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Validation of the SCARLET Advanced Array on DS1

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ABSTRACT

In October , 1998, the first of the NASA New Millenium Spacecraft, DS1, was successfully launched into space. The objectives for this spacecraft are to test advanced technologies that can reduce the cost or risk of future missions. One of these technologies is the Solar Concentrator Array with Refractive Linear Element Technology (SCARLET). Although part of the advanced technology validation study, the array is also the spacecraft power source. Funded by BMDO, the SCARLET™ concentrator solar array is the first spaceflight application of a refractive lens concentrator.

As part of the DS1 validation process, the amount of array diagnostics is very extensive. The data obtained includes temperature measurements at numerous locations on the 2-wing solar array. For each individual panel, a 5-cell module in one of the circuit strings is wired so that a complete I-V curve can be obtained. This data is used to verify sun pointing accuracy and array output performance. In addition, the spacecraft power load can be varied from a small fraction of the array capability, up to maximum power. For each of the power loads, array operating voltage can be measured along with the current output from each wing.

Preliminary in-space measurements suggest SCARLET performance is within one (1) percent of predictions made from ground data. This paper will discuss the results of the SCARLET in-space validation, including array performance as a function of changing solar distance and array performance compared to pre-launch predictions.

Key words: Deep Space 1, DS1, Scarlet, concentrator solar array, multibandgap solar cells, Fresnel lenses, interplanetary spacecraft

INTRODUCTION

The Deep Space 1 (DS1) mission was launched from Cape Canaveral Air Station, on October 24, 1998. The objective of the mission was to test 12 advanced technologies in deep space in order to lower the cost and risk to future science missions that would utilize the technologies. In addition to the technology validations, the spacecraft will perform a flyby of Asteroid 1992 KD in July 1999. A potential mission extension could lead to a subsequent comet flyby.

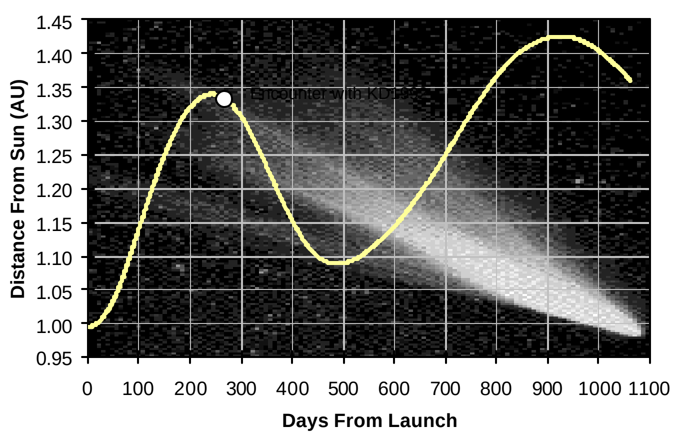

Figure 1. DS1 Mission Timeline of Heliocentric Distance

Among the advanced technologies are ion propulsion, an instrument that will study electrically charged particles, one that combines a camera/spectrometer in a miniaturized package, and new technologies for communications. This paper discusses the advanced SCARLET solar array, a 2.5 kW photovoltaic concentrator array that provides the DS1 spacecraft power.

Descriptions of the array configuration have been presented previously (1). However, a brief description will be included here. SCARLET consists of two wings, each attached to the spacecraft through a yoke and solar array drive unit. Each wing consists of four deployable composite honeycomb panels (Figure 2). Each panel includes a Fresnel lens concentrator grid that deploys with the panels. The Fresnel lenses provide a concentration ratio of approximately seven to the solar cell modules. The system is designed to be modular. Each panel consists of a number of five cell modules connected in series. Ten modules then form a circuit string. Operating string voltages are approximately 100 volts. Voltage varies during the mission due to the change in spacecraft-sun distance and the spacecraft power load which is dominated by the ion propulsion unit. The power supply varies the array operating voltage depending on the required power level.

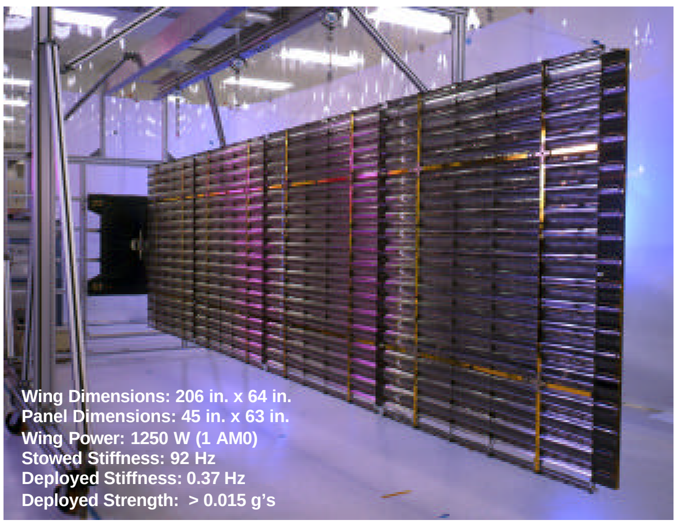

Figure 2. DS1 Scarlet Wing

The concentrator lenses are mounted above the cell modules on a deployable superstructure (Figure 3). This structure is passively linked to the panel deployment synchronization to move the lenses from their stowed position, close to the cell substrate, up to their optical distance by the end of deployment. The arched Fresnel lenses were selected for SCARLET due to their ability to maintain focus on the cells even with significant lens distortion. Multi junction cells are used on DS1, demonstrating one of the technology features, i.e., the ability to use reduced quantities of high efficiency cells, to reduce overall array costs. Although the original intent was to utilize 2 -junction devices, schedule difficulties led to the eventual use of activated Ge base cells or "3J" cells on the array.

In view of the novel design of SCARLET there were many concerns for its successful operation by the spacecraft team prior to launch. These included deployment, and the ability to establish and maintain accurate pointing. Due to the concentration ratio and design of the concentration system, it was calculated

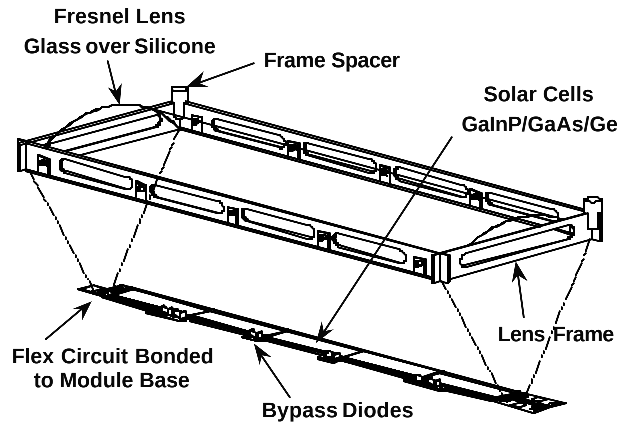

Figure 3. Scarlet Module: Lens and Receiver

that wing pointing would need to be maintained within 1.5 degrees in "roll" to achieve high output. The "pitch" restriction was much less severe and not considered a problem. Because solar energy is concentrated in narrow bands on the cells, panel heat transfer is complex and thermal analysis errors were possible that might not reveal warping. Ground measurements of the array performance were also felt to be less accurate than desired. The difficulty in accurately measuring an array using multi junction cells is known and requires an extremely faithful solar simulator spectrum (2). Such equipment was not, in general, available to AEC-Able for this mission. The mix of 2- and 3- junction cells was a further complication. In-space operating temperatures were expected to vary between the two cell types, further complicating the ground based predictions. The efforts to determine the space performance with the ground testing were more extensive than for typical single junction planar arrays, and still estimates of the predicted accuracy ranged as high as +/- 5%. Fortunately, DS1 provides for the acquisition of extensive performance data, something that few flight photovoltaic systems have ever had.

TECHNOLOGY VALIDATION MEASUREMENTS

As part of the technology validation, DS1 provides a set of power telemetry data to AEC-Able on a periodic basis. The telemetry channels that are available for solar array data collection are the following: solar array voltage, both solar array wing currents, voltages and currents of each of four solar array modules on each wing (one per panel), and temperature readings from each of ten RTDs (Resistance Temperature Devices) located on both wings.

The voltage, the wing currents and the temperatures from the solar array have been available in the down-link data since the solar array deployment. The first extensive data gathered on the eight solar array modules was completed a week after launch. The on-board activity, called SIVPerf (Solar array IV Performance), collected voltages and currents of each solar array module. The IV profiler circuit in the High

Voltage Power Converter Unit (HVPCU) connects one of the eight solar array modules with one of sixteen load resistance values. For each load resistance, corresponding measurements of voltage and current were collected on the spacecraft and sent down as telemetry data. The resulting data was used to generate an IV curve for each module which was then compared with the pre-flight IV curves. This activity was scheduled to be executed on-board at least once a month in order to validate the solar array performance versus heliocentric distance, temperature, and environmental degradations.

Another on-board activity, called SCAL (Solar array CALibration), was used to perform the on-orbit calibration (pointing accuracy) of each wing using the eight solar array modules. Performed eight days after launch, this activity measured the solar array sensitivity to alpha and beta pointing combinations. The experiment turns the spacecraft to an offset beta position, then scans through several alpha positions. The grid pattern of alpha-beta positions is made up of 17 positions sweeping from -8 to +8 degrees in beta and 19 positions sweeping from -4 to +4 degrees in alpha. In practice, the spacecraft deadband motion continually varied pointing around a selected position. Since the wing pointing knowledge was available for each measurement, this did not pose a problem. During each solar array positioning, the temperatures of the array, the solar array drive motor (SADA) positions, and spacecraft attitude are measured. Throughout this experiment, the short circuit load is applied to the solar array modules. Since a complete SCAL runs an entire workday, and since the spacecraft would operate only on batteries during the extreme off pointing positions, this activity was performed only as needed. It will be repeated in the event that changing thermal distortions, accumulated environmental degradations, or electrical failures are suspected of having altered the optimum pointing angle.

The DS1 spacecraft system designers also came up with another on-board activity that verifies the projected voltage and peak power. Referred to as SPeak (Solar array Peak power), this activity also provides determination of the optimum solar array operating voltage set-point in the HPCU to allow for maximum thrust levels. Continuous thrusting can be supported even when the power demand to the spacecraft exceeds the solar array output capability by utilizing battery power. During SPeak, the IPS, which is connected in parallel with the spacecraft loads, is commanded to a power level that is about 100 W less than the projected peak power output from the array. This forces the spacecraft loads to be partially powered from the batteries for the duration of the test. At the start of the activity, the set-point in the HVPCU is set at an arbitrary level that corresponds to about six volts greater than the projected peak power point (PPP) voltage. With the IPS on, the set-point is incremented down (decreasing voltage) until the set-point reaches a level which was arbitrarily set at about six volts below the PPP. The data acquired from this activity was then used to confirm the PPP voltage and provided the DS1 mission engineers with the information to select the appropriate voltage set-point in the HPCU. This set-point, which is set by a command from ground, is selected to be as close as possible to the PPP voltage so as to maximize the available power to the spacecraft.

In addition to these data, SCARLET was instrumented so that deployment release mechanism and wing latching would be indicated and transmitted to mission operations.

DEPLOYMENT

The first activity required from the SCARLET system in space, deployment, occurred 1 hour after launch. Activation of the High Output Paraffin (HOP) actuators activates the mechanism to release the panel tiedown cables. After the cables are released, the wing deploys powered by torsion springs and rate-limited by viscous dampers.

Power to the Solar Array Tiedown Mechanisms (SATMs) was autonomously commanded at about 1 hour after launch. The spacecraft was in eclipse on the far side of the Earth. Telemetry was recorded at 5 second intervals. Forty minutes later, when the real time link was reestablished at JPL, it was evident that the array was deployed: The indicator switch states were all in agreement and power was being produced.

Analysis of the recorded data allowed the duration in seconds of the deployment events of HOP heating to SATM release and damped wing motion to full deployment latching to be determined. The HOP heating durations on each of the four actuators ranged from 70 to 85 seconds. These values agree well with the duration from ground test, 77 seconds, for a HOP temperature of 18 C. The thermal modeling of the temperature transients from fairing jettison after launch to deployment in eclipse predicted a HOP temperature of 15 C. The duration of the wing deployment depends on the damper temperature, which was forecast to be near zero. The damper body and silicone fluid and thermostat were modeled by a single node, as the primary intent was to determine how early the thermostat could turn on causing the damper heater to draw power. The actual fluid temperature would certainly lag behind the cooling of the casing exterior and the thermostat body. So the flight temperature was probably between 0 and 15 C.

Placing the average wing deployment time on the curve of predicted time versus temperature, Figure 4, suggests the fluid temperature was near 11 C. In summary, all telemetry data indicates the deployment occurred precisely as designed. This was a significant milestone, and the first, for technology validation because - although the highlight of the technology is the optical/thermal/electrical performance of the concentrator/cell module - the kinematic control and joint mechanisms were all new.

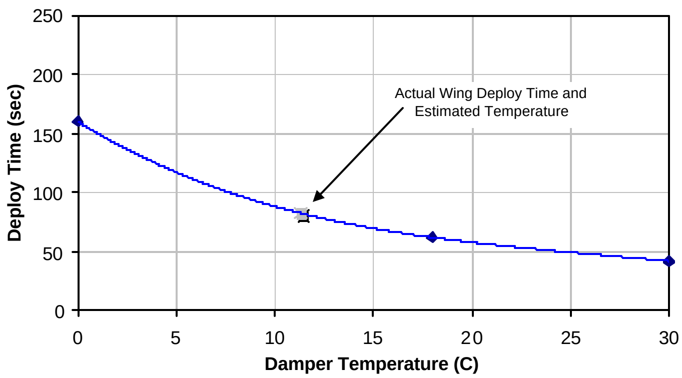

Figure 4. Deployment Duration vs. Temperature

POINTING

The proper alignment of a concentrator system is critical. System performance is dependent on all elements (cells, modules, lens frames, panels, hinges, yoke,…) being assembled accurately, deployed reliably, and being resistant to thermal distortion. Numerous industry efforts to build concentrator systems have failed at various stages prior to launch due to the inherent design and manufacturing difficulties. The industry has had success of late with low concentration ratios, for example the planned Hughes 702 reflective trough concentrator at 2X. SCARLET is the first system on-orbit to provide significant concentration benefits. The Fresnel optics provide an advantage in tolerance to shape error that reflective systems lack. While it was demonstrated that manufacture of the piece parts and assembly of SCARLET was straightforward, the proof of success - power production - required on orbit data. Would each and every lens be pointed accurately to the sun within the accumulated errors of piece part fabrication, sub-assembly, system assembly, thermal distortion, spacecraft knowledge and pointing control? The eighth day of the mission provided the answers to these questions.

On-Orbit Calibration

The sequence for pointing validation was SCAL. To determine if each wing was positioned by the spacecraft (for beta) and the wing gimbals (for alpha) at the angles which provided maximum power, the wings were steered to various positions over a range of $\pm$ 4 in alpha and $\pm$ 8 in beta. The alignment of the system was judged by the short circuit current (I_{sc}) output of the tap modules on each panel, a direct indication of the light flux on the cells. The sequence ran for about 6 hours, where each beta position was selected and the various alpha positions were steered through. As different modules were selected the measured current fluctuated according to the I_{sc} potential of that module.

A typical data set shows the performance of the total system begins to falloff just beyond 1 degree as expected. When the data for each module is plotted a parabolic curve fit can be used to estimate whether the alignment is centered or skewed. The population of data shows scattering due to spacecraft drift. However, the best fit curves form a fair assessment of the focal line offset on each cell module. When the offsets are compared against the design specifications, as in Figure 5, the success of the system in achieving far better alignment than required is clearly evident.

In the event the SCAL data had shown any significant difference in current between modules or wings, a topology study was planned to determine the best beta correction for the spacecraft and the best alpha correction for each gimbal. The results of SCAL demonstrated that SCARLET achieved the pointing accuracy goals not only for the design and assembly of the wings, but of integration with gimbals and the spacecraft structure, and for integrated performance with the spacecraft issues of position knowledge, pointing control, and drift.

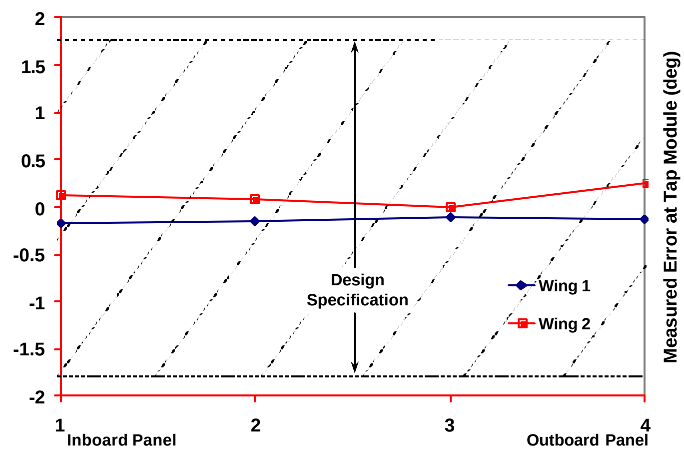

Figure 5. Pointing Validation Summary

TEMPERATURE

The first critical validation of the power model is the operating temperature of the array. Each wing was equipped with RTDs: Four on the inboard panel and four on the outboard panel. As shown in Figure 6, the cluster of four RTD's were located: (1) Next to cell on the front facesheet (as close as module base width allowed), (2) On module-to-module centerline on the front facesheet, (3) Directly behind the cell on the back facesheet, and (4) On the module-to-module centerline on the back facesheet. On the second wing only the top RTDs nearest the cells were recorded, due to channel restrictions. Therefore the flight data set consists of 8 RTDs on Wing 1 and 2 on Wing 2.

A fairly detailed finite difference model was developed, starting in 1996, to analyze the complex heat balance and thermal gradients beneath the lens. The line focus and regular module-to-module spacing allows for accurate temperature predictions using a half-symmetry 2-D model.

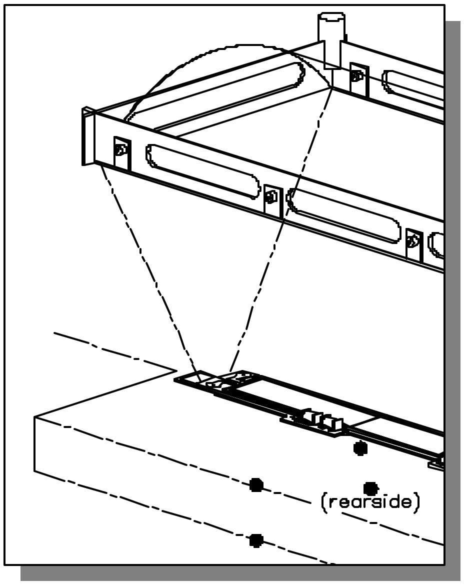

Figure 6. RTD Locations on Wing: 2 Frontside, 2 Rearside Locations

The model was refined in 1997 based on thermal balance testing performed in a 1-sun vacuum environment at NASA Glenn Research Center. Further refinements were made to the model late in 1998, but these changes were after the final on-orbit power predictions were submitted in April of 1998. The modeling prediction for operating temperature versus heliocentric distance for both models is shown in Figure 7. The difference at 1 AU is less than 3 degrees. Both models are shown *without* the 10 C margin used in the power prediction, because the flight data demonstrates it was not needed, as will be shown below.

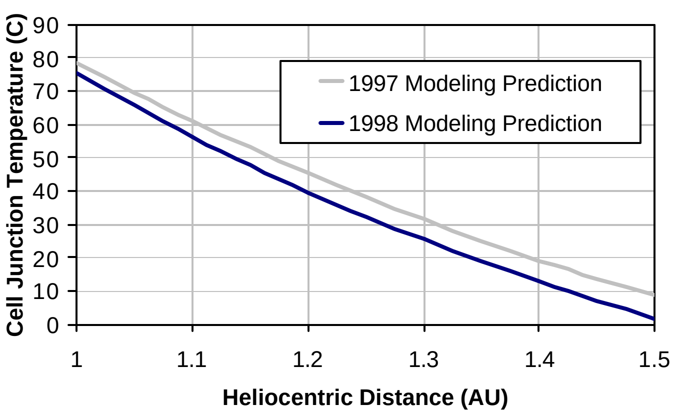

Figure 7. Modeling Predictions of Cell Temperature at P_{max} at 1 AU

On the 37th day of the mission the ion engine was, for the first time, commanded to thrust at increasing increments up to maximum power. The data available just on all the front RTDs (nearest the cells) for array power levels between zero and near full power are plotted in Figure 8.

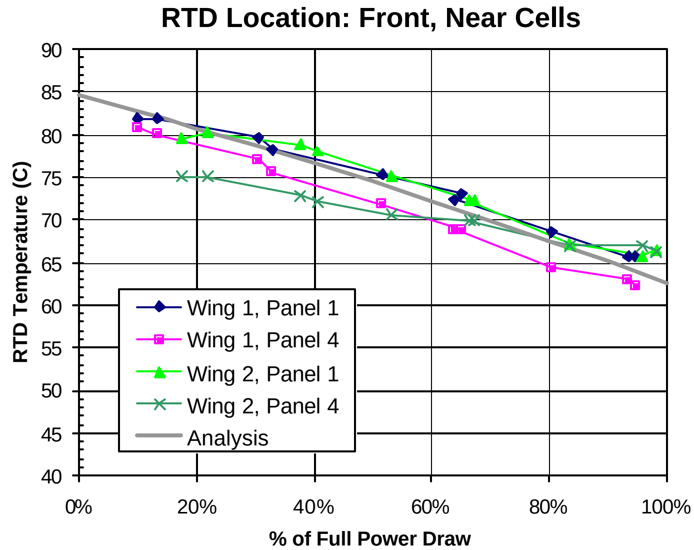

Figure 8. Steady State Temperature vs. Power Draw

The 1998 model prediction curve is also plotted for comparison. The general agreement is excellent. Several observations about the data can be made: (1) The agreement is fairly precise, on average, near maximum power for the RTDs nearest the cells and (2) The flight data of the other RTDs shows the gradients of heat spreading across and through the panel were slightly larger than the model forecast.
The most likely effects which would reduce the efficiency of thermal spreading are: (1) The core to facesheet conduction is limited by the joining adhesive, and (2) The facesheet conductivity is lower due to thickness or resin fraction. The net effect of incorporating corrections would likely be of little benefit to the current power modeling correlation since the current thermal modeling predicts the near-cell temperature precisely and is only off by 2.5 C on the back of the panel between modules.

The data showed that panel 1 is higher than panel 4 by a few degrees at maximum power draw. This is probably because the higher view factor to the spacecraft at the inboard panel increases the temperature slightly. The temperature difference between the 1st and 4th panels on wing 1 appears less at lower power draw. This is probably due to the fact that the tap module string on panel 4 has a lower open circuit voltage. The value for power draw is calculated from the average wing current at the load voltage. At high load voltages (low power draw) the contribution in current (and thereby power) from the panel 1 string is higher than the wing average or the panel 4 tap module string, so the temperatures for panel 1 should be reduced (increasingly at lower power draw). This effect is most dramatic for Panel 4 on Wing 2, which has the highest open circuit voltage. At very low power draw from the array, the strings on this panel are producing the majority of the power and hence run coolest.

This discussion of temperature modeling validation has dealt mainly with the comparison of predicted RTD temperature to flight results. The agreement in the gradients between the RTDs does not guarantee that the actual cell temperature has been accurately predicted. An examination of open circuit voltage generally allows the best determination of the temperature of a cell (assuming V_{oc} at 28 C and temperature coefficient are known). Discussion of the open circuit voltage is included in the next section, Power, where the results of SIVPerf sequences on the module and trends of array-level voltage vs. AU are examined.

POWER

The validation of power production relies on two sequences: SIVPerf and SPeak. As discussed earlier, SIVPerf measures the full IV curve of a single module within a string of 10 modules on each panel, for a total of eight module level curves. SPeak produces a partial IV curve for each wing, as a byproduct of a sequence intended to optimize thrusting. The SIVPerf results will be discussed first.

SIVPerf

This sequence was intended to be run on the earliest day possible after launch using all tap circuits and temperature sensors (8 taps and 10 RTDs) to verify initial performance prior to on-orbit calibration. Then nominally every month as a minimum to validate performance versus AU, temperature, and environmental degradations. The first SIVPerf was run on mission day 7, October 31, 1998. Examination of the first data set was not encouraging. The fill factors on several curves were low. It was noted that on average, the tap modules were producing about 4% less power than expected based on the pre-flight LAPSS tests. The preliminary results suggested that for mission planning purposes it would be best to use the worse case array power predictions until full array IV curves could be obtained the week of 9 November 1998. As a consequence of delays due to various spacecraft anomalies, peak power results (from the first full power thrusting) were postponed until November 30th. When these data were analyzed it was found the early extrapolation from the tap module results were too conservative. The wings were actually producing at or above the nominal power prediction. It is not clear why some of the tap modules have shown low fill factors while the array overall is performing well. Only one other SIVPerf sequence has been run, so there is limited data available.

SIVPerf runs have been limited because during the second running of the sequence on mission day 18, November 11th, an anomaly was observed: The heaters to the paraffin array release devices were powered. Due to the interruption of the sequence the data point for V_{oc} is missing on the 7th module and the 8th was not recorded at all. (It wasn't noticed until later that on the first run, 9 November, the last data point on the 8th module was dropped. At that time no spacecraft anomalies were observed.)

After careful study over a number of weeks, JPL determined that - when *this* sequence is running - commands from the Power Distribution Unit (PDU) to the Power Processing Unit (PPU) for thermal control can result in spurious command generation. This software bug was difficult to correct. After substantial analysis of the anomaly and verification of software upgrades in the testbed at JPL, the next SIVPerf has been scheduled for May, 6 months after the last test.

The SIVPerf sequence provides certain types of data the SPeak test cannot: namely, data to the left of peak power on the IV curve (towards short circuit). The short circuit current is of interest as it validates the lens optical efficiency and functions as a monitor for UV or radiation darkening, or outgassing contamination. A comparison of the I_{sc} values for the modules on day 7 and 18 shows no change when corrected for insolation changes due to heliocentric distance. This indicates that there is no significant darkening taking place in the initial weeks on orbit. However, contamination of the lenses from spacecraft (or array) outgassing may have already occurred. Resistance to long term UV and/or radiation darkening cannot be deduced from this limited data, but initial indications are that these effects are small as expected.

The predicted Isc is compared to the flight results in Figure 9. The first point on the graph, "temperature correction," is the product of the modeling to include cell testing done by JPL using a high altitude balloon, optics efficiency, sun distance, temperature coefficients and operating temperature results. The second set of points show the UV darkening and contamination modeled to occur so early in the mission it was determined that it was best carried in the "BOL" prediction. The last set of points show the time-factored degradation results.

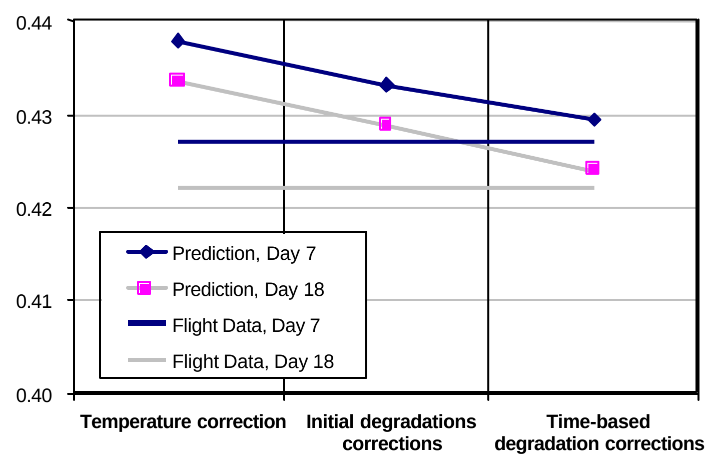

Figure 9. Isc Modeling vs. Flight Module Data

The open circuit voltage is of interest because it can be used as another method, besides the RTD results discussed earlier, to validate the thermal model. Open circuit voltage is reduced linearly with increasing temperature (keeping the intensity constant) in accordance with the voltage coefficient, which was modeled as -5.0 mV/°C per cell. In Table 1, the average values for wings 1 and 2 are scaled by the average ratio of the tap circuit V_{oc} to the array V_{oc} from LAPSS testing, then compared to the predicted values.

Average Module V_{oc}, volts	String Equivalent V_{oc}, volts	Predicted Array V_{oc}, volts	Ratio Flight to Predict
11.55 (Day 7)	114.83	104.8	1.10
11.51 (Day 18)	114.38	105.0	1.09

Table 1. Flight Tap Module V_{oc} vs. Predicted V_{oc}

The flight results are much higher than expected. The prediction was based on LAPSS results and corrected for only three effects: (1) Peak power operating temperature, (2) Temperature rise when under low power draw, and (3) Thermal coefficient for voltage. To match the model to the flight voltage the cell operating temperature would have to be 40 C lower, or the thermal coefficient would have to be 55% lower. Neither option is considered reasonable. The array level voltage varies over the mission as the heliocentric distance varies. This gives a rich data source for voltage study that should be explored before any conclusions are drawn from the aberrantly high module level voltages.

Given the intermittent thrusting over the first 120 days of the mission, 75% of the time the array power draw was only about 15% of capacity. Thus the voltage is near the point of interest: open circuit. A few of the available data points were tabulated and a trendline was fitted as shown in Figure 10.

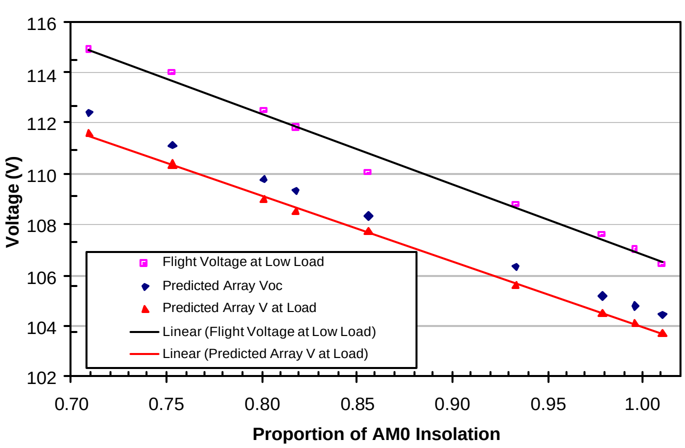

Figure 10. Array Voltage at Low Load vs. Flux

The voltage data is plotted against the flux level since the mission day and the heliocentric distance are both non-linearly related to the light input, but correction factors such as a temperature offset are not. For the values for predicted array voltage at V_{oc} a trendline is not shown because the prediction must still be adjusted to the load point for the fractional power draw at that time.

Rather than use further modeling adjustments to arrive at this value, which adds more modeling uncertainties, flight data was used. As shown by the top line in Figure 11, the trendline for the flight array voltage shows about a 6 volt decrease from zero power draw to 100% of the maximum power output capability. The curve is fit to the trend of voltage from 10 to 50% power, as this neglects the curved ends of the trend that result from mis-matched string V_{oc}'s at low power draw and the rounding of the IV curve knee on the high draw end. This voltage shift includes two simultaneous effects: (1), temperature reduction due to removal of energy from the cell (electrical power) with the consequent increase in cell voltage, and (2), the change in voltage along the IV curve from V_{oc} to the load voltage. If these effects were modeled separately the voltage would rise due to reduced temperature, but given a constant temperature, it would fall in response to the higher power demand.

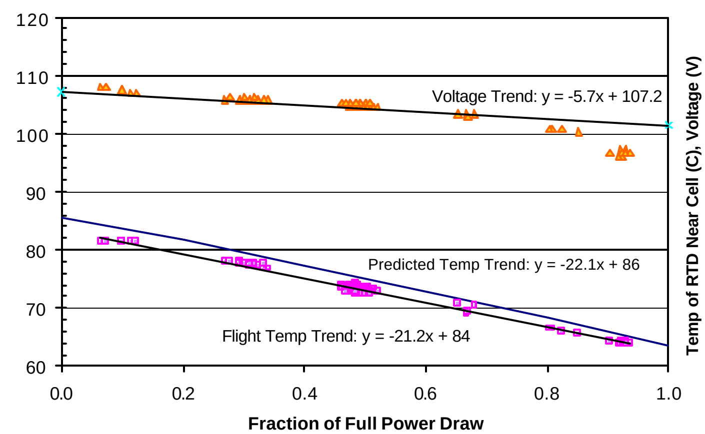

Figure 11. Array Voltage and Temperature vs. Power Draw on Mission Day 33

Scaling each V_{oc} prediction point by the fractional power draw times 5.7 volts produces the lower curve of Figure 10. The result is that the prediction is about 3% lower than the flight data. There are five variables which may be changed in the model to arrive at a better fit: (1) Peak power operating temperature, (2) Temperature rise when under low power draw, (3) Thermal coefficient for voltage, (4) Change in voltage with power draw (flight data curve fit), and (5) Flux level effect on cell voltage.

The first three were discussed earlier in the module-level V_{oc} analysis and the fourth was just reviewed. When the module data was taken, between days 7 and 18, the spacecraft was very near the 1.000 AU distance point. Further into the mission the cell voltage is increasingly affected by flux level. This is the fifth variable. The voltage of the cell is related for flux as follows:

Voltage at Concentration = (V at 1 Sun) + F [ln(flux)],

where the factor "F" for the multi-junction cells on DS1 is believed to be about 50 mV. The flux level on the cell under concentration at 1 AU is 7.14 AM0 suns, so the voltage increase is 0.1 volts, or 5 volts per string.

The variation in this parameter versus AU, and in operating temperature versus AU, and the others listed above (except the fourth which *is* flight based), produce different trends that can be compared to the flight trend to evaluate the fitness of adjusted modeling parameters. To bring the average error to zero, the operating temperature would have to be 13 C lower, or the thermal coefficient would have to be 22 % lower. The former is extremely unlikely as the agreement of the thermal model with the flight RTD data has been shown earlier. The thermal coefficient was established by well-controlled module/lens testing performed by JPL. Cell level testing indicated that the coefficient might be somewhat lower, but more than 10% is not likely. In short, no plausible combination of offsets in these variables nulls both the average error and local error. A slope trend difference always remains. Rather than adopting factors which do not feel right, one must ask if the error isn't in the flight data itself.

The system was calibrated with known power supplies and sizable separate nonlinear corrections were needed for different channels. The lead power engineer at JPL believes "the voltage is reading 2-3 volts high" at these open circuit voltage levels based on observations of many channels over the mission. If the flight data is lowered 2.5 volts the model result is a negligible 0.2 to 0.7% low. Analysis which incorporates data to be accumulated over the next months of the mission may allow the cause of the discrepancies between the observed and predicted voltage to be understood.

The entire IV curve can be obtained during the SIVPerf sequence. The curves for the first module are shown in Figure 12.

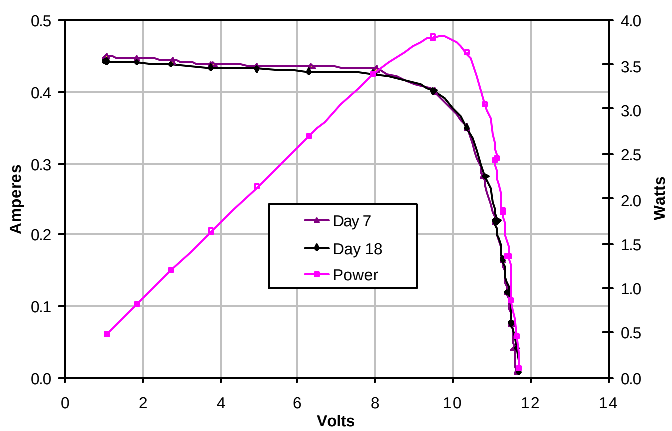

Figure 12. Tap Module Performance - Wing 1, Panel 1

For this particular module, the power output has not fallen although the incident light has dropped 1%. For three others the fill factors were lower than expected and one decreased significantly between days 7 and 18. The obvious question is: If one of eight modules is losing performance, then what is happening at the array level? This question was examined by the SPeak sequence.

<u>SPeak</u>

The first (and only to date) SPeak sequence, on mission day 90, began by incrementally increasing the ion engine power level, stopping at two intermediate points between nominal bus loads and maximum power. This was done to allow intermediate power level data to be recorded and to let the array cool to near the full power operating temperature before moving to the full power load voltage. The last setting was chosen to be about 100 W in excess of the expected maximum power. The battery was relied upon to supply the differential power. The EPS was designed with the capability to utilize the batteries as a buffer to allow maximum thruster output without collapse. If the proper low voltage set point and thruster level are selected, this algorithm allows the solar array to operate at peak power and provides data for array level performance. The SPeak sequence adjusts the set point voltage through a range yielding more data along the performance curve near peak power. The SPeak software will step down the thrust level if the battery discharge exceeds a predetermined level.

During this test run, the load voltage set point was intentionally stepped lower at 0.3 V increments to obtain detailed data. When the array peak power was approached, the increments of voltage resulted in negligible array power output change. Plotting the wing currents against voltage rather than time, yields the more familiar "IV" curve. A detail of the data near the knee is shown in Figure 13.

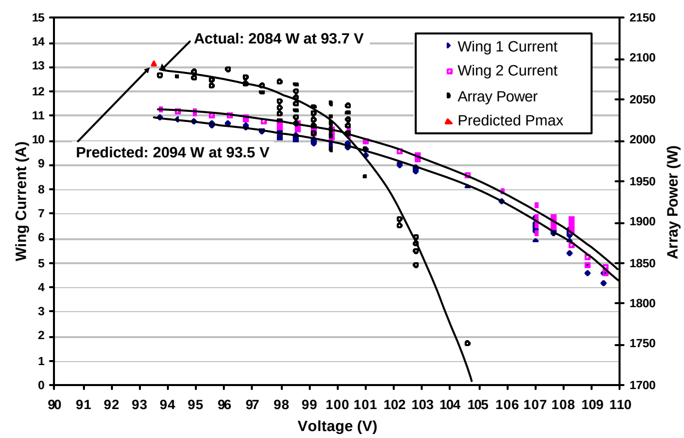

Figure 13. SPeak Data, Array Output at 1.1185 AU

The power output has leveled off to 2084 watts, as the voltage was reduced to the last recorded value of 93.7 V. Flight values from the best fit curve are compared to model predictions in Table 2.

Value	$V_{mp\ (volts)}$	$P_{max\ (watts)}$
Prediction (P)	93.5	2094
Flight Results (FR)	93.7	2084
FR/P Ratio	1.003	0.995

Table 2. SPeak Results Comparison

The excellent agreement between the forecast and the flight results - for the best data set available to date on the mission - is the clearest validation of the SCARLET technology.

CONCLUSION

The performance of SCARLET on Deep Space 1 substantially validated all aspects of the novel structural platform, Fresnel optics, multi-junction cell module performance, and electrical design. The major features of safe stowage through launch, deployment, and sun acquisition were clearly demonstrated on the first day of the mission. Stability of the array system, in particular, the ability to maintain the relatively tight pointing, has been verified over more than six (6) months. The array performance has continued to achieve design specifications without imposing any special requirements on the spacecraft.

A number of detail parameters, such as open circuit voltage, have shown minor deviation from the design predictions. Causes have been proposed, some of which include errors in the data itself, but no array problem is suspected. Continuing acquisition of data throughout the mission is expected to better help identify the cause of these discrepancies. SPeak, for example, has only been performed once. However, it is important to note that none of the discrepancies impact the array capability to provide the required mission power over the mission lifetime. To a certain extent they reflect the unusually high level of array diagnostics that are available.

In fact, given the range of variables in the cells (2 and 3 junction), coverglass (IR reflecting and non-IR reflecting), and lens coating (with antireflecting and without), the present limitations of the data quantity and quality, it is a testimony to the soundness of the SCARLET design and manufacture that the array performance has met the mission needs and that the power output has so closely tracked the nominal forecast.

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Additional mission information may be obtained at: http://nmp.jpl.nasa.gov/ds1/gen/index.