TOPEX/POSEIDON ELECTRICAL POWER SYSTEM - AUTONOMOUS OPERATION

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ABSTRACT
The main objective of the TOPEX/Poseidon Satellite 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). The power system is designed to maintain a certain level of autonomy. This paper presents the autonomous operations planned, their on-orbit performance and how some of the operations were modified as certain unpredictable circumstances were discovered.

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°. 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 were sized for a five year mission.

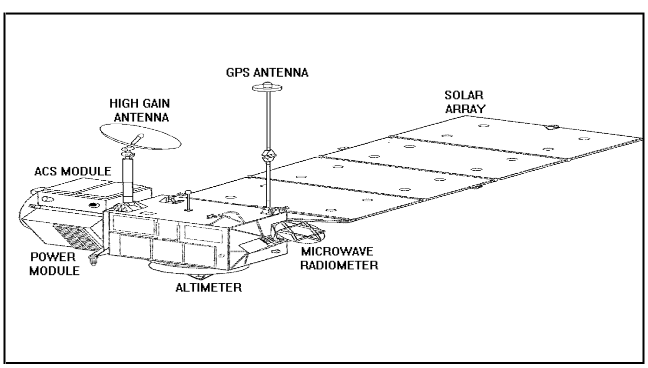

Figure 1. TOPEX/POSEIDON SATELLITE

Electrical Power Subsystem Overview
A block diagram of the Electrical Power Subsystem (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 supply power whenever the load requirements exceed the SPRU output and during sun occultations. The SPRU contains a pulse width modulated switching power stage whose duty cycle is governed by one of several feedback control loops depending upon the operating mode.

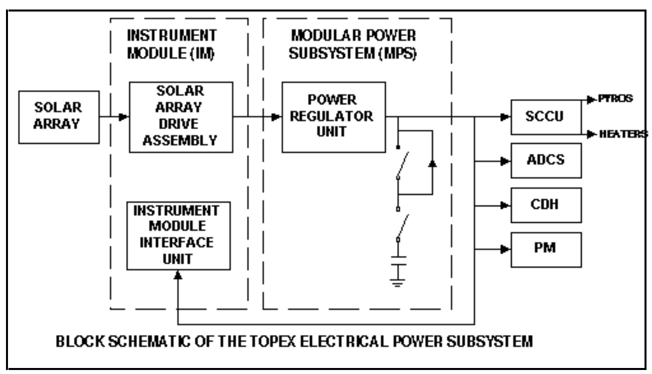

Figure 2. EPS BLOCK DIAGRAM

In the peak power tracking mode, the SPRU electronically extracts the maximum power from the solar array by operating at its peak power point. When the batteries are at or near full charge, the SPRU operates in the voltage/temperature (V/T) control mode in which it supplies the load current plus the battery taper charge current necessary to maintain the battery at the selected 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 yaws the satellite about the nadir axis such that the solar array drive 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 sun crosses solar panel normal and before sun incidence becomes -10°, the satellite is flipped so that the power module is always on the anti-sun side.

A detailed description of design, analysis and development of the TOPEX Electrical Power System was presented at IECEC-91 [1,2]. For a detailed description of the TOPEX power system performance, please see IECEC-96 TOPEX Power System Performance (session 50). The main goal of this paper is to present the pre-launch plans for autonomous operations, their on-orbit performance and how some of the operations were modified as certain unpredictable circumstances were discovered.

AUTONOMOUS OPERATION

The Power Subsystem is designed to maintain certain level of autonomy which is achieved by incorporation of appropriate redundancy and the use of Power Monitor (PMON) and Telemetry Monitor (TMON) software functions. Incorporation of automation reduces the life cycle costs, extends the on-orbit operational life, and results in improved system performance.

Description of PMON Computer Program

The purpose of the PMON computer program is to provide (via telemetry) a real time assessment of power subsystem orbital energy balance and battery state of charge (SOC). Parameters, used in the energy balance and SOC computations are: a) Initial battery SOC at PMON start-up; b) battery charge efficiencies; and c) telemetry offset for zero battery current. The values of these parameters can be modified at a later time to reflect aging of the batteries. The PMON computer program continuously computes and formats the following items for telemetry: (a) accumulated solar array energy and load bus energy; (b) SOC for each battery; c) time since last battery discharge; d) time into satellite day; and e) time duration at least one battery was at full SOC.

The PMON also captures and formats the following parameters for telemetry once per power orbit: a) accumulated solar array energy and load bus energy at end of day; b) battery SOC at end of day (end of charge cycle) and end of night (end of discharge cycle); c) load bus voltage at end of night; d) battery coulombic discharge and net coulombic charge at end of day; and e) time duration batteries were at full SOC at end of day. A power orbit begins when the satellite is occulted by the Earth (and the batteries begin a discharge) and ends at the end of the charge cycle.

The on-board calculations of the PMON program are used by the fault protection software TMON. Because TOPEX does not have 24 hour telemetry coverage, several hours can elapse between data downlinks. If these computations were processed by the ground software, the satellite would not be adequately protected from power emergencies. For example, several hours could elapse before the battery SOC could be calculated by ground personnel. This could be too late to react to an emergency caused by a failure on the spacecraft. The PMON calculations enable the fault protection software to autonomously check the EPS.

Description of TMON Computer Program

The TMON Computer Program is really a set of functions called groups. Each of the TMON groups monitors certain telemetry (TM) parameters each minute and makes a decision according to preprogrammed algorithm. The algorithms are selected to improve the performance of the power system. For ease of explanation, certain TMONs are grouped together and are described below.

Safehold Battery Overcharge Protection:
If the ACS software has initiated safehold and the satellite is past 20 minutes into satellite day then command V/T level 4.
If the ACS software has initiated safehold and the satellite is past 4 minutes into earth occultation then command V/T level 1.

These 2 groups are used to control battery overcharge during periods of safehold. During TOPEX safehold, the solar array is turned normal to the sun, which results in battery charge currents of ~30A. The charge level during full sun periods is normally maintained at V/T level 2.

Anomalous Behavior:

On August 6, 1993, the satellite entered safehold during a full sun period and the first group commanded the SPRU to V/T level 4.

Analysis

It was clear that these TMON groups were really only addressing safehold periods where the charge level was V/T 4 before entering safehold. Another problem with these groups is that they only shortened the time at the high charge currents without eliminating them.

Solution/Resolution

The short term solution was to disable the first group during periods of full sun. The permanent solution was to disable these TMON groups and add 3 new TMON groups to take their place. The 3 new groups are described below.

Modification

The first new TMON group commands the SPRU to V/T level 2 if the satellite daytime counter is between 36 - 37 hours and not already in V/T level 2. This group ensures that the satellite will always be in V/T level 2 while in full sun. Normally the SPRU is commanded to V/T level 2 after 24-36 hours of full sun operation. If the satellite is not in V/T level 2 after 36 hours, then some problem must have occurred. The 37 hours check was included so this group would not interfere with the normal commanding of V/T level 3 at the end of the full sun period.

The next 2 groups that were added are similar to the Safehold Battery Overcharge groups described above except that they use the constant current charging mode of the SPRU. The first group commands the SPRU to constant current mode 3 (1 A/battery) after 4 minutes of safehold night. If the SPRU is in constant current mode, the second group commands the SPRU to the former V/T mode after 15 minutes of satellite day. Note that the first group will not meet limit conditions during full sun because of the check for constant current mode. The second group will also work while using V/T level 3 because it changes back to the former V/T level instead of a preset V/T level as in the group it replaces. The time was changed from 20 minutes in the previous group to 15 minutes in the new group because of solar array degradation. In fact, this time will have to be updated every 2 years throughout the mission to compensate for array degradation. Eventually, there will be no need for these groups as the solar array power will degrade to a level at which the battery charge current will be less than 20 A.

Current Mode to V/T Mode:
If SPRU is in current mode, then command to V/T mode.

The power system has a provision to trickle charge the batteries at one of the three constant current levels (0.75A, 1.5A, 3.0A). This mode of operation was planned to be used in a case where the V/T mode of operation fails to reduce the taper charge current to sufficiently low charge levels in the range of C/50 to C/200. The V/T level circuit redundancy was incorporated and lower taper charge current levels can be accomplished by lowering the V/T level. Hence, the use of constant current charge mode was not anticipated during the TOPEX mission.

If the SPRU is commanded into constant current charge mode (CCCM) and is not able to come out of CCCM due to a failure, then the batteries cannot be charged. Hence, shortly after launch it was decided not to operate the SPRU in CCCM. Due to the fact that TOPEX does not have 24 hour uplink/downlink, the emphasis was placed on more autonomous operation. Thus, if the SPRU goes into CCCM for whatever reason, this TMON commands the SPRU back to V/T mode.

Although a SPRU failure during CCCM could end the mission, the probability of this failure is very low based on history of the SPRU on other satellites. As explained in the previous section, it was determined that CCCM could be beneficial to the batteries by eliminating the high charge currents experienced at the beginning of an orbit during safehold. Obviously, this TMON group prevents the use of CCCM. For this reason, the TMON group was disabled.

Battery Low SOC:
If SOC for any battery < 50%, command loads off-line.

The minimum battery state of charge (SOC) experienced during normal operations is 88%. If the state of charge of any battery falls below 50%, this TMON group powers off the non-essential loads (experiments, etc.) which will result in more time to correct the problem. The conditions for this TMON group have never been met on the TOPEX satellite but this group is considered one of most important fault protection safeguards on board the satellite.

Battery Failure:
If the half battery differential voltage >.5V and battery charging is enabled or any battery temperature is greater than 28°C, then disable battery charging.

Each battery has dedicated circuitry to measure half battery differential voltage. This is the difference in voltage between top half of the battery (cells 1 through 11) voltage and bottom half of the battery (cells 12 through 22) voltage. All cells in a battery and all three batteries experience the same environmental conditions using a closed loop thermal control system (consisting of heaters, heat-pipes, etc.). This system keeps all three batteries within specified temperatures. The maximum temperature difference between batteries is limited to 5°C and the difference in temperature within a battery in any plane parallel to the baseplate is limited to 3°C. Under these conditions, the half battery differential voltage at beginning of life should not exceeded 50 millivolts.

Battery performance degrades with higher operating temperatures, so the thermal control system maintains the temperature of the batteries within the boundary of 0°C and 20°C to obtain optimum performance. However, if the differential voltage exceeds 0.5V or the temperature of the battery goes higher than 28°C, then that battery is prevented from further charging. On-board logic circuitry allows removal of only two batteries from the unregulated bus. Under these conditions, these batteries can still be discharged through isolation diodes. Thus loads are not deprived of power, but charging and thereby over heating of the batteries is prevented.

Because the battery differential voltage has never exceeded 60 mV and the battery temperature has never exceeded 9°C, these 3 groups (one for each battery) have not met their activation conditions. It is possible that with normal battery degradation that these groups could activate in the future.

Subsystem Current Too High:
Determine if any of 4 subsystems (Command & Data Handling Subsystem, Instrument Module, Attitude Control Subsystem and Propulsion Subsystem) has exceeded 130% of expected power demand and then an alarm is sent to mission operations for ground resolution.

If the load demand exceeds 130%, then energy balancing might become a problem. This also may indicate that the subsystem drawing excess power may have a problem that needs to be resolved. Thus, whenever, any subsystem draws in excess of 130% of its normal operating power, then an alarm is sent to mission operations. The activation conditions for this group have never been satisfied.

Battery Temperature:
If any battery temperature > 28° C, then send an alarm to mission operations.

If the temperature of the battery exceeds 28°C (which indicates a problem), then that battery is prevented from further charging by these TMON groups and an alarm is sent to mission operations. As mentioned earlier, the battery temperature has not exceeded 9° C so this group has never activated.

Battery Discharge in Day:
If the satellite is at least 5 minutes into day and any battery is discharging, then shed the loads.

Since the solar array output power capability is greater than 2000 watts, and the specified power module peak output load power requirement is 1200 watts for 10 minutes, the batteries should never be called upon to provide power during orbital day time. Some scenarios which can result in battery discharge during daytime are as follows: a) Load demand is higher than 2000 watts; b) Improper orientation of the solar array towards the sun results in low solar array output; and c) SPRU circuitry fails or malfunctions. Failure or malfunction of the SPRU is checked and cleared by a set of five TMON groups described in the following section.) Orbital day is predicted by the PMON by monitoring when the solar array voltage is greater than 45 volts. However, if the problem is not cleared within five minutes then the discharge of the batteries is reduced by shedding the switchable loads by this TMON group.

Anomalous Behavior:

A few days before the start of the eclipse season, this TMON group was enabled for checking and commanding. On day 242 (August 29, 1992), this TMON group sensed an out of limit condition and initiated a load shed relative time sequence (RTS) which shut down the NASA Altimeter.

Analysis

Due to a long penumbra duration, the level on the two solar array current sensors dropped below 2 amps, thereby requiring the batteries to share the load demand. Consequently, the batteries started discharging. During this time the solar array voltage dipped but did not drop below 40 volts (decreasing from about 90V to about 62.5V). Therefore, the TDAY counter read the previous orbits' value (the TDAY counter read more than 150.186 minutes) and did not get reset. All the conditions for this TMON group were met so the TMON software issued a load shed RTS command that shut down the Payloads.

Solution/Resolution

Duration of the penumbra varies as a function of variation in beta-prime angle. In the case of the TOPEX Satellite, beta-prime angle varies from 0° to about 75°. The TOPEX Satellite experiences full sun at beta-prime angle greater than 58°. Thus, in the neighborhood of 58°, the penumbra lasts longer. As the beta-prime angle decreases the penumbra duration decreases.

Penumbra duration is measured as follows: The time at which the solar array voltage starts decreasing is defined as "Penumbra Starting" and the time at which the solar array voltage decreases to lower than 40 volts is defined as "Penumbra Ending" (and start of Umbra.) Thus, depending upon the load demand and the solar array output capability, the start of the battery discharge may or may not occur at the same time as the start of the solar array voltage decrease. Thus, the measurement of battery discharge duration before TDAY reset gives approximate penumbra duration. This data is presented for DOY 1992/242 in Table 1. From this table, one can see that if this TMON group is disabled while the beta-prime angle is between 51° and 58°, then the interaction with long duration penumbra can be avoided. The beta-prime angle changes from 51° to 58° in about 3 days.

In addition to the problems with the long duration penumbra, the limits for this TMON group can be exceeded during a orbital maintenance maneuver or a lunar-solar eclipse. For this reason, this TMON group has been temporarily disabled during solar eclipses.

Eclipse Start Time	**Duration for which batteries discharged before TDAY is reset**	**Comments**
03:43:25	0 min. [TDAY did not reset]	Solar array voltage dipped slightly [from 90 V to 74 V] and batteries discharged (about < 1 amp) for about 10 seconds.
05:36:53	About 4 min. [TDAY did not reset]	Solar array voltage and current dipped slightly [from 90 V to 62 V and 6 A to 1 A each], and batteries discharged (> 2 amps) for about 4 minutes.
07:26:11	About 47-73 sec.	3.3 minutes eclipse per PMON; Beta prime =< 57°
09:20:02	About 49 sec.	4.9 minutes eclipse per PMON; Beta prime =< 56°
11:11:47	About 33 sec.	6 minutes eclipse per PMON; Beta prime =< 56°

Table 1. TDAY ERROR FROM DOY 1992/242

Modification

This TMON group was modified to include the exclusion of beta-prime angle in between 51° and 58°. Also, TDAY exclusion period shall be changed to "119 minutes to 130 minutes" [earlier it was 119 minutes to 150 minutes.]

V/T Control and PPT Circuit Fault Isolation:
If the solar array voltage is > 45V and the solar array current < 4A, inhibit the following in order: battery V/T control 1-3, primary peak power tracker (PPT).

These 5 TMON groups work together to clear an apparent failure in the SPRU. They are activated in sequence, one after another, when the solar array voltage is greater than 45 volts (indicating that the satellite is in orbital day and SPRU should be working) and the total solar array current is less than 4 amperes. Under these conditions, substantially less power than expected for normal operation is being delivered to the loads and charging of the batteries. The set of five TMON groups inhibit "constant current charge mode (secondary)" and one of the following redundant circuits at a time: Peak Power Tracker-2, battery #1 V/T control circuitry, battery #2 V/T control circuitry, and battery #3 V/T control circuitry. Failure of any one of these circuits shall isolate itself without affecting the good circuit. However, if one of these circuits degraded in such a way as to impair the operation of the good circuit, it can result in limiting the SPRU to low power operation.

Assume that the SPRU is configured for normal operation, i.e., in V/T charge control mode with three battery V/T control circuits operating and with both peak power trackers in operation. If the solar array voltage is greater than 45V and current is less than 4A, then the first group reconfigures the SPRU by inhibiting the battery #1 V/T control circuitry and CCCM (secondary). If one or both of the battery #1 V/T control circuitry and constant current charge mode (primary) inhibit circuit have failed, then the fault will be cleared and this group stops there and informs mission operations that such SPRU reconfiguration was accomplished. However, if these circuits did not cause the problem, then the conditions that caused the problem will still be present. Now the second group restores the operation of the battery #1 V/T control circuitry and inhibits the operation of the battery #2 V/T control circuitry. The other TMONs perform in a similar way checking each batteries' V/T circuits and both peak power tracker circuits.

Anomalous Behavior:

These 5 groups were disabled for checking and commanding post launch because during ascent and solar array deployment, these TMON groups might misinterpret intermittent sunlight incidence on the folded solar array as a day-night or night-day transition. A few days before the start of the eclipse season, the first group was enabled for checking and commanding. On day 242 (August 29, 1992), this TMON group sensed an out of limit condition and initiated a load shed RTS command which shut down the NASA Altimeter.

Analysis

Similar to the previous TMON group, a long penumbra duration caused the solar array voltage to be greater than 45 volts while the solar array current sensors were reading less than 1 amp each. This condition caused the batteries to discharge while in the penumbra region, activating this TMON group.

Solution/Resolution

Just like the previous TMON group, this set of TMON groups can be disabled from its operation while the beta-prime angle is in between 51° and 58°, then the interaction with longer penumbra duration can be avoided.

Modification

This group was modified to include the exclusion of beta-prime angle in between 51° and 58°.

Battery Over-Voltage Check:
If bus voltage > 32.6V and V/T level < 4 then change to V/T level 4.

Although it was decided to use V/T level 4 during the initial phase of the mission, it may later be changed to a higher V/T level depending upon the normal degradation of the battery. Battery over-voltage protection is accomplished by this TMON group in the event of a V/T Circuit failure. If the selected V/T level less than 4 and if the battery voltage is > 32.6V, then a failure of the pre-selected V/T level is assumed and V/T level 4 is commanded. This TMON group has never been activated.

Battery Under-Voltage:
If battery voltage < 24.0 for any battery, enable load shed and inhibit load turn-on sequences.
If battery voltage < 26.0 for any battery, then send an alarm to mission operations for resolution.

During the first two years of the mission, the battery voltage was not expected to go below 26 volts. In addition, the battery voltage was not expected go below 24 volts by the end of the five year mission. This prediction is based on proper thermal control of the battery, loads not exceeding specification limits, and other operating conditions. However, if the conditions are such that the batteries are discharged to less than 26 volts, then the ground personnel should take proper action to prevent continuation of such a situation. Thus an alarm is sent by this TMON group when the battery voltage is < 26 volts to inform mission operations that ground resolution is required. However, if the ground did not take any action and if the battery voltage reaches < 24 V, then all the switchable loads would be shed. This is accomplished by the second group.

After 3.75 years of cycle life, the TOPEX minimum battery voltage has degraded to 26.36 V. The second TMON group (26.0 V) will probably have to be changed within the next year to account for normal battery degradation.

CONCLUSIONS

Previous sections presented detailed descriptions of autonomy functions incorporated into the EPS. These functions are performing in an excellent manner in spite of continuous evolution of some of them due to unpredicted circumstances which forced engineers to reevaluate the assumptions made before launch.

Through the use of the PMON and TMON software functions, the TOPEX power subsystem has been able to maintain a successful mission with minimal degradation. The current predictions for battery and solar array life exceed the five year mission goal. The close monitoring of the TMON software has certainly contributed to this success.

ACKNOWLEDGMENTS

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