96261

TOPEX/POSEIDON ELECTRICAL POWER SYSTEM - LESSONS LEARNED

P.R.K. Chetty and R. Richardson
Orbital Sciences Corporation
20301 Century Blvd.
Germantown, MD 20874

Robert Sherwood
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, M/S 264-355
Pasadena, CA 91109

ABSTRACT

The main objective of the TOPEX/Poseidon Spacecraft is to monitor the world's oceans for scientific study of weather and climate prediction, coastal storm warning and maritime safety. The operational conditions of this satellite imposed challenging requirements for the on-board Electrical Power System (EPS). Going through various phases of its development and on-orbit performance verifications, there were certain events and/or circumstances we would have liked to avoid. Some circumstances were avoided with preventative measures, other potentially detrimental events were not. Thus, a number of very valuable lessons were learned which are presented in this paper.

INTRODUCTION

The TOPEX/Poseidon Satellite, herein abbreviated TOPEX (Ocean Topography Experiment), measures the Earth's ocean surface topography (wave heights) from space using radar altimeters. TOPEX was launched on August 10, 1992 into a nominal circular orbit with an altitude of 1334 Km and an inclination of 63.1 degrees.

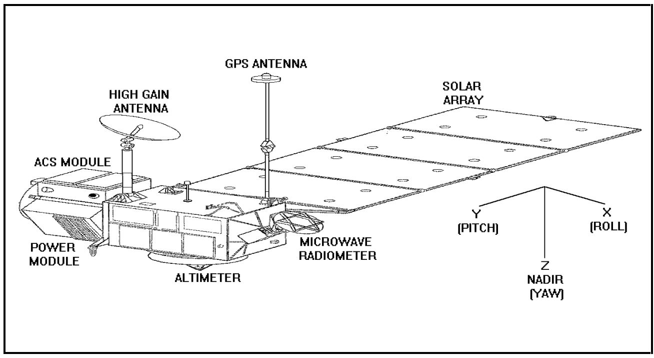

Figure 1. TOPEX/POSEIDON SATELLITE

A diagram of the TOPEX satellite is shown in Figure 1. The satellite's electronics are designed for a three year primary mission. Because of a potential mission extension, the solar array, batteries, and propellant are sized for a five year mission.

Electrical Power Subsystem Overview

A block diagram of the EPS is shown in Figure 2. Solar array power is transferred through the solar array drive assembly via a total of 16 slip rings, eight parallel slip rings for each polarity. The standard power regulator unit (SPRU) serves as the power processing interface between the solar array and the satellite load. Three 50 AH batteries located in the power module supply power whenever the load requirements exceed the SPRU output and during sun occultations. The SPRU contains a pulse width modulated switching regulator whose duty cycle is governed by one of several feedback control loops depending upon the operating mode. In the peak power tracking mode, the SPRU electronically extracts the maximum power from the solar array by operating at its peak power point. All the available power from the solar array that is in excess of the spacecraft load demand is used to charge the batteries. When the batteries are at or near full charge, the SPRU operates in the voltage/temperature control mode in which the SPRU supplies the load current plus the battery taper charge current necessary to maintain the battery at the selected voltage/temperature (V/T) curve. In this mode, since the solar array peak power is not required, the SPRU shifts the solar array operating point towards the open circuit voltage of the I-V curve.

The attitude control subsystem (ACS) yaws the satellite about the Z-axis such that the solar array drive (Y) axis is perpendicular to the sun. The solar array drive serves as the second axis of orientation by rotating the plane of the solar array approximately normal to the sun. When the sun crosses solar panel normal and before the sun incidence angle becomes -10°, the spacecraft is flipped so that the power module is always on the anti-sun side.

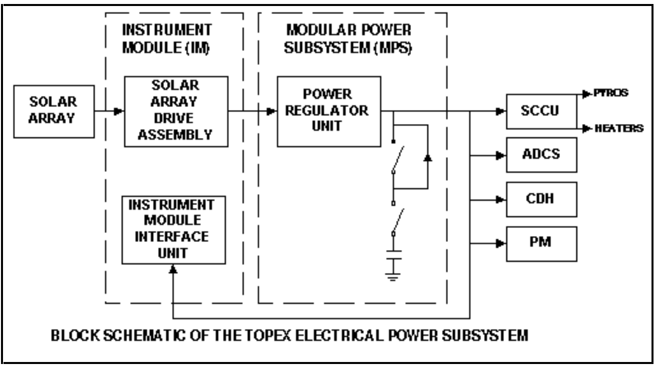

Figure 2. EPS BLOCK DIAGRAM

A detailed description of design, analysis and development of the TOPEX Electrical Power System was presented at IECEC-91 [1]. Although the EPS is currently performing in an excellent manner, certain events and/or circumstances occurred that, in retrospect, we would have preferred to avoid. Thus, the main goal of this paper is to present the lessons learned from this invaluable experience of going through the power system development and operations.

LESSONS LEARNED

a) Solar Array Deployment and ACS Mode-2 Transition

A number of deployment ground tests were conducted which indicated that, depending on the temperature, the time needed for the complete solar array deployment could range anywhere from 5 minutes to 23 minutes.

The ACS was configured to transition to Earth-sensor and gyro control (Mode-2) five minutes after the start of solar array deployment. Since the actual deployment took eight minutes, the ACS transitioned to Mode-2 prior to solar array lockup and started initiating spacecraft yaw control. The ACS operations could have interfered with the solar array deployment, but the solar array had completed most of its deployment within the first 5 minutes and reached its asymptotic region of deployment. It took an additional 3 minutes to complete the last 10% of deployment. The remaining deployment, even though a small amount, was just enough to cause the solar array to lock up.

The lesson that should be learned from this is that the ACS should not have been configured to transition to Mode-2 five minutes after the solar array deployment command was issued. Instead, more time should have been allowed based on realistic ground test and analysis data. A formal interface agreement between the power and ACS subsystems would have eliminated this communication problem.

b) Battery Tender Loving Care Implementation

Due to higher than normal differential half battery voltages observed on-board the Upper Atmosphere Research Satellite, the Gamma Ray Observatory satellite, and other satellites using similar batteries, implementation of certain operational measures for TOPEX were thought to be very appropriate even though the battery related parameters and circumstances were not identical. In view of this, the following operational changes were made to the batteries:

(1) Limit peak charge current to 20 amps maximum per battery, by off-pointing the solar array appropriately;

(2) Limit overcharge by controlling the recharge fraction, (charge/discharge ratio) to 1.05 +/- 0.03 at 6°C, and by using V/T levels 2-4;

(3) Limit taper charge currents during full sunlight periods to less than 200 mA per battery; and

(4) Use LOW current sensor data rather than HIGH current sensor to improve the C/D ratio computational accuracy when the battery currents are equal or lower than 3 amps per battery.

Limiting the peak charge current was accomplished by off-pointing the solar array. The thermal effect of this operation was a decrease in the average maximum array temperature from approximately 65°C to 27°C. This resulted in lower stress on the solar array interconnects due to lower temperature excursion as well as in reduced amount of bowing of the solar panels due to lower front-to-back temperature gradient. Overall, these effects should result in increasing the life of the solar array. However, this could have not dictated lowering the qualification temperature levels of the solar panels as it directly depends on the solar array offset control reliability. In addition, the decision to offset the solar array was not made until shortly before launch, long after the solar arrays had been built and tested.

The lesson learned is that even if there is no requirement to limit the battery peak charge current, as long as the energy balance can be achieved, it is better to off-point the solar array to improve the life of the solar array by lowering its operating temperature. Thermal degradation is the largest solar array degradation factor so lowering it can increase array life significantly.

An additional lesson can be learned from the operational changes made to the TOPEX batteries. The effects of limiting the peak charge current, taper charge and overcharge have generated excellent battery performance to date. Anomalies such as those observed on other NASA spacecraft (GRO, UARS, EUVE) have not been observed on TOPEX. Portions of the TOPEX battery management strategy have been implemented on other missions to extend battery life. Clearly the TOPEX battery management strategy should be adopted for future missions with similar battery operational environments.

c) Solar Panel front-to-back thermal gradient

Figure 3 exhibits the solar panel front-to-back temperature differential for two out of the four panels during the full sunlight season with 0° sun off-pointing. Although this was not the nominal operational position for the solar array during full sun, it was placed in this position for 24 hours during the Perseids meteor shower in order to protect the array from meteoroids. A detailed explanation of this procedure is presented in Section e. The worst case thermal gradient through the solar panel from front-to-back was predicted to be 16° C, assuming that the sun incidence is normal to the solar panels. The front-to-back temperature differentials are computed using the array temperature sensors. During the meteor shower, the maximum front-to-back differential temperature of panel #1 was about 17.5° C compared to the predicted maximum value of 16° C. This is because the prediction was based on an average satellite power consumption of 1043 watts compared to the actual level of 866 watts. This caused more power to be dissipated on the solar array than the design assumption. The solar array is designed to provide, at the end of five years of mission life, about 1043 watts of power to the satellite loads after processing through the SPRU.

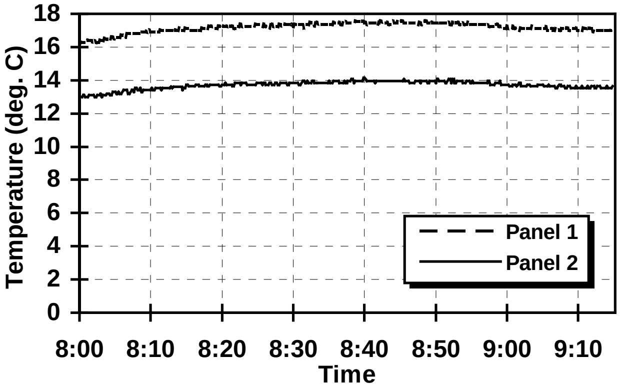

Figure 3. SOLAR ARRAY DIFFERENTIAL TEMPERATURE

The lesson learned here is that it is advisable to run the thermal calculations with more realistic average satellite load power figures and then qualify the solar panels for the corresponding front-to-back thermal gradients.

d) On-Board Computer (OBC) Configuration

Sometime shortly after launch, the command register in the solar array drive remote control unit had inadvertently initialized to zero. In this configuration, if a solar array drive command is issued, the solar array will be driven to "zero degree position" instead of desired position. In fact, a command was issued shortly after launch (8/15/92) to drive the solar array without prior verification that the command register was set properly. Luckily, close monitoring by the engineers involved caught the error when the solar array started rotating in the wrong direction (towards zero degree position.) The problem was corrected 12 minutes later by stopping the drive and properly setting the command register.

Had it not been caught in time, what would have happened? Ground coverage for commanding the TOPEX satellite was limited to four hours per day. Because all the instruments were turned on, any delay in catching the solar array position error would have depleted the battery considerably. The depth of discharge on the battery might have reached 50% which could have initiated safehold.

The lesson here is that whenever open loop or semi-closed loop control is activated for the solar array sun pointing, the contents of the command registers should be verified.

e) Solar Array Orientation During Perseids Meteor Showers and Satellite Safehold

To minimize the damage to the solar array due to increased meteor activity during the Perseids meteor shower, the solar array attitude was changed such that the edge (thickness) of the solar array is along the velocity vector of the three axis stabilized TOPEX spacecraft in orbit. This configuration was used to minimize the frontal area of the solar array to the meteors. Such a solar array flying configuration was maintained for 24 hours in August 1993, 5 hours in August 1994 and 7 hours in August 1995. This solar array configuration effectively eliminates the solar array offset which is used to control the battery peak charge current to less than 20 A. This was not a problem during the August 1993 Perseids meteor shower because the satellite was in full sun operations with no battery use required.

During the 1994 and 1995 Perseids Meteor Shower, the battery peak charge currents while the solar array was offset zero degrees were significantly higher (28 to 29 A) than normal operations (< 20 A). Presumably, the SPRU reached its output current limit (108 A) during these meteor shower activities. The differential voltage on battery-2 and battery-3 was one DN (0.0056 V) higher in peak power tracking than was normally experienced during V/T 4 operations. This level only lasted a few counts and returned to normal immediately after the solar array offset was restored to 54°.

The satellite has seen the same effects on the battery differential voltage during the satellite safehold in November 1995. During this safehold, the solar array was normal to the sun for about 8 days. Fortunately, no other short term effects have been observed on any battery parameters since the solar array offset was returned to its previous offset.

The lesson here is that short periods (1-8 days) of high battery peak charge currents due to removing the solar array offset do not seem to create any negative short term effects on the battery health. The long terms effects of such operations remain to be seen.

f) Solar Array Current Before and After the Yaw Flip

Figure 4 exhibits the solar array current over four orbits starting from two orbits before the yaw flip maneuver. The TOPEX satellite was flying backwards before the yaw flip. In this configuration, the solar array was receiving a considerable amount of Earth albedo. The Earth albedo raises the temperature of the solar array. This higher array temperature lowers the array voltage which results in a higher current at the peak power point. After the yaw flip maneuver, the TOPEX spacecraft was flying forward and the solar array was receiving no Earth albedo (back of array facing out to Space.) The solar array maximum current is about 3.0 amps lower after the yaw flip than before the yaw flip. Please note that this Figure exhibits the solar array current from 1 of the 2 sensors. The total array current is twice what this Figure indicates.

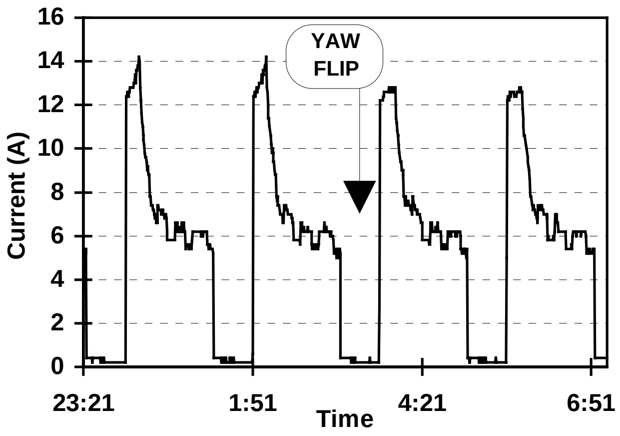

Figure 4. SOLAR ARRAY CURRENT NEAR YAW FLIP

The lesson here is that all planned future satellite orientations need to be understood early in the design phase to determine their effects on the power system. The large current difference of the solar array before and after the yaw flip maneuver changes the battery charge current significantly. Although this has not proven to be a problem on the TOPEX satellite, other satellites that operate closer to their design limits could have battery energy balance problems due to the reduced solar array current.

g) Safehold Mode Initiated V/T Level

During a computer failure initiated satellite safehold, the EPS hardware will initiate an internal safehold mode. Because satellites usually turn off their instrument loads during safehold, this safehold mode lowers the V/T level to protect the batteries from being overcharged. For power systems such as TOPEX operating at V/T levels 2-4, this safehold V/T level is 1. This logic is based on the heritage design experience from multi-mission modular spacecraft. At V/T level 1, the batteries cannot be fully charged. For this reason it was decided to disable the MPS hardware safehold in January 1994. Unfortunately, this does not protect the batteries from the overcharge condition experienced from the high charge currents and low satellite loads of safehold operations. A better strategy would be to lower the V/T level by one level but no lower than V/T level 2. This would shorten the period at which the batteries are at high peak charge currents.

The lesson to be learned is that the MPS safehold circuit is an inadequate design that needs to be updated. Had the MPS safehold been active during the 1995 safehold, the batteries would have experienced a severe discharge (around 50%) before mission operations would have been able to react. Presently, disabling this safehold mode is the only solution to this problem.

h) SPRU Power Cycling During Solar Array Shading

During Orbital Maintenance Maneuver (OMM) #5 in January 1994, the solar array voltage showed several transients when the array current was in the range of 1.5-2.0 A. This behavior is exhibited on Figure 5. During the maneuver, both the battery maximum depth of discharge and the solar array minimum temperature were higher than predicted. After further analysis it was determined that the satellite orientation during the maneuver was causing the solar arrays to be shaded by part of the satellite. This shading caused several effects on both the power and thermal subsystems of the satellite.

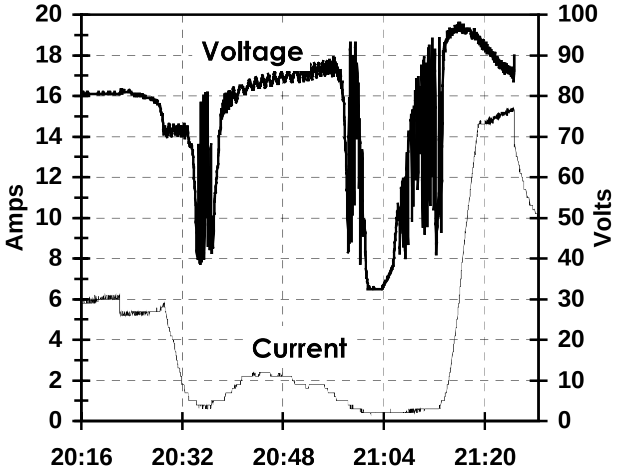

Figure 5. SOLAR ARRAY VOLTAGE & CURRENT DURING OMM-5

During the periods of solar array shading, the array power was already decreased due to the low incidence angle of the satellite position. After an analysis was done to determine the decrease in power that the array shading would cause, it was found that an additional amount of power was being lost. The following are possible causes of the power loss.

(1) Solar panels #1 and #2 become reversed biased when they are shaded by the satellite body. This results in heating of the shaded solar panels because the power generated by the unshaded solar panels is dissipated within the shaded panels.

(2) There is a considerable decrease in solar array efficiency when a portion of the solar array is shaded.

Another reason for the decrease in power was evident in the transients seen in Figure 5. These transients are caused by the SPRU cycling off and on. When the solar array power falls below 225 W, the SPRU no longer has enough power to operate and shuts down. During OMM-5, the SPRU spent a considerable amount of time in this transient power region.

There are several lessons to be learned from this orbital maintenance maneuver:

(1) In terms of satellite loads and battery charging, the solar array minimum power is really the minimum operating power of the power regulator.

(2) Shading of the solar array can cause unpredictable secondary effects on the overall solar array power. Although shading can be eliminated during normal operations by changing the orbit design, shading can be a problem during maneuvers.

(3) Power and thermal prediction programs should be integrated for better accuracy in the predictions.

CONCLUSIONS

The valuable experience of operating the TOPEX satellite has produced many lessons which can be helpful in the design and operation of future missions. A summary list of the most important lessons learned include:

- Offsetting the solar array can increase the array life.
- The TOPEX battery management strategy has increased the battery life considerably.
- Always verify initial values in the storage registers when entering new control modes that could affect the power system.
- High charge currents for short periods (< 1 day) do not have short term effects on battery health.
- Improve the design of the safehold circuit in the MPS.
- Consider the primary and secondary effects of solar array shading when designing maneuvers and predicting the power during maneuvers.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by Orbital Sciences Corporation through an agreement with the National Aeronautics and Space Administration. The authors gratefully acknowledge the contributions of the many individuals at the Jet Propulsion Laboratory and Fairchild Space. Special thanks to Sheldon Rosell, the TOPEX/Poseidon Project Mission Manager at JPL. Thanks also to Dr. Robert Richter, the thermal system analyst on the TOPEX project.

REFERENCES

1. P.R.K. Chetty, L. Roufberg, and E. Costogue; "TOPEX Electrical Power System"; 26th Annual Intersociety Energy Conversion Engineering Conference (IECEC-91); Boston, MA, August 4-9, 1991.