noontime. Reflector overlap at the ends of the cell string is limited to about 1.3cm (± 10 -degree β -angle coverage) due to space constraints, thus, data obtained for β -angles greater than 10 degrees will show the effects of reduced reflector illumination on an end cell.

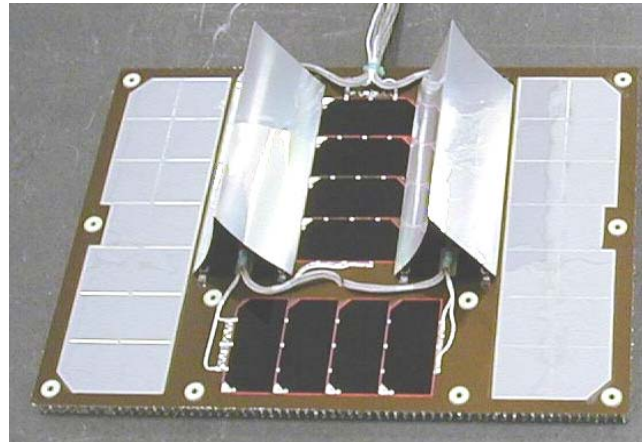


Fig. 4. CellSaver GEO flight test panel.

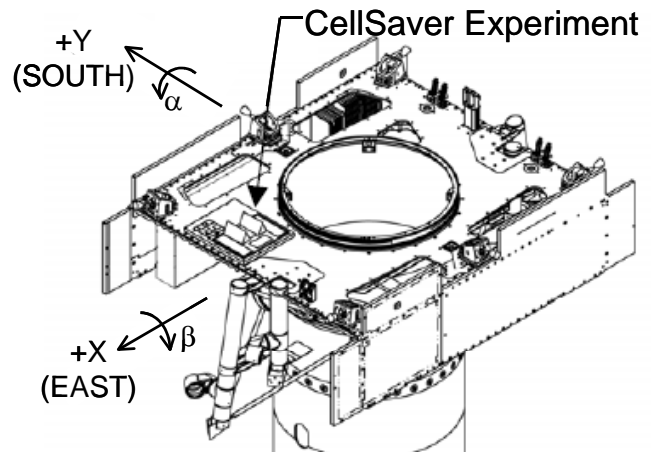


Fig 5. Anti-earth (-Z) side of the spacecraft

Because the experiment is body mounted, it does not radiate off the back like a deployed solar panel. To compensate for this, optical surface reflectors (OSR's) are

used to reduce the CellSaver cell-string operating temperature to 75°C-80°C, which corresponds to the expected operating temperature of a deployed CellSaver solar panel in GEO.

The current versus voltage (I-V) curves of the CellSaver and planar TJ cell strings are measured by a relay resistor circuit. This circuit enables 17 resistance values by open/closed combinations of the relays. The voltage is measured across each resistance value to obtain the 17 points for an I-V plot. Two sensors on each string measure the planar and CellSaver cell temperatures. The sensors are located under the two middle cells in each string.

Prior to launch, the experiment was subjected to acceptance testing including thermal cycling, sine, random and acoustic vibration with the CellSaver reflectors in the deployed state. The flight experiment was visually inspected for any damage and functional electrical tests were performed before and after every environment. The experiment passed all tests at the subsystem (test package) level. After integration onto the spacecraft, the CellSaver experiment successfully underwent thermal vacuum testing with the spacecraft [5].

Flight Test Results

CellSaver data is obtained on a non-interference basis with the primary spacecraft operations so the CellSaver experiment is not run continuously. To date, full data sets have been obtained near and at the spring and fall Equinox. Table 2 summarizes the test dates and corresponding incident sun angles, sun distance, temperature range and calculated equivalent 1-MeV electron radiation dose. The experiment was exposed to significant radiation during orbit-raising (1.2×10^{14} 1MeV electrons equivalent) but absorbs radiation at a much slower rate on-station. Future measurements will occur approximately once a month to provide data over many different α and β angles.

Table 2. Test Dates and Corresponding Conditions

Date	Days on Orbit	Ave Sun Angle (deg)		Sun Distance (AU)	Average Actual Temp (°C)		Total Radiation (1 MeV e-)
		α	β		CSaver	Planar	
7/31/01	LAPSS	0	0	1.0000	19.0	19.0	0
3/19/04	66	14.9	0.0	0.9959	76.7	72.0	1.20E+14
9/22/04	253	2.7	-1.8	1.0033	79.1	70.0	1.29E+14
9/24/04	255	2.7	-2.5	1.0028	79.9	70.5	1.29E+14

Each IV curve is measured over a 10-minute period with data points taken approximately every 30 seconds. The string temperature corresponding to each IV data point is measured so the data can accurately be adjusted to a reference temperature. A reference temperature of 75°C has been chosen because this is close to the actual measured temperatures for the planar and CellSaver strings and near the predicted steady state operating temperature for a deployed CellSaver solar panel in GEO.

The flight-data has been normalized to 1.0AU normal sun-incidence at 75°C so that consistent comparisons can be

made between the flight data sets and the initial LAPSS data and degradation over time easily visualized. The inverse square law is used to correct for sun distance. The cosine law is used to correct for incident sun angle, except for α -angles greater than 10 degrees where the CellSaver off-angle performance curve [5] is used. Temperature corrections are made using the EMCORE Triple Junction BOL voltage and current temperature coefficients of $-5.6\text{mV}/^\circ\text{C}$ and $3.3\mu\text{A}/\text{cm}^2/^\circ\text{C}/\text{sun}$, respectively [6].

Figure 6 shows the IV curves from the CellSaver and Planar strings obtained in the pre-flight LAPSS test and on-orbit. Table 3 shows the maximum power and open circuit voltage and the ratio between CellSaver and planar performance for the same tests. Table 4 shows the data normalized to the initial LAPSS data. Figure 7 shows the ratio of CellSaver to planar maximum power and open circuit voltage versus time on-orbit.

Discussion of Results

The measured power reduction after 8.5 months in space, including several days of orbit-raising through the radiation belts, is about 4.5% for CellSaver and 5.0% for planar. The measured degradation is consistent with expectations of 1% current loss for coverglass/adhesive darkening due to UV, and a 1% reduction in cell current and 3% reduction in cell voltage due to radiation at 1.3×10^{14} 1MeV electrons [6].

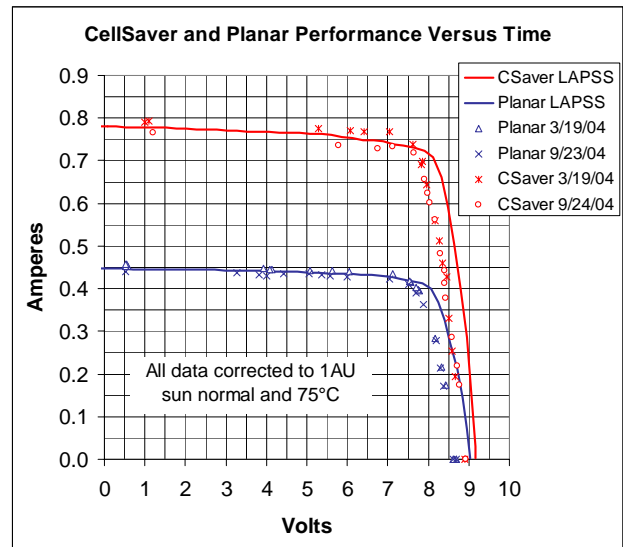


Fig 6. CellSaver and Planar String IV Curves.

Table 3. Measured Power & Voltage Versus Time.

Date	Days On Orbit	Adj. Temp (°C)	Pmax (W)			Voc (Volts)		
			CS	PLNR	CS/PLNR	CS	PLNR	CS/PLNR
7/31/01	0	75	5.754	3.238	1.777	9.177	9.017	1.018
3/19/04	66	75	5.636	3.146	1.792	8.892	8.692	1.023
9/22/04	253	75	5.469	3.042	1.798	8.928	8.682	1.028
9/24/04	255	75	5.491	3.076	1.785	8.931	8.689	1.028

Table 4. On-Orbit Data Normalized to Initial LAPSS Data.

Date	Days On Orbit	Adj. Temp (°C)	Pmax		Voc	
			CS	PLNR	CS	PLNR
7/31/01	0	75	1.000	1.000	1.000	1.000
3/19/04	66	75	0.979	0.972	0.969	0.964
9/22/04	253	75	0.950	0.939	0.973	0.963
9/24/04	255	75	0.954	0.950	0.973	0.964

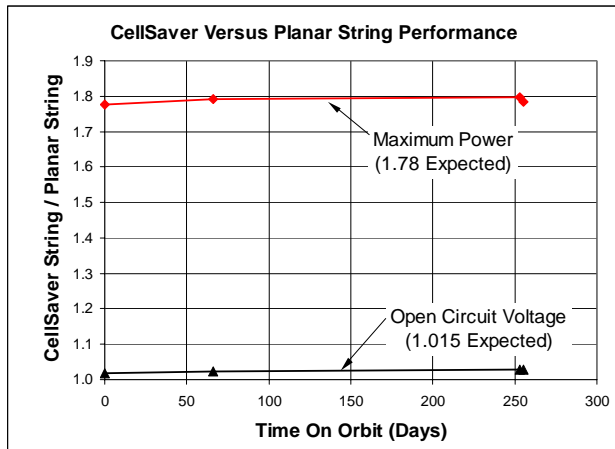


Fig 7. CellSaver/Planar Power and Voltage Ratios.

Thus far, the CellSaver string performance at maximum power has degraded about 0.6% less than the planar string. This is contrary to the pre-flight expectation that the CellSaver string would degrade slightly faster than the planar string due to reflectance reduction, which can be caused by contamination, radiation and thermal cycling. Experimental inaccuracies that have been estimated to range from 1-2% may explain this result. As more flight data is collected the degradation trend will become clearer and a more accurate model of on-orbit CellSaver reflectance loss will be obtained. Based on the ground test results, loss of reflectance due to the combined effects of contamination, radiation and thermal cycling is predicted to cause the CellSaver string to degrade a total of 3% to 4% more relative to the planar string over the life of the mission.

Most notably, unexpected degradation has not occurred like was observed early in flight with both the BSS 702 reflective concentrator array or the 3X Light Concentrating Panel (LCP) experiment flown on Mightysat II.1 [7]. In both cases the excessive degradation was attributed to contamination. If the CellSaver result holds, it would support previous contamination analyses [3] that suggest CellSaver degradation will be significantly less than the BSS 702 concentrator because of the lower out-gassing rates and more benign contaminants produced by the cooler operating CellSaver panels (125°C versus 75°C).

The 3% voltage reduction observed with the planar string is consistent with the calculated radiation dose of 1.3×10^{14} 1-MeV electrons and the EMCORE TJ Cell qualification test data [6]. Interestingly, voltage degradation for the

CellSaver string is less compared to the planar string by about 1%. This result, although within experimental inaccuracies, could be explained because essentially all of the voltage degradation is due to electron and proton radiation and the reflectors provide extra shielding against omni-directional particulate radiation for the CellSaver cells. If this trend continues and the reduction in cell radiation degradation becomes significant with CellSaver, future analysis will quantify the beneficial effect of CellSaver radiation shielding.

Conclusion

A CellSaver experiment providing a direct comparison between concentrator and planar multi-junction solar array technologies has been successfully placed in GEO and is producing valuable data. Experimental data acquired to date are consistent with the expected performance for power output and operating temperature. CellSaver power output is degrading at about the same rate as the planar string located beside it. Voltage degradation for CellSaver appears to be slower due to the radiation shielding effect of the reflectors. The anomalous degradation observed on the BSS 702 arrays and the Mightysat II.1 LCP experiment has not been observed. Though additional time on orbit is required to confirm these preliminary results, all flight and ground testing to date show that CellSaver is a promising near-term method to reduce spacecraft power generation cost and weight without significant array redesign or qualification.

References:

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