TOPEX/Poseidon Radiation Issues: Displacement Damage in Optocouplers

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Summarv

The TOPEX/Poseidon satellite, a joint French (CNES) – United States (NASA) project, was launched in 1992 in order to observe and measure the Earth's oceans from space and improve our understanding of ocean circulation and its effect on global climate. The satellite, at an orbit of 1336 km altitude and 66° inclination, has instruments and sensors on-bored with unprecedented accuracy. These include a dual frequency altimeter, a microwave radiometer, a laser retroreflector array, a Doppler tracking receiver and a global positioning system receiver. This highly successful program has completed its three year primary mission, and is now performing its secondary phase. Some of the important results achieved during the primary mission include: important development and validation of ocean circulation models, discovery of the effects of the tropical oceans on the mid- and high-latitude oceans via Kelvin and Rossby waves, demonstration of the first operational ocean circulation forecast system in the open ocean, discovery of a new class of large-scale intraseasonal oscillations of the ocean at mid and high latitudes, and demonstration of the utility of tracking ocean eddies and their effects on offshore operations and ecosystems.

During the four plus years that TOPEX/Poseidon (T/P) has been in orbit it has experienced a number of anomalies and failures that are the result of the radiation environment in which it flies. Some of these events are likely caused by ionized single particle strikes on sensitive circuit nodes. Single-event upsets (SEUs) of several sensitive components had been anticipated, are logged as they occur, and have been mapped at the latitude and longitude of occurrence. Other single event effects (SEES) experienced by the spacecraft were unanticipated including transients in the earth sensor electronics caused by proton reactions. An unanticipated SEU-induced safehold from an upset of a bit in a key control register also occurred. Additionally, spacecraft charging has been blamed for loss of some multiplexed temperature sensors as well as a recent problem with solar array pointing. In this paper, we focus on the radiation-induced effects that the spacecraft is experiencing due to continuing exposure to electrons and protons. Typically, this would imply an emphasis on total ionizing dose (TID) effects, but we will direct our attention to permanent displacement darnage effects. These effects are becoming increasingly important as high-precision, unhardened linear bipolar parts are finding increased usage in space systems The work described in this paper involved two major tasks: the effort to define and quantify the radiation environment actually experienced by the spacecraft in the absence of dosimeters in the on-board instrumentation, and the application of this environmental information, along with specific ground-bawd test data, to failures of optocouplers used in several key circuits on TIP.

T/P uses 4N49 optocouplers as part of the thruster firing subsystem, as well as in heater and valve actuation circuits. Telemetry data indicates that several of the 4N49 devices in the thruster subsystem stopped functioning after approximately two years of operation, and, as we will demonstrate, these failures appear to be consistent with expected degradation from radiation during that time period. There are two different circuit applications of the 4N49 devices in each thruster circuit, and the only failures that have been observed have been in the application that requires a relatively high current-transfer ratio in combination with a low LED drive current.

Operation of the thrusters is only required at specific times in the T/P mission, and for this reason, as shown in Table 1 below, no systematic data are available about the exact period when failures first recurred in the circuit applications of the 4N49. There were a total of 16 thruster/pairs on the mission, but two of these were never fired. The remaining 14 all worked between 29 and 35 days after launch. However, 10 of these 14 pairs were never used after day 35, and thus no information is available about their operational status after that time. The remaining four pairs were used at the times shown in Table 1. Thruster pairs A4 and C4 were activated several times, and therefore it is possible to estimate the point in the mission where they failed with far more accuracy than for thruster pairs A2 and C3. All four thrusters in the set { A4, C4 } still worked satisfactorily after 647 days, but three of the

four thrusters in that set failed after 786 days. The fourth thruster in (A4, C4) worked through day 1014, but failed at 1252 days, which was the next time that these thrusters were activated. Thus, three of the thrusters in { A4, C4) failed between days 647 and 786. The fourth member of {A4, C4) failed between days 1014 and 1252. The failure points can then be estimated as 1.96 $\pm$ 0.19 years for the first three thrusters, and 3.1 $\pm$0.33 years for the fourth thruster. The four thrusters in set (A2, C3) worked satisfactorily after 35 days, but were not used until day 1252 at which point all four had failed. Thus, the time at which these four thrusters failed cannot be determine very well. Even though we do not know the precise distribution of failures among the eight thrusters, the fact that all eight had failed when they were used at day 1252 is important, because it suggests that the majority of devices in a larger population will fail by that time.

Table 1. History of thruster use and operational failures of optocouplers on TOPEX/Poseidon

	Days after Launch										
Thruster	23	35	63	133	231	360	538	647	786	1014	1252
A2-A	ok	ok	--	--	--	--	--	--	--	--	**F**
A2-B	ok	ok	--	--	--	--	--	--	--	--	**F**
C3-A	ok	ok	--	--	--	--	--	--	--		**F**
C3-B	ok	ok	--	--	--	--	--	--	--	--	**F**
A4-A	--	ok	ok	ok	ok	ok	ok	ok	**F**	**F**	**F**
A4-B	--	ok	ok	ok	ok	ok	ok	ok	**F**	**F**	**F**
C4-A	--	ok	ok	ok	ok	ok	ok	ok	ok	ok	**F**
C4-B	--	ok	ok	ok	ok	ok	ok	ok	**F**	**F**	**F**

Notes:
(1) Sixteen thruster pairs were fielded on TOPEX.
(2) Two were never used; the other 14 were all operational early in the mission (= day 35)
(3) After day 35, only the 4 pairs above were activated. Thus, there are no data after day 35 for 10 of the 14 pairs that were used early in the mission.
(4) Dashes in the above table indicate that the thruster was not used at that particular time.
(5) Failures have only been observed in the "Thruster Status" application, not in the "Thruster Driver" circuit. Thus, all thrusters are still operational even though the status logic does not function properly.

In order to explain the observed optocoupler failures on T/P, a laboratory radiation effects investigation of optocouplers similar to those used on T/P (4N49) was initiated. Although optocouplers have been used in aerospace applications for many years, there is a great deal of confusion about their radiation degradation. Some types of optocouplers have been tested to radiation levels above 100 krad(Si) by exposure to Co^{60} gamma rays with only slight degradation, and these results, some of which are contained in archival data bases, have frequently been used to argue that optocouplers are relatively immune to radiation damage.

Much of the confusion arises because optocouplers can have widely differing structures with correspondingly significant differences in response to radiation. Depending on its structure, the LED emitter in the optocoupler can be quite sensitive to displacement damage caused by protons or neutrons. The same can be said for the detector portion of the coupler: if the detector is a phototransistor it can be sensitive to displacement darnage, in contrast to a ***pin*** photodiode which has significantly less sensitivity to displacement effects. Susceptibility to ionization effects for both the emitter and detector can vary with the nature of surface layers and the presence of oxides and follow-on devices on the same chip as the detector.

Recent work has shown that some types of optocouplers, including the 4N49 used on T/P, are very sensiti ve to space radiation [1]. Although ionization effects can sometimes be significant, far more degradation occurs when these devices are irradiated with protons because of displacement damage in the light-emitting diodes and phototransistors. Not all LEDs are strongly affected by displacement damage, but the 4N49 employs an amphoterically Si doped LED, which is sensitive to displacement damage effects [2]. Other types of optocouplers (such as the 6N-series manufactured by Hewlett-Packard) use a different LED technology, which does not exhibit the sensitivity to proton displacement darnage that is characteristic of amphoterically Si doped LEDs. In addition, the 4N49 also uses phototransistors whose bipolar gain is sensitive to displacement damage, which serves to compound the damage effects on the 4N49 optocoupler.

In order to confirm the sensitivity to displacement damage of the 4N49 optocouplers, devices from two manufacturers were irradiated using Co^{60} gamma rays, which produce only very small amounts of displacement damage, and protons of various energies. Degradation of current transfer ratio (CTR) was relatively minor for Co^{60} exposure, but as shown in Figure 1 for 200 MeV proton irradiation, the CTR degrades rapidly with proton fluence for the same equivalent dose ranges as used in the Co^{60} exposure. Note also that degradation of CTR is only weakly dependent on drive current when the drive current is low, but the degradation is significantly less when the LED is heavily overdriven. The high and low current conditions in Figure 1 correspond to the conditions on TOPEX/Poseidon. These results and others will be presented in detail in the full paper.

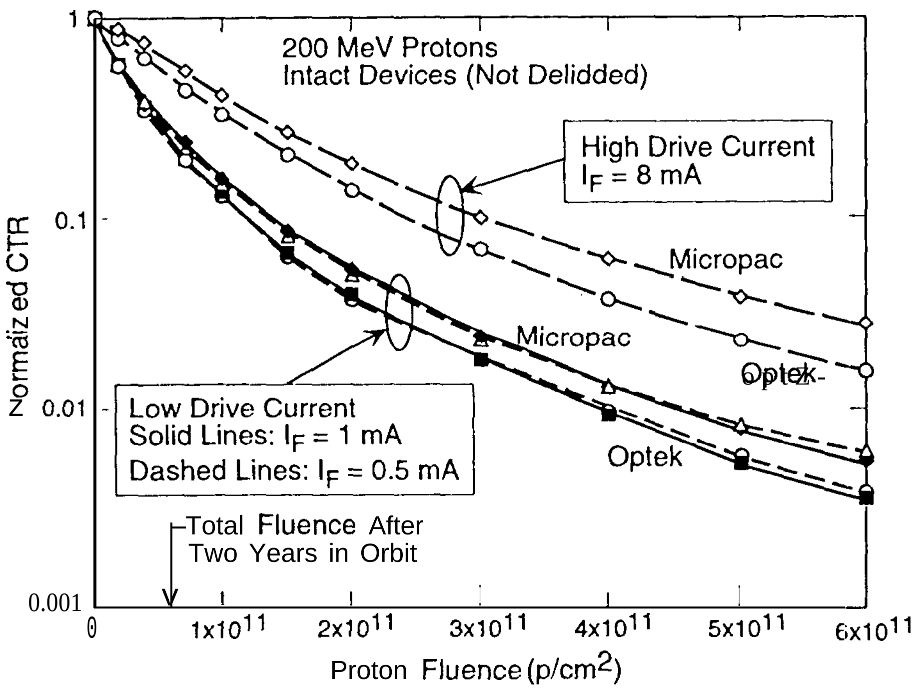

Figure 1. Degradation of 4N49 Optocouplers after irradiation with 200 MeV protons.

Having determined the degradation characteristics of the T/P optocouplers in laboratory proton irradiations, the next step is to determine as closely as possible the actual proton doses at which the failures occurred during the T/P mission. Unfortunately, there are no radiation dosimeters or measuring instruments on-board T/P, so the actual exposures must be inferred indirectly from other data. For this purpose, solar cell power output degradation on-board T/P was used as one measure of proton dose into displacement damage, although the energy range of these protons is different than those reaching the optocouplers through significant amounts of shielding. Using these data in combination with data from other spacecraft and model predictions of the T/P radiation environment, estimates were made of the proton doses at the optocoupler locations at the time the optocouplers failed. The results are shown in Figure 2 which provides 4-year doses for both protons and electrons for the T/P mission. The method by which these data were arrived at and their rationale, will be explained fully in the paper. Note that for locations inside the spacecraft, typical of optocoupler placement, nearly all the dose is from protons. When taken together with the data in Figure 1 and the operating conditions of the 4N49s which failed earliest, the data in Figure 2 tend to confirm that the optocouplers failure because of proton-induced displacement damage. These results allow T/P mission operations engineers to predict expected failure lifetimes of the remaining optocouplers on-board TOPEX/Poseidon.

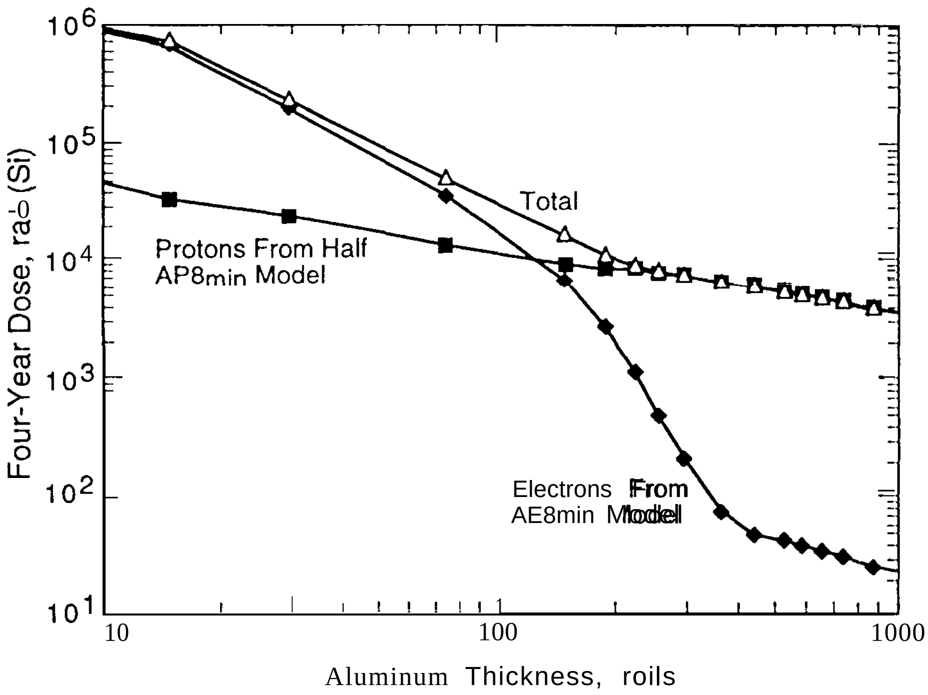

Figure 2. Revised 4-year doses using the scaled proton model for the T/P environment

Several lessons *learned can* be drawn from this work: 1) specific dosimetry instrumentation should routinely be included in the spacecraft monitoring telemetry; 2) flexibility of operation, redundancy, and design margin are the keys to success in the face of radiation effects that are unexpected or stronger than anticipated; and 3) in-flight radiation experience is of immense value to other projects. In particular, the same type of optocoupler is used in the Cassini mission to Saturn, and is planned for use in the SEAWINDS mission. The T/P failures and their analysis will assist other projects in understanding and mitigating similar radiation effects problems.

1. B. G. Rax, C. I. Lee, A. H. Johnston, and C. E. Barnes, "Total Dose and Proton Damage in Optocouplers", accepted for publication in IEEE Transactions on Nuclear Science NS-43, (1996).

2. B. H. Rose and C. E. Barnes, "Proton Damage Effects on Light Emitting Devices", J. Applied Physics 53, 1772 (1982).