International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111805U · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536129

Assessment of Gamma and Proton Radiation Effects on 100 Gbps Commercial Coherent Optical Transceiver

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ABSTRACT

The Acacia AC100M is a 100 Gigabits per second (Gbps) commercial, coherent optical transceiver module with digital signal processing (DSP) application specific integrated circuit (ASIC). The AC100M was characterized with noise-loaded input to simulate power-starved link operation on the receiver and decoder for performance testing. Gamma radiation and 65 MeV proton radiation test campaigns at Defense MicroElectronics Activity (DMEA) and UC Davis Crocker Nuclear Laboratory (CNL), respectively, were completed to assess single event effects (SEEs) and total ionizing dose (TID) effects on the AC100M. After exposure to gamma radiation with TID level of ~13.7 krad(Si), communication with the AC100M module was lost and power cycling of the module and evaluation board could not restore nominal operation. The AC100M ASIC survived and experienced no performance degradation from proton equivalent TID exposure up to 66.7 krad(Si) with proton radiation. After proton equivalent TID level of 101 krad(Si), the AC100M did not functional nominally after power cycling. The calculated AC100M ASIC proton SEE cross section was 4.39×10^{-10} cm^2 at the 65 MeV proton energy level.

Keywords: Optical communications, coherent optical communications, coherent optical transceiver, radiation effects on optical transceiver

1. INTRODUCTION

Coherent optical communications systems on satellites have the potential to contribute meeting to world-wide data capacity demand. Digital signal processing (DSP) application specific integrated circuits (ASICs) for coherent optical communications systems are a key technology needed for space-based applications. To develop coherent optical communications systems for space applications, the performance of commercial ASICs must be evaluated with consideration of the radiation effects from the space environment. There have not yet been published studies on space radiation testing and qualification of commercial optical coherent transceivers with DSP ASICs beyond work of the contributing authors [1]. Acacia Communications, Inc. (Acacia) (Maynard, MA) developed the first industry product line of 100 Gigabits per second (Gbps) coherent optical transceivers with DSP ASICs for analog-to-digital conversion and soft-decision (SD) forward error correction (FEC). With ground-based long-haul system experiments over 1000 km, Acacia demonstrated 120 Gbps coherent, polarization-multiplexed (PM) QPSK optical transceiver package [2]. In this work, we evaluate gamma and proton radiation effects on a commercial 100 Gbps coherent optical transceiver, specifically the Acacia AC100M. We hope that these results will be of use to the satellite and aerospace industries.

The space radiation environment has the potential to damage or degrade optical transceiver systems. Proton-induced singe event effects (SEEs) in optoelectronic receivers can contribute to link bit error rate (BER), and displacement damage can occur in optoelectronics [3]. Total ionizing dose (TID) effects and SEEs can also damage supporting microelectronics. We experimentally investigated (i) the susceptibility of the AC100M ASIC to single event effects (SEEs) and (ii) the AC100M ASIC performance for TID levels consistent with space operation. Two SEE and TID test campaigns were completed with gamma radiation at Defense MicroElectronics Activity (DMEA) and 65 MeV proton radiation at UC Davis Crocker Nuclear Laboratory (CNL). The devices under test were optical transceiver assemblies (OTAs) with the AC100M C form-factor pluggable (CFP) coherent optical transceiver module on the ATCA evaluation board (EVB). Figure 1 shows the AC100M optical transceiver module (left) and the OTA consisting of the AC100M integrated on the ATCA EVB (right).

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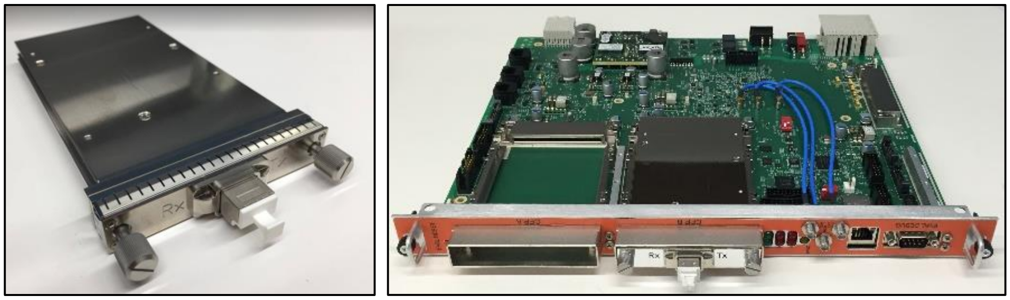

Figure 1. (left) Acacia AC100M CFP optical transceiver module; (right) AC100M optical transceiver assembly with AC100M integrated on ATCA evaluation board.

2. METHODOLOGY

2.1 Pre-Radiation AC100M Receiver Characterization

Prior to radiation testing, the AC100M receiver was characterized with noise-loaded input to simulate the most stressing link operation (i.e. power-starved link) and maximize stress on the receiver and decoder for performance testing. The noise loading was accomplished by connecting the AC100M transmit output to a variable optical attenuator (VOA) followed by an erbium doped fiber amplifier (EDFA). The amplifier output was filtered with a 100 GHz optical band-pass filter (OBPF). Figure 2 (left) is a block diagram of the AC100M receiver characterization setup and Figure 2 (right) is the laboratory test setup for the pre-radiation AC100M receiver characterization.

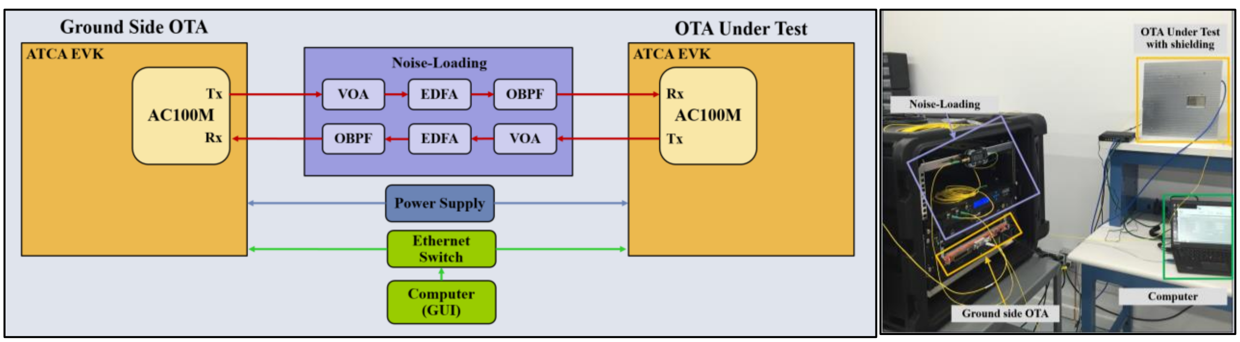

Figure 2. Pre-radiation AC100M receiver performance characterization setup. (left) AC100M receiver performance characterization test setup block diagram; (right) laboratory test setup for pre-radiation AC100M receiver characterization.

The raw BER and number of uncorrected blocks from the OTA under test AC100M receiver were recorded for ground-side OTA AC100M transmitter optical output power levels of -14.5 dBm to -13.5 dBm in 0.1 dBm increments. Figure 3 (left) shows the OTA under test AC100M receiver raw BER as a function of ground-side OTA AC100M transmitter optical output power. Figure 3(right) shows the OTA under test AC100M receiver performance through the number of uncorrected blocks as a function of ground-side OTA AC100M transmitter optical output power. The soft decision (SD) forward error correction (FEC) threshold for the AC100M receiver is ~ -14.1 dBm optical transmit power. At the SD-FEC threshold, the raw BER is ~ 0.017.

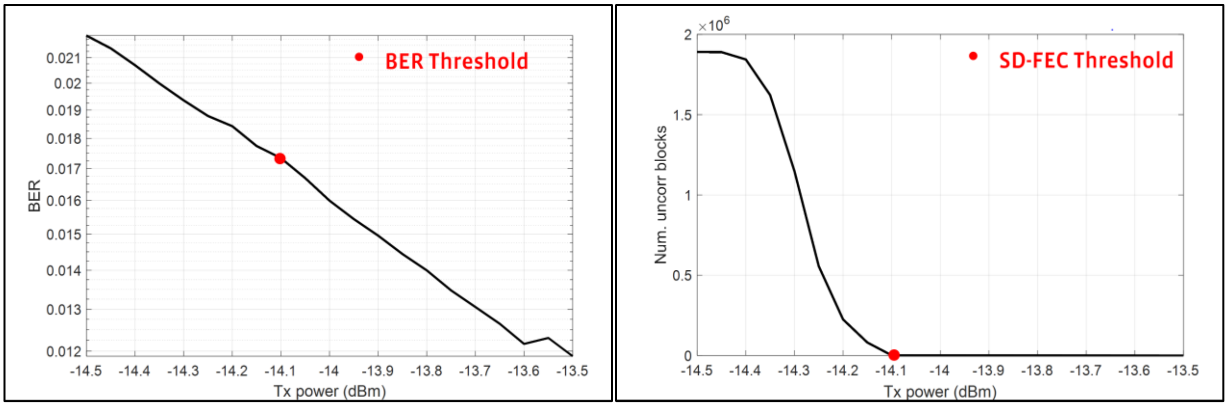

Figure 3. Pre-radiation AC100M receiver performance characterization data. (left) raw bit error rate as a function of OTA ground side AC100M optical transmit power; (right) AC100M receiver performance characterized through number of uncorrected blocks a function of OTA ground side AC100M optical transmit power.

For the radiation test campaigns, the AC100M receiver performance test setup with noise-loading (Figure 2(left)) was implemented, and the EDFA input power to the OTA under test AC100M receiver was backed off by 0.4 dB from the SD-FEC threshold. For both radiation test campaigns, dynamic testing was conducted, in which the OTA under test was powered and operated. The BER and number of uncorrected blocks were recorded over time. Fault monitoring was also conducted and the AC100 EVB GUI recorded a log of faults or failures. After detection of a SEE, the radiation gamma was powered off and the AC100M and/or the EVB were power cycled to restore nominal operation. The SEE number, type of SEE, and the time duration of SEE occurrence were also recorded. A different AC100M OTA was used for each radiation test campaign.

An aluminum test fixture was created for the OTA under test and served as radiation shield and heat sink for the ATCA with AC100M. A 4-cm layer of steel was mounted on the test fixture above the AC100M module for additional radiation shielding. Both the aluminum test fixture and additional steel layer had a hole over the AC100M ASIC region. The purpose of the shielding was to simulate spacecraft chassis and OTA chassis shielding as well as to protect other components in the OTA from radiation during test campaigns. Figure 4 shows the AC100 EVB OTA mounted to the aluminum test fixture with additional steel shielding over AC100M module.

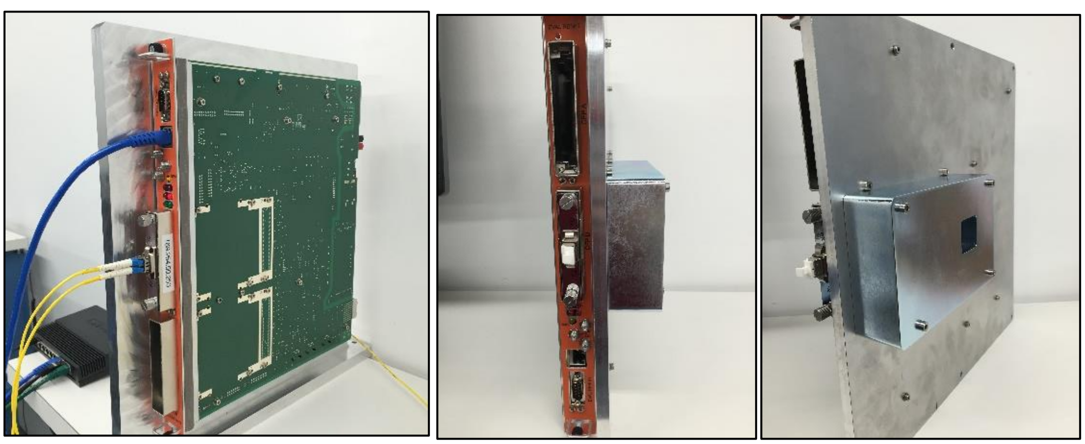

Figure 4. OTA under test mounted to aluminum test fixture; (left) Back side of OTA not covered by aluminum test fixture; (middle) Side view of OTA with aluminum test fixture and additional steel shielding above AC100M module area; (right) top side of OTA cover by aluminum test fixture and with steel shielding above AC100M module area; hole in fixture and steel shielding above AC100M ASIC area.,

2.2 Gamma Radiation Test Campaign

At DMEA, gamma radiation was used for TID testing of the AC100M. The OTA under test was placed inside the gamma radiation chamber and a layer of lead bricks was placed in front of the OTA as an additional radiation shielding layer from the gamma beam, which would spread throughout the gamma radiation chamber. A small gap in the lead brick shielding was made above the AC100M ASIC area to provide more exposure to gamma radiation in comparison to the other components in the OTA. The test setup in the gamma radiation chamber is shown in Figure 5. The BER and number of uncorrected blocks were recorded over time. The OTA under test was exposed to a TID level of ~15.75 krad with dose rate of ~2.12×10^2 rad/min.

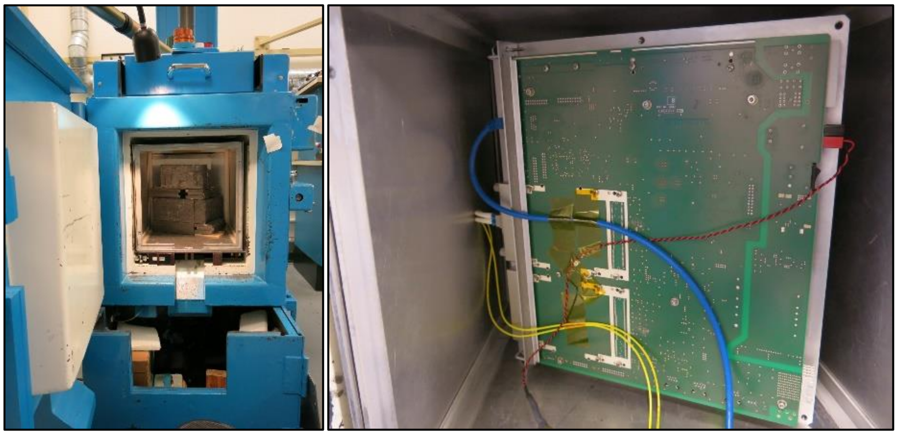

Figure 5. Gamma radiation test campaign test setup at DMEA. (left) Gamma radiation chamber with OTA under test behind lead brick shielding; small gap in lead brick shielding above AC100M ASIC area; (right) back-side of OTA under test in gamma radiation chamber.

2.3 Proton Radiation Test Campaign

At CNL, 65 MeV proton radiation was used for SEE testing followed by equivalent TID testing. The OTA under test setup at CNL is shown in Figure 6. The OTA was placed in front of the proton beam with the AC100M ASIC region aligned directly in line of penetration by the proton beam.

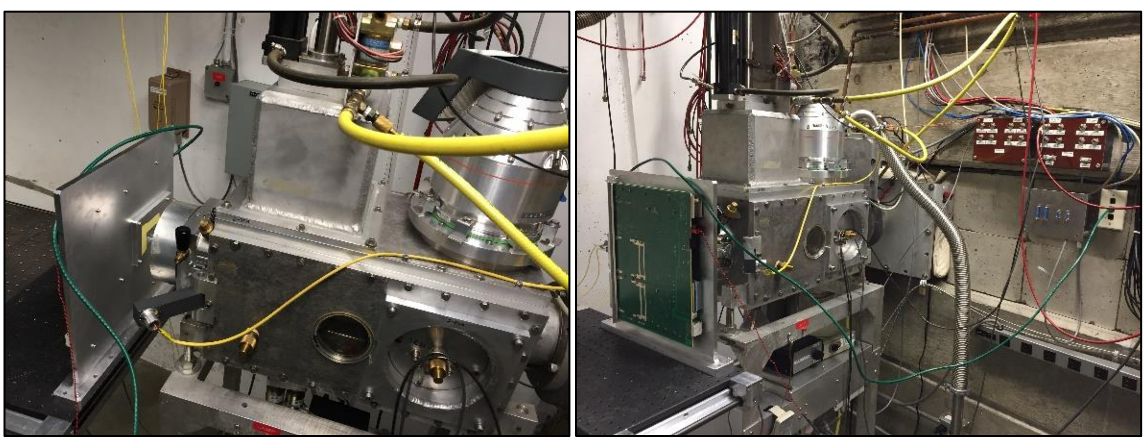

Figure 6. Proton radiation test campaign setup at UC Davis Crocker Nuclear Laboratory; (left) AC100M-ATCA EVB with aluminum shielding layer and additional 4 cm steel shielding over AC100 CFP module in front of proton beam; (right) AC100M-ATCA EVB set-up in front of proton beam, showing angle from behind EVB.

Nine rounds of dynamic proton SEE testing on the AC100M ASIC were completed with flux levels ranging from 8.64×10^4 protons/cm^2·sec to 1.26×10^8 protons/cm^2·sec. These proton flux levels are higher than flux levels, which a low earth orbit (LEO) or geostationary earth orbit (GEO) mission would encounter, but higher flux levels were needed to induce SEEs within reasonable test duration of a few minutes per SEE. For a 1200 km altitude orbit, trapped proton fluxes at 65 MeV energy level can reach flux levels up to 1×10^3 protons/cm^2·sec. Appendix Section A.1 further describes the OMERE radiation environment modeling for 65 MeV trapped proton fluxes. The AC100M ASIC was exposed to a cumulative equivalent TID level of ~8.56 krad(Si) from SEE testing. Equivalent TID testing was completed after SEE testing with seven rounds of dynamic testing to reach a cumulative TID level of ~101 krad(Si). After each round of TID testing, the AC100M module and EVK were power-cycled to evaluate if the AC100M ASIC had survived the irradiation. For the first six sets of TID testing, the proton beam flux was set to levels ranging from 1.27×10^8 protons/cm^2·sec to 1.34×10^8 protons/cm^2·sec, yielding TID of ~6 to ~12 krad(Si) in each interval and a cumulative TID of level of ~66.7 krad(Si) at the end of the sixth round of testing. The last round of TID testing irradiated the ASIC with a flux of 3.85×10^8 protons/cm^2·sec, providing for additional ~35 krad(Si) to reach a cumulative TID level of ~101 krad.

3. EXPERIMENTAL RESULTS

3.1 Gamma Radiation Test Campaign

At TID level of ~2.09 krad, there were 53 uncorrected blocks detected. Power cycling of the AC100M and EVB restored nominal operation. Communication with the AC100M was lost at TID level of ~13.7 krad. Power cycling of the AC100M module and the EVB did not clear the module communication fault or restore nominal operation. Based on data and fault monitoring logs of the AC100M and EVB, the loss of communication was caused by a failure of a DC power converter on the AC100M PCB. We conclude that component failed due to scattered gamma radiation of less than 1 krad. Figure 7 shows the recorded data of BER (left) and number of uncorrected blocks (right) as a function of time during gamma irradiation prior to the ~13.7 krad level. Prior to the ~13.7 krad level, the BER remained below the ~0.017 BER threshold.

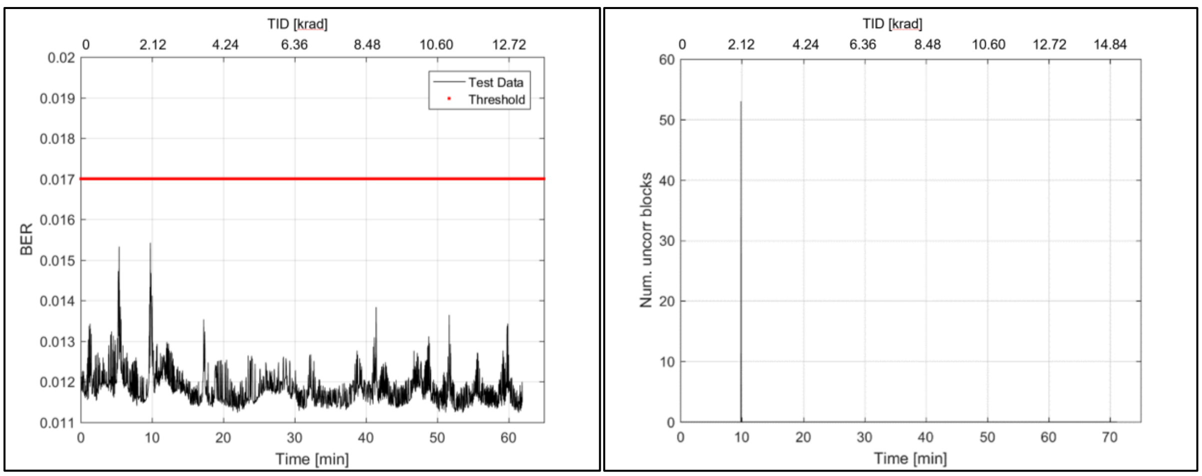

Figure 7. AC100M gamma radiation test campaign results; (left) Bit error rate recorded over time for testing below TID level of ~13.7 krad; BER was below 0.017 threshold. (right) AC100M receiver number of uncorrected blocks recorded over time. One occurrence of a number of uncorrected blocks (53) greater than zero.

3.2 Proton Radiation Test Campaign

Table 1 summarizes each round of proton SEE testing based on the number of SEE occurrences, test round duration, average proton beam flux, and the calculated total fluence. For each SEE test round, the total fluence was calculated as the product of the test round duration and average flux.

Table 1. Proton SEE test campaign results per test round. Number of SEE occurrences, duration, average proton beam flux, and calculated total fluence listed for each test round.

SEE Test Round	Number of SEE Occurrences	Test Round Duration [seconds]	Average Flux [protons/cm^2·second]	Total Fluence [protons/ cm^2]
1	0	380	8.64×10^4	3.28×10^7
2	0	357	6.20×10^5	2.21×10^8
3	1	343	1.30×10^6	4.46×10^8
4	1	184	6.23×10^6	1.15×10^9
5	3	350	6.36×10^6	2.23×10^9
6	0	427	2.97×10^6	1.27×10^9

7	3	1225	3.22×10^6	3.94×10^9
8	11	1860	6.34×10^6	1.18×10^{10}
9	4	249	1.26×10^8	4.85×10^{10}

From nine rounds of SEE testing, there was a total of 23 proton-induced SEEs and a cumulative fluence of 5.25×10^{10} protons/cm^2. The total number of SEEs was divided by the cumulative fluence to calculate the SEE cross section. The calculated proton SEE cross section for the AC100M ASIC is 4.39×10^{-10} cm^2 at 65 MeV proton beam energy level. Table 2 summarizes all proton SEE testing rounds with the total number of proton-induced SEEs, the cumulative fluence, and the calculated proton SEE cross section.

Table 2. Proton SEE test campaign summary. Total number of proton-induced SEEs, cumulative fluence, and AC100M ASIC proton SEE cross section from 65 MeV protons calculated.

Total Number of Proton-Induced SEEs	23
Cumulative Fluence	5.25×10^{10} protons/ cm^2
AC100M ASIC 65 MeV Proton SEE Cross Section	4.39×10^{-10} cm^2

Table 3 summarizes the results of each round of proton TID testing. The AC100M survived proton irradiation to TID level of up to 66.7 krad, and AC100M nominal functionality was restored through power cycling the module and board after each TID test round. After TID level of 101 krad, the AC100M module could not nominally function after multiple attempts of power cycling.

Table 3. Proton TID test campaign summary. average proton beam flux, cumulative proton equivalent TID, and description of results of power cycling described.

TID Test Round	Average Flux [protons/cm^2·second]	Proton Equivalent Cumulative TID [krad]	Results of Power Cycling
1	1.27×10^8	14.3	Restored nominal function
2	1.28×10^8	20.1	Restored nominal function
3	1.30×10^8	31.8	Restored nominal function
4	1.28×10^8	43.3	Restored nominal function
5	1.29×10^8	54.7	Restored nominal function
6	1.34×10^8	66.7	Restored nominal function
7	3.85×10^8	101	Unable to restore nominal function

4. CONCLUSION

We evaluated Acacia AC100M optical coherent DSP ASIC for SEE and TID effects through gamma and proton radiation test campaigns. The Acacia AC100M survived gamma irradiation to TID level of ~13.7 krad, at which point communication with the AC100M module was lost, and power cycling of the module and evaluation board could not restore nominal operation. Initial hypotheses include failure of a DC power converter at this TID level of gamma radiation. From the proton radiation test campaign, the calculated AC100M ASIC SEE cross section was 4.39×10^{-10} cm^2 at 65 MeV proton energy level. The AC100M ASIC survived and experienced no performance degradation from proton equivalent TID exposure up to 66.7 krad(Si). After proton equivalent TID level of 101 krad(Si), the AC100M did not functional nominally after power cycling.

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APPENDIX

A.1 OMERE RADIATION ENVIRONMENT MODELING FLUX MAPPING

The OMERE (version 5.0) flux mapping module was used to model the integral flux of 65 MeV protons with AP8-MIN trapped proton model and IGRF magnetic field model for mission starting in 2020. At 0-degree longitude, 65 MeV trapped protons can reach integral flux levels up to 1×10^5 protons/cm^2·sec.

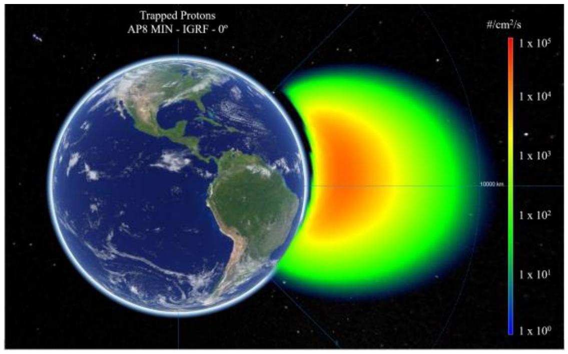

Figure A.1 Integral flux mapping for 65 MeV trapped protons. The OMERE flux mapping module is used to model trapped protons with AP8-MIN and IGRF for Earth's magnetic field. Integral flux levels range from 1×10^0 protons/cm^2·sec (blue) to 1×10^5 protons/cm^2·sec (red).