

Early Mission Power Assessment of the Dawn Solar Array

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ABSTRACT

NASA's Discovery Mission Dawn was launched in September 2007. Dawn will be the first to orbit two asteroids on a single voyage. The solar array for the Dawn mission will provide power under greatly varying illumination and temperature conditions. Dawn's ion propulsion system (IPS) will provide the spacecraft with enough thrust to reach Vesta and Ceres and orbit both. The demanding mission would be impossible without ion propulsion -- a mission only to the asteroid Vesta (and not including Ceres) would require a much more massive spacecraft and, a much larger launch vehicle.

Although typical Earth orbiting solar arrays experience changes in power over the mission lifetime due to environmental conditions, these changes are minuscule when compared to the Dawn solar array power change throughout their mission. The array capability at 1AU is of the order of 10.5 kW, and the array capability at 3 AU is estimated at 1.4 kW. Although analysis estimates the power margins to be generous, uncertainty in the calculations may reduce these margins by a factor of 2.

The only way to determine the array capability is to use the full spacecraft load (~ 3.1kW) to move towards the peak power point. At present, the total spacecraft load will not match the full capability of the array for several years. In order to calibrate the array, two 'off-pointing' exercises were performed on the spacecraft, one at 45° and one at 60° 'off-sun'.

INTRODUCTION

Dawn is part of the National Aeronautics and Space Administration's (NASA's) Discovery program of solar system exploration missions. Its mission is to help understand the conditions and process acting when planets were coalescing by exploring the two most massive objects in the main asteroid belt (between Mars and Jupiter). These two bodies, 1 Ceres and 4 Vesta, are believed to be remnants from the formation of the solar system. Ceres and Vesta are quite unlike asteroids visited by other spacecraft. Ceres is so large that it is included in the category of dwarf planets, along with Pluto. Its mean radius is about 475 km. Among the intriguing possibilities for Ceres is that it may have a subsurface ocean of liquid water. Vesta has a mean radius of about 265 km. It appears to be a more evolved body than Ceres. Spectroscopic observations suggest it may have been very hot in the past, perhaps with extensive lava flows across its surface. Comparison of these two protoplanets, through studies with the same set of instruments, is

expected to reveal a great deal about the dawn of the solar system.

Additional background on the project, including the design of the flight system and the mission, can be found at: <http://dawn.jpl.nasa.gov/> and in reference 1.

No spacecraft has ever attempted to orbit a body in the main asteroid belt, and no spacecraft has ever been planned to orbit two targets. Even a mission to orbit only one of Dawn's destinations would not be possible within NASA's constraints with conventional chemical propulsion. The mission to both bodies with a single spacecraft is enabled by solar electric propulsion, implemented on Dawn as an IPS. The planned mission activities are far in excess of the capability of conventional chemical propulsion systems.

The IPS thrust and the specific impulse both depend upon the input power. At its maximum throttle level, the IPS draws 2.5 kW. As the spacecraft recedes from the Sun, the IPS will be throttled down, but to complete the mission, Dawn needs to have the capability to power the IPS and other spacecraft subsystems even in orbit around Ceres, at a heliocentric distance of up to 3 astronomical units (AU). The sizing of the solar arrays was driven by the requirement to provide at least 1.4 kW at that range at the end of the mission, with a design lifetime of 10 years. The solar distance during the mission is shown in Fig. 1

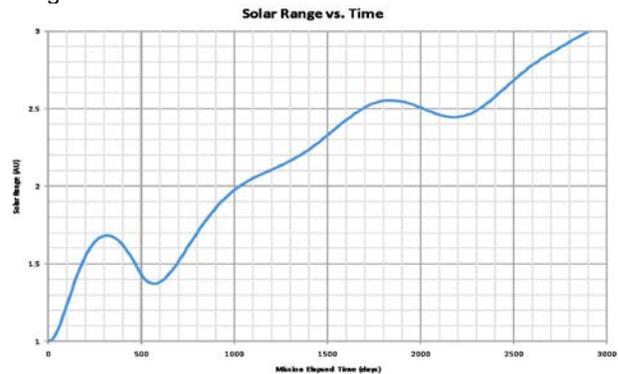


Fig 1. Dawn solar distance vs. mission duration

Unlike missions with conventional propulsion, which predominantly coast, most of the Dawn mission is devoted to IPS thrusting. Indeed, the spacecraft will thrust for more than 70% of its 8-year primary mission. This unique feature of IPS missions strongly couples the design of the trajectory and the mission plan to the detailed performance of the spacecraft. There are many constraints on the design of the trajectory, including the need to spend sufficient time in orbit at Vesta to complete

science observations before departing to reach Ceres within a programmatically determined schedule.

To design a trajectory that can be flown within all the constraints, it is essential to have accurate predictions for power available to the IPS at all times in the mission. The plan for thrusting in the present depends on how effective thrusting is expected to be at all times in the future, in order to guarantee that the spacecraft does not thrust to a position and velocity from which the mission cannot be completed with its subsequent thrusting capability. More generally, because greater power translates to both greater thrust and greater specific impulse, knowing that more power is available allows the design of a trajectory that is more efficient, yielding greater margin for the completion of the mission objectives. This is described in greater detail in [3] and [4].

Erroneously over predicting power available can lead to the design of an ultimately unachievable thrust profile. Significantly under predicting power deprives the mission of the opportunity to convert the superior thrusting capability into valuable technical resources such as longer times for operations at Vesta or greater robustness to any subsystem or system anomalies that interfere with interplanetary thrusting. As a result, the project needs to be able to predict solar array power with high accuracy throughout the mission.

DAWN ELECTRICAL POWER SUBSYSTEM

The Dawn electrical power system (EPS) takes power from the solar arrays and distributes it to the high voltage IPS and the spacecraft low voltage bus. The high voltage bus range is 80V to 140V. The low voltage bus range is 22V to 36V. The power subsystem schematic is shown in Fig. 2.

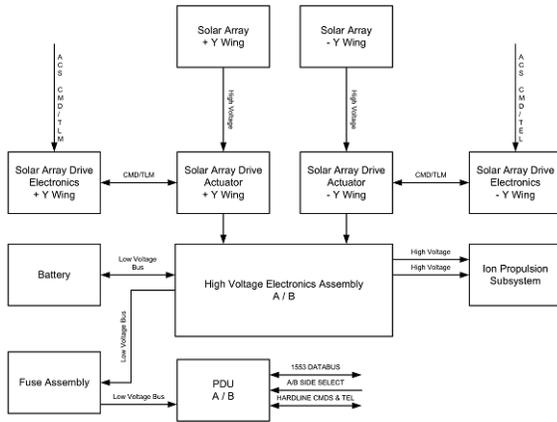


Fig. 2. Dawn EPS Block Diagram (PDU is power distribution unit)

SOLAR ARRAY IN-FLIGHT PERFORMANCE

The solar array consists of two wings of 5 panels each. The panels are populated with Emcore advanced triple-junction (ATJ) solar cells. Each panel is electrically composed of two segments with 14 solar cell strings; each string consists of 41 CIC's (cover interconnect cell) in series. A schematic of the spacecraft is shown in Fig. 3. The array is instrumented with two Isc cells each symmetrically placed one each on the fifth outer panel of each wing. Similarly there are two Voc cells, each symmetrically placed on the fourth outer panel of each wing. There are also four temperature sensors (PRTs) located one each behind the Isc and Voc cells.

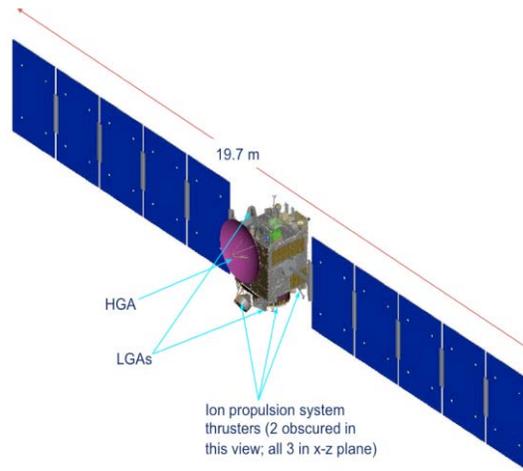


Fig. 3. Dawn spacecraft Flight configuration

Dawn was launched on September 27, 2007. The solar array deployment was nominal and the array has continued to provide power to the spacecraft throughout the mission. The spacecraft has two basic power operating modes, when the spacecraft is using ion propulsion for thrust (i.e. thrusting) and when the spacecraft is coasting. The total array power required when the spacecraft is thrusting at maximum power is ~ 3100 W. Fig. 4 shows the array parameters reflecting a characteristic transition from coast mode to thrust mode. There is a preconditioning period where the total spacecraft load increases to ~ 1000 W followed by the initiation of thrust which then climbs and stabilizes providing a total of ~ 3100 W to the spacecraft.

The maximum power used by the IPS is 2500 W. The array will be capable of generating in excess of 3000 W until the spacecraft is at ~ 2.0 AU, this will not occur until the July 2010 time frame. In the present operations mode, the spacecraft stops thrust on a weekly basis to returned stored data to Earth. The figures below illustrate the response of the solar array parameters to the spacecraft power demand transitions. Figs. 4 and 5 show characteristic array performance before, during and after a transition from low (cruise) to high (thrusting) power. This

transition in Fig. 4 occurred at a heliocentric distance of 1.4 AU. At this distance, the array capability is estimated to be close to 6.0 kW. Since the spacecraft can draw no more than 3.1 kW, the detailed shape of the array I-V curve at higher power remains undefined. The difference in wing currents reflects the differences noted in ground testing.

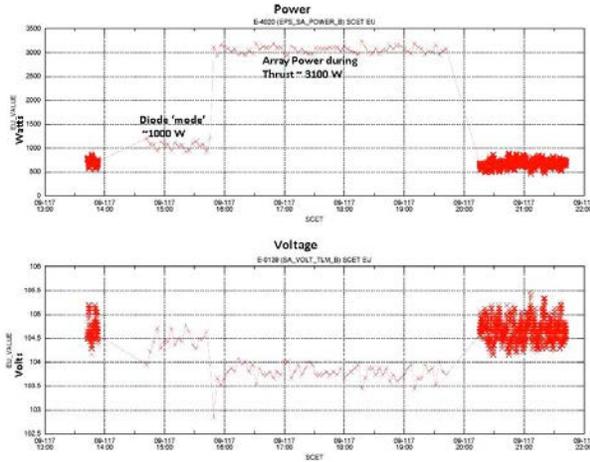


Fig. 4. Power and array voltage performance during transitions from cruise to thrust mode and back.

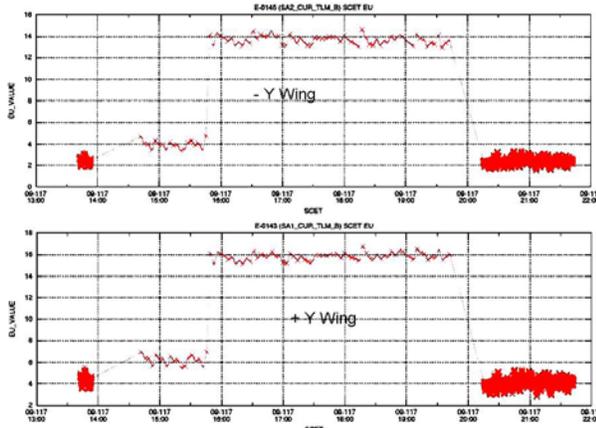


Fig. 5. Wing currents during transitions

The accurate measurement of solar array power levels is usually difficult, especially early on in the mission. There are various reasons for this, most typical being that array performance diagnostics are not normally built into the spacecraft and array designs. The Dawn array is especially difficult to assess early on because of the way in which it operates. Unlike a typical Earth orbiter, the Dawn array will experience wide variations in power and voltage over the mission, approximately a factor of 9 for the array power and up to 75% in operating voltage (as discussed above). In operation all strings of the array are on throughout the mission. String switching is not utilized. In essence, the IPS operates as a peak power tracker. The Dawn array is operated in an unconventional manner compared to most arrays. It operates to the right of

maximum power point rather than the left as is more typical. Although the reasons for this involve stability for the EPS, this creates difficulty in determining the total array capability under reduced power draw. First, this portion of the curve has greater error than the normal "flat" portion. Consequently it is subject to intensity errors (common to all array measurements) and also temperature measurements in that a small voltage difference can lead to a relatively large current change.

Similarly, measurements during the mission will be performed with minimal temperature data as shown above, so that measured currents will not be accurately identified with a precise temperature. Unfortunately for determination of actual peak array power, the tracking occurs to the right of the peak power point, the steep portion of the I-V curve between V_{max} and V_{oc} [Fig. 6]. In this regime, small changes in operating voltage can result in large changes in current. In addition, in this portion of the curve the impact of temperature on voltage is very significant, unlike a system which operates to the short circuit side of the maximum voltage point. As a result a modest change in temperature results in a change in voltage and a large change in current. A further complication for Dawn is that the impedance of each of the array wings is slightly different resulting in a slightly different operating voltage point on each wing. Again, for operation to the left of P_{max} this is of little impact, but in the regime where the Dawn array operates, it is significant. In addition, although low intensity ground test measurements corresponding to operation at solar distances up to 3 AU were performed these were all at a nominal 28C. Although the low intensity measurements were found to account for the majority of LILT (low intensity low temperature) behavior, the low temperature impact was not well characterized. Thus the off pointing tests would also reduce temperatures reducing remaining LILT uncertainties. Coupled with the importance of accurately predicting array power over the mission to fine tune thrusting, this required the use of a very deliberate array test sequence.

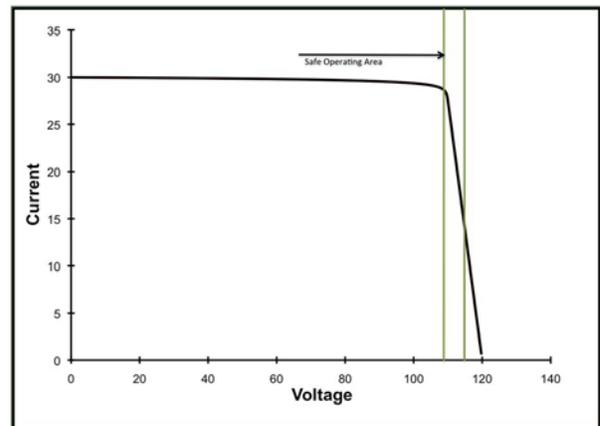


Fig. 6. Dawn array power-voltage curve showing operating range.

Fig. 7 is an illustration of the impact of temperature on power measurement accuracy. It depicts an I-V curve for a high voltage high power array. The lower curve is the same as the upper with 5% reduced current. This could reflect the loss of a number of circuit strings as an example. In the voltage range typical of Dawn, 119 V for example (with Pmax at ~ 108V), detailed examination of the two curves will show ~ 5% current difference (actually slightly lower). If however, the voltage is shifted corresponding to a difference in operating temperature by 2 degrees, the power at the 119V load point, the current will be shifts by ~ +/- 50%. Obviously an unachievably accurate knowledge of the temperature would be required to actually extract the fact that the current had dropped by the much lesser amount of 5%. Since this is not practicable early in the mission at the expected power loads, a test method was developed to allow array operation much closer to the peak power point and much less sensitive to small temperature uncertainties.

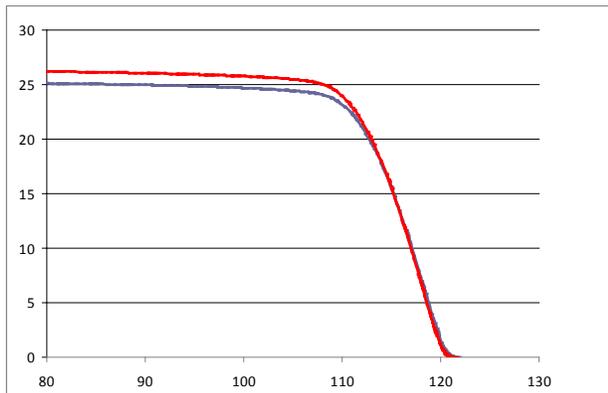


Fig. 7. I-V example showing impact of 5% current difference

Determining the power that will be available throughout the mission, in order to calibrate the power prediction tool remains a critical goal of this mission. Knowing accurately the present value of the total power available (before all EOL degradations occur), and also better knowing the power available in the future, will allow for the optimization of the trajectory and time spent at Vesta and Ceres. To calibrate the power prediction tool, an 'off-pointing' activity on the spacecraft was performed. The activity was designed to 'off-point' the array from the sun normal until the array power was below the total power required from the spacecraft, and then incrementally increase the power demand from cruise to thrust mode, thus determining the peak power available. The activity was performed when the spacecraft was coasting and at 1.6 AU heliocentric range. The array was turned 60° from sun and allowed it to thermally stabilize. This effectively reduced the incident solar intensity on the array to the equivalent of 2.26 AU. Based on ground testing the array power would be expected to fall to

approximately 2.1 KW, well below the maximum power requirement of the full spacecraft including the IPS. After the array had thermally stabilized, thrust was initiated, and the array was monitored as the voltage continued to decrease until it reached the highest sustainable power.

Fig. 8 summarizes the array performance during the 60° 'off-point' activity. The activity is initiated during cruise mode when the array is providing ~ 800 W to 900 W of power to the spacecraft. The array is then commanded 60° off-sun. There is a concurrent gradual increase in power demand to a total of ~ 1000 W due to the conditioning of an ion thruster before thrust. The array voltage responds by initially going to lower voltage to maintain the power demand (array currents not shown) and slowly returning to the steady state value. The total time to reach the 60° off-point position is ~ 3 min. As the array cools down due to the lower intensity, the voltage slowly approaches the steady state value of ~ 118 V, characteristic of the 1000 W load under these conditions. The IPS then ramps up to reach the peak power point. The ramp-up process is performed in ~ 3min. As the power is ramped up, the array voltage responds by moving to lower voltage (climbing the power curve from the right). As the maximum capability of the array is reached, the increase in current as the voltage reduces towards the maximum power voltage point eventually reaches a maximum power value. If this is insufficient to meet the total power requirement (further reduction in voltage no longer brings about an increase in array power) the array 'collapses' and no longer provides power, the IPS is turned off and the voltage goes to Voc ~ 122.5 V (the battery is carrying the load at this time). The spacecraft returns to low power mode, and the array is returned to sun normal. The array is subsequently allowed to thermally equilibrate (not shown).

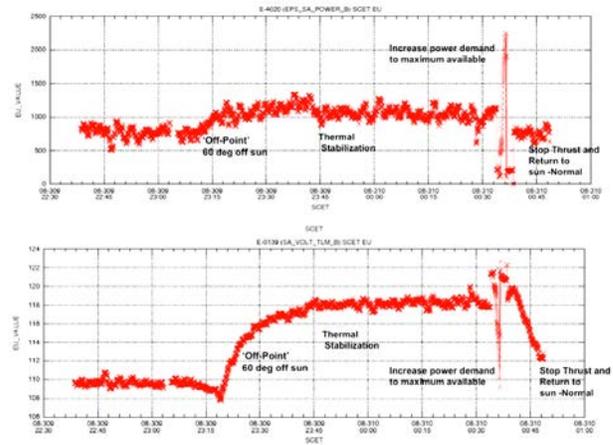


Fig. 8. Solar array power (top) and voltage (bottom) during the 60° 'off-point' activity at 1.6 AU heliocentric range.

When the array performance is considered as the average of the cell population, we observe a good qualitative correlation with the expected performance.

Since there are only four temperature sensors on the outermost panels of each wing, it becomes a challenge to quantitatively correlate the observed performance, reducing but not eliminating power determination uncertainty. Also, each of the 20 array segments will be providing power according to the cell distribution on that segment, the harness length of that segment, and the temperature of that segment. Additional analysis is required to quantitatively obtain the total array capability with a small uncertainty.

CONCLUSION

The Dawn mission is an ambitious mission with very high science payback. It is enabled by the use of ion propulsion. The power level of the array will vary by a factor of ~9 over the course of the mission and accurate knowledge of this will play a large part in determining how much science can be performed at the two asteroid targets. These measurements needed to be done when the actual array performance greatly exceeds the spacecraft power draw. In order to perform accurate array performance measurements, it was necessary to use the spacecraft in an engineering test mode by purposely turning the arrays off sun to predetermined offsets in order to draw full array power. In this way, actual measured power would be matched against predictions to reduce analysis uncertainties, thereby increasing prediction accuracy. Complicating these analyses, the off pointing testing did not lend itself to simple static measurements but needed to evaluate changing temperatures, array voltage, and array power. The off pointing testing of the array has provided valuable information for updating the power prediction model. We expect to perform additional calibration activities in the near term to more fully define the array performance.

ACKNOWLEDGEMENT

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