Proton-Induced Transients in Optocouplers: In-Flight Anomalies, Ground Irradiation Test, Mitigation and Implications

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ABSTRACT

We present data on recent optocoupler in-flight anomalies and the subsequent ground test irradiation performed. Discussions of the single event mechanisms involved, transient filtering analysis, and design implications are included. Proton-induced transients were observed on higher speed optocouplers with a unique dependence on the incidence particle angle. The results indicate that both direct ionization and nuclear reaction-related mechanisms are responsible for the single events observed.

I. INTRODUCTION

Optocouplers, also known as optoisolators, are devices that are typically used by spaceflight designers to provide electrical isolation between circuits such as subsystem-to-subsystem interfaces. Typically, these devices consist of an LED transmitter coupled with a p-i-n photodiode or phototransistor plus follow-on electrical circuitry. Figure 1 illustrates a typical optocoupler.

Recent publications [1,2] have discussed the total ionizing dose and displacement damage characteristics of several types of optocouplers. In the past, these devices have been utilized in low-speed applications, or with transient filtering techniques that were employed to reduce non-radiation induced noise in circuits. As a result, single event transient (SET) issues were inadvertently avoided. However, as higher speed systems are being designed, transient filtering techniques are often not incorporated, and the problem of SETs in optocoupler circuits needs to be addressed.

Satellite system designers and parts engineers, however, are not always aware of single event transient issues. Over the past few years, several publications have noted the effects of SETs in linear devices [3-5], combinational logic [6-8], and optical subsystems [9-20]. The optocoupler, being a combination of an optical system and a linear device, has not previously been investigated in this regard.

The Hubble Space Telescope (HST) installed several new instruments as part of the second HST servicing mission (SM-2) on February 14, 1997. However, an in-flight anomaly occurred shortly thereafter during an orbital pass through the South Atlantic Anomaly (SAA) that triggered an apparent interrupt to the instrument processor. Of the candidate devices that may have seen a Single Event Upset (SEU) induced by a proton, the most likely was an optocoupler. Six of these anomalies were observed during ten days of engineering calibration for the new instrument. In addition, a similar flight anomaly was observed in a second new instrument during this engineering calibration time period, albeit the anomaly did not involve the instrument processor.

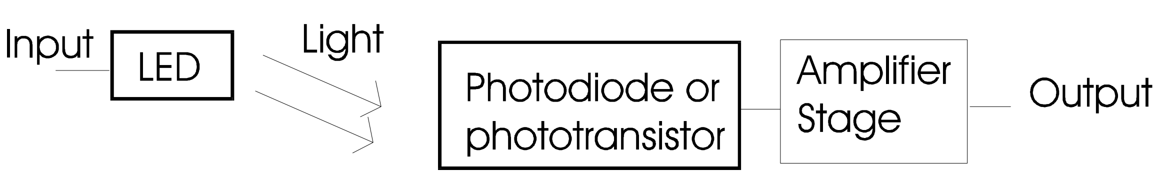

Figure 1 Typical Optocoupler Block Diagram

The authors would like to point out that although the optocoupler anomalies may have jeopardized mission success, system-level workarounds (software code changes and mission operation modifications) have been implemented following anomaly occurrence that have allowed for the new HST instruments to operate without impacting mission objectives. Nevertheless, we observe that the HST orbit (35 degree inclination, 600 km altitude) is relatively benign from the radiation perspective. A more severe radiation environment might not have allowed for system-level workarounds to be effective at mitigating the effects of proton-induced SETs in the optocoupler circuits. This paper investigates proton-induced SETs in several optocoupler circuits and proposes hardening solutions.

II. THEORY OF PROTON-INDUCED TRANSIENTS

Photodiodes have a long history of use as energetic particle detectors. Previous publications by Marshall, et al. [9-20] have discussed the sensitivity of many photodiodes utilized in optical data bus systems to direct proton-induced ionization. Typically, these photodiode devices are shaped as thin cylinders with a depletion depth dependent on the optimized optical wavelength response. In the case of indirect bandgap material such as Si, large depleted volumes are required to attain adequate light absorption. As a result, these devices have an increased susceptibility to proton transients as compared to smaller diodes. The previous studies investigated SEEs in photodiodes, but phototransistors are also excellent energy detectors so we would expect to observe similar phenomena for comparable receiver circuits.

The charge gathered by a proton strike on the photodiode is amplified and propagated to the output circuitry of the optocoupler. If the transient is of sufficient pulsewidth and voltage amplitude, an external effect may be observed. For lesser photodiode events, the follow-on circuitry filters out the transient such that no observable output effect is noted. Factors that affect the circuit's transient filtering performance include: bandwidth, slew rate, circuit gain, and power supply voltage. The role of each of these is discussed below.

Devices under test (DUTs) are listed below in table 1. They include types of optocouplers from multiple manufacturers.

One interesting note is that the relatively low-speed HP 4N55 has a similar photodiode to the HP 5631 device. Thus, an excellent comparison of the filtering capabilities of the optocoupler's amplifier stage was undertaken by proton-testing the two devices.

III. TEST SETUP:

The test setups from the varying organizations had many similarities including: the input of each channel of the optocoupler was biased either off (no light from the LED) or on (LED on), and a digital oscilloscope was attached to the device output to allow for pictorial view of the single event-induced transients. Both GSFC and NRL utilized high-speed digital oscilloscopes (500 MHz and 1GHz), while LMSC used a 40 MHz model. This prevented the LMSC setup from capturing/counting transients of less than 25 ns (i.e., they were limited by the bandwidth of the oscilloscope).

Table 1: DUT list.

Manufacturer	Device	Lot Date Code	Photodiode/ transistor	Rated Vcc in V
Hewlett Packard	HCPL-5401	9642	D	5
Hewlett Packard	HCPL-2201	9538	D	5
Hewlett Packard	HCPL-5631	9427	D	5
Hewlett Packard	HCPL-5631	9707	D	5
Hewlett Packard	QCPL-6637	9611	D	5
Hewlett Packard	HCPL-2430	9630	D	5
Hewlett Packard	4N55	9702	D	2-18
Hewlett Packard	6N140A	9707	D	2-18
Micropac	6N140	NA	D	2-18
Micropac	6N136	9624	D	2-18
Micropac	4N35	NA	D	2-18
Micropac	4N49	M9628 + special process version	T	2-18
Optek	4N48	9644	T	2-18

Note: HST DUTs are the HCPL-5401 and the HCPL-5631 optocouplers

In addition, the GSFC and NRL test setups routed the output from each optocoupler channel into a discriminator circuit that groups the transient output pulses into the following pulsewidth categories: <50 ns, 50-100 ns, 100-200 ns, >200 ns. Each of these bin outputs was fed into separate counters. The LMSC setup utilized a counter attached to a trigger from a 40 MHz oscilloscope.

All DUTs were exercised in 5V/TTL level test setups. This transient voltage amplitude mimicked typical TTL level pulses.

A. TEST FACILITY:

GSFC and NRL utilized University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL). CNL has a cyclotron capable of producing energetic protons up to a maximum energy of 67.5 MeV. Lower energies were produced by attenuating the beam by placing Al shields in-line. For example, the energy was degraded to 38.2 MeV using a 375 mil Al shield. The resulting beam energy straggle is not important for these experiments.

LMSC made use of the Indiana University Cyclotron Facility (IUCF). The IUCF cyclotron is capable of producing energetic protons up to maximum energy of 192 MeV. Multiple lower energies were utilized during testing.

B. TEST RESULTS

Table 2 below summarizes the observed results. Cross-sections are shown “per channel” since some of the tested optocouplers had more than one channel internally.

Transients were observed on the fast optocouplers when the LED was biased off. However, when the LED was biased on, transients were only noted when Vcc was reduced to the specified low-end of the device’s operating power supply voltage (Vcc - 10%).

It is critical to note that several of the devices though having differing part numbers, utilized either a similar photodiode and/or amplfier stage design as other optocouplers under exmination.

Figure 2 is an oscilloscope trace of a typical SET from the QCPL-6731 device. This device is an inverting optocoupler, i.e, the output is high when the device is off. No external filters (capacitors or resistors) were added. Transient pulsewidths that were observed on the fast optocouplers were roughly inversely proportional to the measured maximum bandwidth of the DUT.

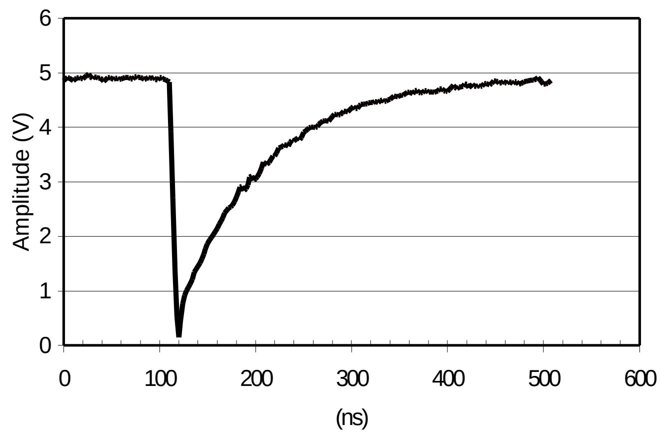

Figure 2: A sample SET from the QCPL-6731

Figures 3 and 4 illustrate the effects of beam incidence angle versus measured error cross-section. Discussion of these results will be performed in section 4A.

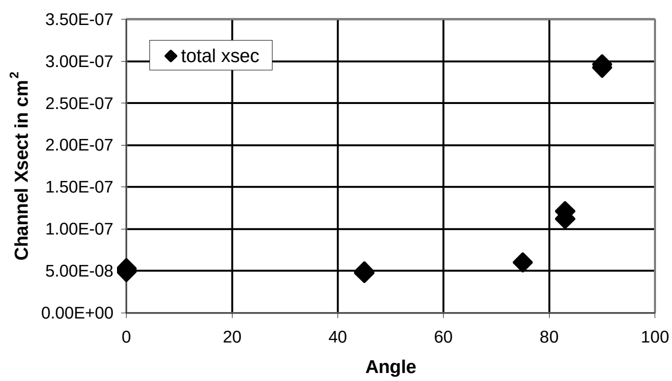

Figure 3: HCPL-5631 Error Cross-Section vs Angular Incidence at 61.8 MeV.

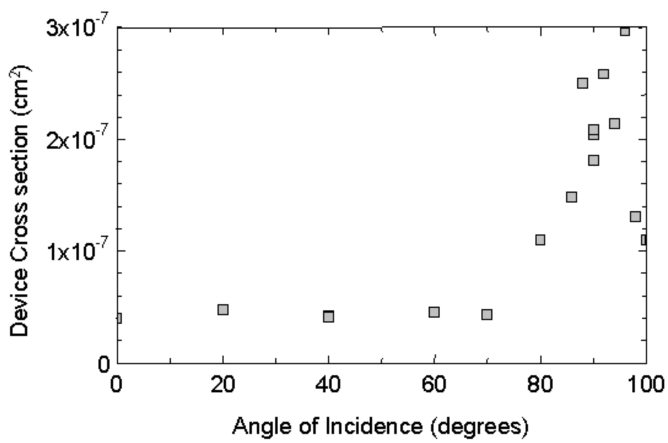

Figure 4 QCPL-6731 Error Cross-section vs. Angular Incidence at 61.8 MeV

Manufacturer	Part Number	Lot Date Code	Device Speed Rating (max)	Test Organization	Proton Energy in MeV	LED Bias Condition	Nominal Vcc/ Test Vcc in V	SETs ?	Results
Hewlett Packard	HCPL-5401*	9642	20 Mbps	GSFC/Ball	63	Off	5/5	Yes	σ = 4.2 E-8 cm^2/channel: measurements with a 500 MHz oscilloscope (TTL level, 20-25 ns transients out of AC follow-on logic)
Hewlett Packard	HCPL-2201*	9538	20 Mbps	LMSC	45-192	Off	5/5	Yes	σ = >1 E-9 cm^2/channel @192 MeV: measurements limited by use of 40 MHz oscilloscope (> 1.5V, 20-50 ns transients out of optocoupler)
Hewlett Packard	HCPL-5631*^	9427, 9707	10 Mbps	GSFC/Ball	63	Off	5/4.5, 5	Yes	σ = 5.1 E-8 cm^2/channel: measurements with a 500 MHz oscilloscope (TTL level, 20-60 ns transients out of AC follow-on logic)
Hewlett Packard	QCPL-6637*^	9611	10 Mbps	NRL	63	Off	5/4.5, 5	Yes	σ = 3.7 E-8 cm^2/channel (20 pf cap.) σ = 2.8 E-8 cm^2/channel (100 pf cap.): measurements with a 1 GHz oscilloscope (output transients of 55 ns +/- 10%)
Hewlett Packard	HCPL-5631*^	9427, 9707	10 Mbps	GSFC/Ball	63	On	5/5	No	
Hewlett Packard	HCPL-5631*^	9427, 9707	10 Mbps	GSFC/Ball	63	On	5/4.5	Yes	σ = 3.5 E-8 cm^2/channel: measurements with a 500 MHz oscilloscope (TTL level, 20-60 ns transients out of AC follow-on logic)
Hewlett Packard	HCPL-5631*^	9427, 9707	10 Mbps	GSFC/Ball	38.2	Off	5/4.5, 5	Yes	σ = 4.5 E-8 cm^2/channel : measurements with a 500 MHz oscilloscope (TTL level, 20-60 ns transients out of AC follow-on logic)
Hewlett Packard	HCPL-2430*	9630	5 Mbps	LMSC	45-192	Off	5/5	Yes	σ = >1E-8 cm^2/channel: measurements limited by use of 40 MHz oscilloscope (> 1.5V, 20-50 ns transients out of optocoupler)
Hewlett Packard	4N55*	9702	400 kbps	GSFC	63	Off	5/5	No	same photodiode as higher speed optocouplers
Hewlett Packard	6N140A	9707	400 kbps	GSFC	63	Off	5/5	No	
Micropac	6N140	NA	400 kbps	LMSC	45,192	Off	5/5	No	
Micropac	6N136	9624	400 kbps	GSFC	63	Off	5/5	No	
Micropac	4N35	NA	400 kbps	LMSC	45,192	Off	5/5	No	
Micropac	4N49	M9628 + special process version	400 kbps	LMSC	45,192	Off	5/5	No	
Optek	4N48	9644	400 kbps	GSFC	62	Off	5/5	No	

OPTOCOUPLERS Under test: results summary for normal incidence (beam perpendicular to photodiode planar surface)

* = similar physical photodiode
^ = same circuit design in different package

Table 2 Optocouplers Under test: results summary for normal incidence (beam perpendicular to photodiode planar surface).

IV. OBSERVATIONS ON THE TEST RESULTS

Photodiodes make wonderful particle detectors. However, it is dependent on the follow-on circuitry as to how many of these transients have sufficient amplitude and pulsewidth to induce a transient output from the optocoupler. For the slow-speed optocouplers, this circuitry basically filters out the faster transients. For the high-speed devices, a large number of transients are observed. The data comparison between the 4N55 (slow) and the HCPL-5631 (fast) devices illustrate this since they utilize similar photodiode but differing amplifier stages.

In addition, the output transients that were observed were on the order of 1/(maximum measured bandwidth of the optocoupler). Thus, an optocoupler rated at 20 MHz (though it may be capable of operating at 40 MHz) produced transients of ~25 ns. This was observed for several of the devices including the HCPL-5401 and QCPL-6637.

One might also note that the error cross-sections for the HCPL-5631/HCPL-6731 and the HCPL-5401 are very similar. This is likely due to the fact that both devices utilize similar photodiodes with fast amplifier stages that are capable of noticing similar fractions of the diode transients.

A. MECHANISMS AND TRANSIENT RATE PREDICTIONS

Analysis of the proton transient cross-sections and comparisons with knowledge of the coupler's internal components and their geometric configuration allows identification of the sensitive elements and provides the basis for a model to predict on-orbit upset rates. We initially identified the coupler's photodetector as the most likely element leading to the transients. This suspicion is based on extensive previous work on proton transients leading to bit errors in fiber-based data links [9-20]. In that work, the dominant upset mechanism has been identified as direct ionization from proton traversals across the link receiver's p-i-n photodiode which converts the optical signal to a relatively small electrical signal. The p-i-n detector exhibits a relatively large physical cross-section and handles the electrical signal where it is orders of magnitude weaker than elsewhere else in the circuit.

The photodiode internal to the HCPL5631/6637 optocoupler functions similarly to the data link's receiver diode. The major elements in the coupler are a GaAs LED emitting at around 700 nm and a silicon photodiode followed by two gain stages. In this case, the diode is not a p-i-n structure, but rather a substantially thinner device which is easily fashioned in the silicon bipolar process used to fabricate the receiver die. The diameter is 380 μm, and the effective depth over which carriers are collected is ~2 μm. The diode's responsivity (estimated to be 30%), is more than adequate to detect the LED's typical signal level of about -21 dBm.

The low carrier lifetimes suggest that charge collection from ion strikes should be dominated by drift across the relatively thin diode structure. Even though the maximum ion pathlength for charge collection is 380 μm (the diode diameter) the most probable pathlengths are governed by the 2 μm effective diode collection depth. For our 63 MeV proton experiments with proton trajectories perpendicular to the diode's plane, we calculate the charge deposition by direct ionization as 1,200 electron / hole pairs.

Since the coupler nominally supports a 20 MHz bandwidth, we compare the 1,200 electron deposited charge with the "signal" charge present when the -21 dBm optical signal is incident on the diode for 50 ns. With the estimated 25 percent responsivity, this corresponds to 6.3×10^5 electron/hole pairs which is over 500 times greater than the ion-deposited charge. Obviously, direct ionization is not responsible for the observed transients when ions traverse the thinnest dimension of the diode. Further evidence follows from the comparison of the measured cross-sections of around 3×10^{-8} cm^2 versus the 1.13×10^{-3} cm^2 area of the diode. Examination of this ratio reveals that one in about 4×10^4 incident protons causes a transient, which is exactly what we would expect for nuclear reaction-related upsets. Therefore, we conclude that the transients measured with normally incident protons follow from the classic indirect proton upset mechanism which has been studied extensively in memories and other devices.

The order-of-magnitude increase in proton cross-section seen at 90 degree incidence is unexpected based on conventional understanding of the indirect upset mechanism. There have been speculations and calculations supporting the idea that the forward-directed nature of reaction recoil atoms could lead to such an enhancement [21], but to date no one has been able to demonstrate this experimentally. We recognize the possibility of such a mechanism, but our analysis favors an alternate explanation based on the analysis outlined in the previous paragraph. Evaluating the charge deposited by direct ionization with a pathlength of 380 μm reveals that a 63 MeV proton deposits over 2×10^5 ion pairs which corresponds very closely to the coupler's optically induced signal level.

We therefore believe that the cross-section measured at near 90 degrees incidence arises from a superposition of the conventional indirect reaction cross section (perhaps with some enhancement due to forward directed elastic and inelastic recoil atoms) along with a dominant direct ionization cross-section. Unfortunately, the device packaging precluded the use of heavier ions or lower energy protons at 90 degree incidence, either of which might have provided additional insight regarding the role of direct ionization as a mechanism.

The side view (corresponding to 90 degree incidence) of the 2 μm thick diode provides a small target indeed. We calculate the side view physical cross section for pathlengths of 300 μm or greater to be about 5×10^{-6} cm^2 which is nearly 50 times larger than the maximum measured cross section. At first glance this discrepancy places the hypothesized role of direct ionization in doubt. Yet another concern arises from geometric considerations and the very narrow acceptance angle of about 1/2 degree for protons to traverse the entire diameter of the diode. This suggests that for a perfectly parallel proton beam, the direct ionization contribution to the cross-section should only be seen between 89.7 and 90.3 degrees, and the maximum value should be around 5 x 10^{-6} cm^2. From the data of figures 3 and 4, we see that our experiments did not have the resolution to see such a sharp angular feature. Even so, we clearly see increased cross sections between about 90 to 100 degrees, but the peak cross section is increased by only a factor of 10 (not 50).

Both of these apparent discrepancies might be explained by noting that the proton beam is not exactly parallel. In fact, all the protons have undergone multiple scatterings in a high atomic number foil while being degraded by about 5 MeV in energy for the purpose of diverging the millimeter diameter beam to a more useful size of ~ 6 cm, across which the flux is uniform to within ~ 20%. We suggest that this, along with some possible charge collection via diffusion might account for some of the observed smoothing of the "expected" results under parallel beam conditions. Rather than an increase in cross-section by a factor of ~200 over a 0.6 degree window, we instead see an increase of up to a factor of 10 over a 20 degree window. Integrating over this 20 degree window reveals very close quantitative agreement with the expected additional transients resulting from direct ionization.

Prediction of on-orbit transient rates based on the test data and analysis should be approached as a two-part process. The rate for transients from the indirect mechanism would be properly treated as is customary for memories using the one or two parameter Bendel formalism. Transient rates from direct ionization, on the other hand, should be predicted using the tools described for errors in photodiodes as outlined in [20] by calculating the chord length distribution and folding it together with the LET spectrum for protons, with appropriate shielding. This treatment parallels the conventional rectangular parallel-piped (RPP) approach customarily used for predicting heavy ion upset rates. The aggregate on-orbit transient rate will then be the sum of the two contributions.

From our test results, it appears that the total rate will have significant contributions from both sources. For example, if we considered a hypothetical environment comprised of omnidirectional 63 MeV protons, we can easily estimate the relative contributions. For the direct ionization case, after evaluating the appropriate spherical integrals, we see that about 18% of all particle trajectories lie within 10 degrees of the diode's plane. If we fold together the enhancement in the cross-section with the likelihood of arrival within a given solid angle, we discover that just as many upsets occur from direct ionization as we would expect from the direction-independent indirect mechanism. Except for very heavily shielded applications, we might expect the shielded spectrum to favor proton energies lower than 63 MeV in which case the role of reactions will be diminished and the increased LET's will lead to higher direct ionization rates. The relative importance will vary with shielding, orbit, and diode geometry, and these details should be accounted for using the combined rate prediction approach suggested above.

B. IN-FLIGHT PERFORMANCE ON HST

The anomalies observed during HST's passes through the South Atlantic Anomaly (SAA) are as follows:

- 6 events during 10 days of engineering calibration of instrument 1 (HCPL-5631 optocoupler used),
- 1 event during a limited engineering test of instrument 2 (HCPL-5401 optocoupler used).

Transient rate predictions utilizing the ground irradiation test results and the radiation environment prediction by GSFC's Radiation Physics Office (RPO) led to predictions of 1 event every 1.1 days. The preliminary flight event rate (6 in 10 days) is of same order of magnitude.

Software code changes were implemented and mission operations profile modified in a manner that showed no impact to HST mission objectives. The instruments are no longer active during SAA passes, but the required science data collection is not impacted. It should be noted that due to this shutdown, no further optocoupler SET in-flight data will be forthcoming from HST. Plans are underway to develop an optocoupler experiment of this nature for the Space Test Research Vehicle (STRV)-1d.

One should also note that HST has a relatively benign radiation environment at an orbit of 35 degree inclination and 600 km altitude. A more severe radiation environment may not have allowed for effective system workarounds.

C. MITIGATION OF OPTOCOUPLER TRANSIENTS

Mitigation of optocoupler transients may be treated similarly to any linear transient. Methods such as external filtering, synchronized data capture, multiple samples (voting), compensation capacitors, etc. may all prove useful.

The issue of designers utilizing high-speed optocouplers is one that may be solved by the use of "good engineering practices". Take for example an optocoupler rated for usage by the manufacturer at 10 MHz. In the first place, a good spacecraft design will derate (for aging and radiation concerns) the operating frequency used in-circuit by a nominal 20%. Thus, the actual circuit operation is at 8 MHz.

Since we know that the proton-induced transient is proportional to the measured maximum bandwidth of the optocoupler which for the same 10 MHz rated optocoupler may be ~ 18 MHz (thus a transient pulsewidth of 55 ns), a bandpass filter may be added following the output stage of the optocoupler to filter transients without impacting system speed performance. That is, one may include a filter for transients less that 75 ns (including a margin above the 55 ns pulses expected) without impacting the system operating with 125 ns (1/8 MHz) design constraints. Thus, the devices are usable as intended in their designs by simply adding a band pass filter immediately following the output depicted in figure 1.

To illustrate the effects of additional output filtering, we included a simple RC filter in our test setup. As an example of improvements, we saw a decrease in the cross-section from about 10^{-7} cm^2 to about 10^{-8} $cm^2$with the addition of a 2 kohm series resistor. We note however, that active band pass filters are more appropriate, since simple RC filtering may affect the signal pulse shape adversely.

Along similar lines, if long cable runs are intended in the application, they should also be incorporated in the SEE tests, since their capacitive loading will provide some inherent filtering. Similarly, the act of monitoring the output transient can affect the transient duration by adding probe capacitance. We minimized this by the use of an active probe on our 1 GHz scope. The additional capacitance was only 1 pf versus ~20 pf from the standard probe.

We explored an alternate means of affecting the transient cross-section by changing the value of the pull-up resistor on the open collector output of the coupler. Throughout the tests reported in this paper's body, this resistor value was several kilo-ohms. By reducing the value from 2 to 0.51 kOs, we reduced the cross-section from about 10^{-7} cm^2 to about 2 x 10^{-8} cm^2. This pull-up value is the minimum value specified by Hewlett Packard for that coupler, and use of the minimum value causes more concerns for the designer for managing ground snapback issues. Again, this is one tool to consider in trading off various mitigation schemes versus their complexity and adverse effects. We do consider that mitigation schemes can effectively control the transient cross-section with application of "good engineering practices."

V. SUMMARY

As one might expect, high-speed optocouplers are sensitive to proton-induced SETs while the low-speed devices perform self-filtering of the transients. A combination of direct ionization and nuclear-reaction mechanisms produce the observed SEE transients. The transients themselves appear as pulses with a width relative to the bandwidth limitation of the optocoupler.

Circuit designers need to be made aware of the potential difficulties and radiation tolerant methods of designing with optocouplers especially when it involves the use of high-speed logic families. This is true for all devices capable of SETs. It is expected that as designs move to higher speed and lower voltages, this problem will become even more critical.

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