MPTB Radiation Effects Study on the DR1773 Fiber Optics Data Bus

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Abstract

We present a description of the Microelectronics and Photonics Test Bed (MPTB) Dual-Rate 1773 (DR1773) Fiber Optics Experiment, the radiation hardening techniques utilized, as well as the associated radiation ground test results and analysis. A large increase of single event upset (SEU) hardness was observed beyond expected simple photodiode models.

I. Introduction and Background

The NASA Goddard Space Flight Center (GSFC) along with the Naval Research Laboratory (NRL) have been at the forefront of the space community in terms of the use of fiber optic systems in the space radiation environment. Aerospace Standard (AS) 1773 [1], hereafter referred to as DR1773, is a fiber optics data bus standard created by the Society of Automotive Engineers (SAE) Avionics Systems Division (ASD). AS1773 is an extension of the existing fiber optic bus protocol known as the MIL-STD-1773, which is a 1 Mbps bandwidth bus. Because of the success of the Small Explorer Data System (SEDS) 1773 fiber optic data bus (FODB) [2-6], a second generation command and data fiber optic bus capable of both 1 Mbps and an increased bandwidth operation of 20 Mbps has been developed for spaceflight utilization. To characterize the space radiation performance of this new generation fiber optics data bus, GSFC and NRL have conducted proton radiation effects experiments on DR1773 transceiver (i.e., the optical-electrical interfaces for the system) designs. We have designed and implemented a DR1773 space experiment which will fly on the NRL MPTB mission due to launch in the summer of 1997 [7].

The AS1773 protocol specifies a Manchester II unipolar data encoding format for data transmission modulation at 1 Mbps or 20 Mbps on the AS1773 FODB. The electrical portion of the experiment is required to generate and transmit to the transceivers Manchester encoded data words. The electrical circuit must also receive Manchester encoded data words from the transceivers. The GSFC in-flight experiment will operate at the 20 Mbps data rate only.

Previous data has been presented on the ground testing and the highly successful flight radiation performance of the SEDS 1773 FODB [2-6]. In summary, these first generation devices were highly sensitive to direct ionization effects from protons, thus the SEDS 1773 system requires the use of fault-tolerant features that are built-in to the 1773 protocol to gain acceptable bit error rate (BER) performance. In particular, the retransmitting of failed messages accomplishes this task. However, this eliminates a portion of the usable bandwidth of the system: one must have the system timetable set up to accommodate not only the original message, but the retried message as well. Thus, the usable bandwidth is reduced by 50% if every message is capable of being retried.

With this in mind and the lessons learned from photonics irradiations on higher speed devices [8-15], development of more single event upset (SEU) tolerant transmitter and receiver modules for the AS1773 systems was undertaken. The second generation FODB hardware combines small photodiodes with receiver filtering techniques to reduce the BER to acceptable levels without the need for message retransmissions.

A. DR1773 Design and Implementation

Figure one shows a representative AS1773 A fiber optic data bus in its full capacity 32x32 configuration. The main components of an AS1773 system include the hosts (subsystem processor, state machine, etc..), protocol chips, fiber optic transceivers, optical fibers, fiber optic connectors and optical star couplers. The host is the portion of a spacecraft subsytem that interfaces with the AS1773 protocol chip in order to communicate with other subsystems on the spacecraft. The protocol chip interfaces between the host and the transceivers and controls message transfers over the AS1773 bus. The AS1773 protocol specifies a Manchester II unipolar data encoding format for data transmission modulation at 1 Mbps or 20 Mbps on the AS1773 FODB. The transceivers convert optical signals to electrical signals to receive messages from the bus and convert electrical signals to optical signals to transmit messages over the bus. The physical transmission medium includes optical fibers, connectors and star couplers.

The AS1773 is a dual redundant bus, therefore utilizing two star couplers to implement an A and a B bus. A star coupler is a device that sends optical signals from one input port to all of its output ports. The coupler divides the optical power evenly among all output ports. The transmitter optical output power minus the optical attenuation introduced by the star coupler, optical fiber and connectors (all of transmission medium) must provide a power that matches the optical receiver sensitivity margin. This matching is necessary for successful signal transmission over the bus. In the star coupled configuration only one transmitter may have access to the bus during any given time period. A single host terminal will connect to both buses via the protocol chip, thereby providing complete cross strapping of all the subsystems on the spacecraft. A host may configure its protocol chip to operate in either the 1Mbps or 20Mbps mode. The host may also configure the protocol chip to operate as a remote terminal (RT) or a bus controller (BC). Messages can be sent from RT to RT, BC to RT or RT to BC. All message transfers however, are controlled by a single BC. The AS1773 bus shown in figure 1 in its 32x32 star coupled configuration supports up to 32 inputs and 32 outputs. In this configuration, one BC and up to 31 RT's can be implemented on the spacecraft.

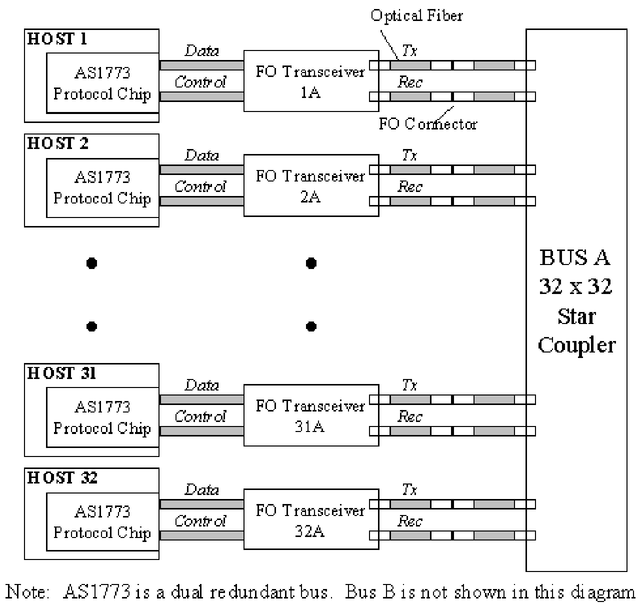

Figure 1: Illustrates a representative AS1773 system. System components include: passive star couplers, optical fibers, electro-optic transceivers, connectors, etc.

B. Devices of Interest

Two manufacturers with differing internal designs are emerging. Boeing Defense and Space Group (hereafter known as Boeing DR1773) has provided samples of their devices for ground and spaceflight radiation experimentation purposes. The second transceiver, the SCI/UNM DR1773, is funded by NASA, designed by the University of New Mexico Microelectronics Research Center (UMD MRC) and fabricated by SCI Corporation. These devices are currently under electrical evaluation.

1) Boeing DR1773

The Boeing DR1773 transceivers are comprised of an InGaAs diode in the receiver circuit, a GaAs LED in the transmitter side, radiation-hardened custom ASICs, and passive components [16,17]. As summarized by Marshall, et al [18], it was expected that only the diodes would effect bit error rates (BER) in the space radiation environment. These devices operate at 1300 nm wavelength. The transmitters had a nominal launched power of -7dßm, while the receivers had a nominal sensitivity of -30dßm.

The Boeing design takes advantage of radiation effects research previously completed to design a hardened fiber optic receiver [as summarized in ref 18]. Besides utilizing a physically smaller diode (a change from a Si PIN photodiode to a InGaAs photodiode), the Boeing engineers performed several clever filtering functions to discriminate against the radiation-induced transients. The hardening techniques utilized include:

- A photodetector (PIN diode) with a small active volume is employed to minimize single event charge collection.
- The analog preamp circuitry is designed with excess drive to minimize single event pulse widths,
- A proprietary asynchronous digital data reconstruction filter is employed to filter narrow-width single event transients produced in the detector and pre-amp.
- The transceiver electronics are fabricated in a radiation hardened, thin epi-layer, 1.2 um CMOS process (UTMC UTE-R).
- A proprietary clock-recovery architecture is employed which avoids high clock speeds associated with conventional over-sampling approaches, thereby allowing the use of a larger feature size CMOS process,
- Radiation-tolerant optical fiber (manufacturer information is proprietary to Boeing) is utilized for the device's input/output pigtails.

2) SCI/UNM DR1773

The SCI/UNM design also takes advantage of radiation effects research previously completed to design a hardened fiber optic receiver [as summarized in ref 18]. Some of their smart filtering/radiation hardening techniques include:

- A photodetector (PIN diode) with a small active volume is employed to minimize single event charge collection.
- Increased wide bandwidth (50 to 70 MHz) amplifiers before the decision (1 or 20 Mbps) circuit in order to reduce the pulsewidth of the SEUs.
- SEU pulses must exceed the detector threshold for 12.5 ns before an error will pass through the 20 Mbps detector.
- SEU pulses must exceed the detector threshold for 75 ns to cause an error in the 1 Mbps detector.
- Honeywell SEU-tolerant flip-flops are used in the 1 Mbps detector and the rate (1 or 20 Mbps) detect circuits.
- All state machines are designed to recover from SEUs without entering any unused states.
- Total dose hardness is achieved by using Honeywell's radiation hard 0.8 um bulk CMOS process (RICMOS IV).

C. Radiation Effects of Interest

There are two primary space radiation effects that we investigated in this study: total ionizing dose (TID) and single event effects (SEE). Displacement damage was not considered in this effort due to previous work showing that it is not expected to be an significant issue for the use of FODB technology in space [8,13].

TID is a long-term effect that degrades performance of a device either parametrically and/or functionally. For a fiber optic receiver, this might appear as a reduced sensitivity level. In a fiber optic transmitter, we might note a reduction in optical power output. Other parameters such as signal skew, current consumption,et al. might also be degraded.

SEE are caused by a single ion (galactic cosmic rays (GCR) or protons) through direct ionization along its path through the device, or by proton-induced nuclear collisions which produce highly ionizing secondary recoils. These effects may be temporary or destructive. Destructive SEEs were not considered based on knowledge of the internal hybrid components and their technology. Single event upsets (SEUs) were expected to manifest themselves as transients occurring on the communication path that may or may not be noted as a bit error on the receiver output depending on the amplitude, location, and width of the transient pulse. For the case of optical diodes, protons are expected to dominate the radiation-induced bit error rates (BER) in space applications through direct ionization mechanisms [2-6, 8-13]. It should be noted that unlike the photodiodes studied here, most microelectronic devices are not sensitive to SEE caused by direct ionization of protons.

II. Radiation Ground Test Program Description

The primary purpose of the ground radiation testing was to fully characterize the DR1773 transceiver devices in order to provide an on-orbit performance prediction for the MPTB mission. A second objective was to provide generic data on the DR1773 transceivers for use by NASA and others.

A. Radiation Test Rationale

Given that the receiver photodiode is sensitive to direct ionization by protons, this will be the dominant mechanism for upset in space. Therefore, we characterized the devices via proton irradiation. This would provide a TID test as well as a SEE test. It is also important to consider the possible susceptibility of associated electronics to heavy ion-induced SEE. Testing for galactic cosmic rays is normally desired, but due to constraints of packaging and limited penetration range of ions created by GCR-simulation sources on the earth, feasibility of testing the entire hybrid transceiver was not considered. It is expected that destructive conditions will not occur on these devices based on analysis. However, GCR particles are expected to have very little impact on BER since there is a relatively low GCR particle density (even worst case).

B. Experiment Test Setup

1) Experimental Parameters

As defined previously [4], the experimental error cross section defined as:

$$N \text{ bits in error} = F \text{ particles/ cm}^2 \times \text{Error cross section in cm}^2$$

where the number of bits in error and the fluence are measured quantities. The error cross section is influenced by data rate, flux rate, time of particle arrival, optical power levels, angle of incidence between incident particle and the device, etc. The TID testing objectives were to check functional, optical, and parameter degradation effects.

2) Experimental test system - Boeing DR1773 Test

Figure 2 illustrates a block diagram of the test setup. Figure 3 is a picture of the test fixture used for irradiation. Boeing devices are labeled on the board. The test setup and operation are based on the MPTB flight experiment and will be described in section 3.

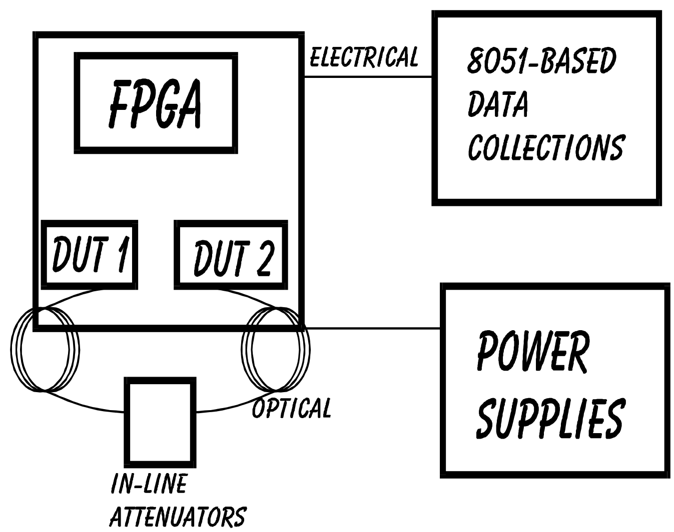

Figure 2: MPTB DR1773 Test Board

3) Radiation Test Facility

Radiation testing was performed at the University of California at Davis Crocker Nuclear Lab (CNL). This facility provides monoenergetic protons of variable particle flux rates. Maximum proton energy available is 63 MeV. Lower proton energies are available through tuning of the cyclotron or by the use of Al degraders. The second option was employed for this test since the results were not sensitive to the induced beam energy straggle.

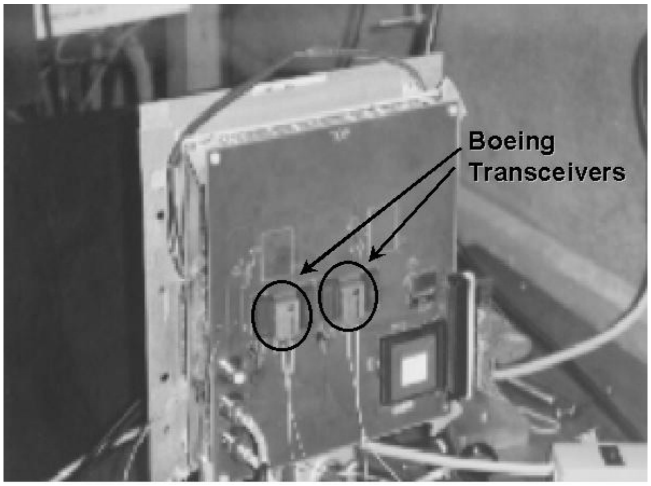

Figure 3: Radiation Test Fixture

4) Radiation Ground Test Results - Boeing DR1773

Test results below are for 63 MeV proton irradiations. Receiver testing was performed using a nominal (-17dB) and two higher (-23 and -25dB, respectively) in-line optical attenuation values between transmitting and receiving devices [19]. The angle of incidence of the proton beam with respect to the plane of the photodiode was also varied. (The proton beam is normal to the plane of the diode for zero degree incidence.). In the 1 Mbps operating mode, no errors were noted on any test run. Total particle fluence was 2.5E10 protons/cm^2 implying a limiting device error cross section of less than 4E-11 cm^2 per device.

For 20 Mbps operation, error cross sections were less than 1.4E-10 cm^2 per device at normal operating conditions. As predicted by Marshall, et al. [11], the BER increased as the attenuation was increased. Increased incident optical power on the receiver diode increases the base noise margin of the system. Figure 4 shows the error cross section vs. induced optical attenuation. Figure 5 shows the error cross section vs. the proton angle of incidence. Note the relative insensitivity to incidence angle, and hence the particle pathlength.

Receiver test results at a lower proton energy (38.2 MeV) varied only by 10-20% from those at 63 MeV. This was not considered statistically significant.

Only a single (cumulative) error was observed during the entire set of transmitter irradiation test runs resulting in a maximum error cross section of 2E-11 cm^2 per device.

Although full parametric checks were not performed, functional, optical parametric, and limited electrical parametric tests were performed. The devices were exposed to an ionizing dose of ~35-40 krads(Si) with no apparent functional or parametric degradation observed. This was an expected result.

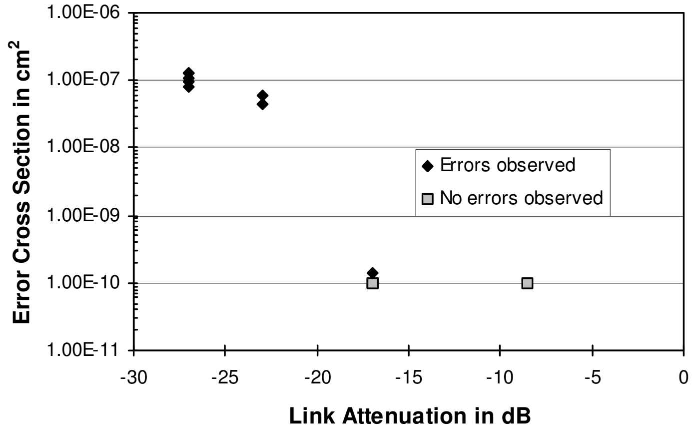

Figure 4: Boeing AS1773 Receiver – Error cross section vs. attenuation – 90 degrees incidence.

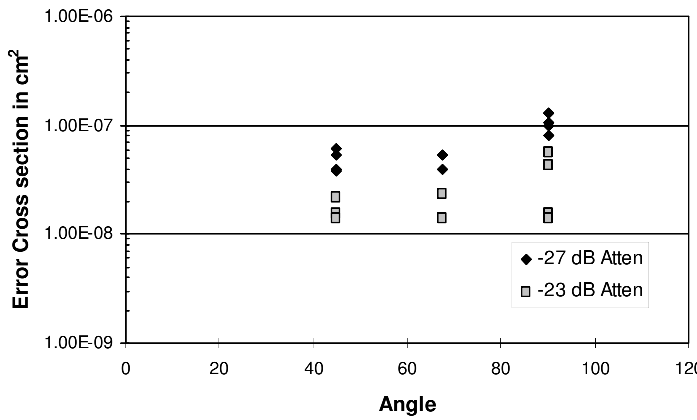

Figure 5: Boeing AS1773 Receiver Error cross section by beam incidence angle.

III. 3.0 MPTB Flight Experiment Study Description

A. Flight Test Methodology

Figure six is a simplified block diagram of the DR1773 MPTB flight experiment. A radiation hardened optical fiber and an optical star coupler provide the transmission medium. The transmitting device sends a digital data word over the optical link. Once a data word has been recognized by a receiving device, it is compared with the data word transmitted. If the data words are different, then an error is counted. The total number of data words transmitted through the link is also counted. Transceiver currents are monitored continuously along with temperature and a dosimeter circuit that monitors total dose degradation. The data received will be compared to the data transmitted. If the data words are different then an error counter will be incremented, corresponding to an SEU occurrence. The bit error rate will be calculated for each device as follows:

BER = (number of errors) / (total number of transmissions) x 32 bits

Each DUT has a corresponding error counter assigned. The transmitted word length is 32 bits in length.

The transceiver currents are monitored continously to assess any TID related degradation. A temperature sensing device and a dosimeter circuit that measures the total ionizing dose exposure are located on the experiment card, and are continuously monitored as well.

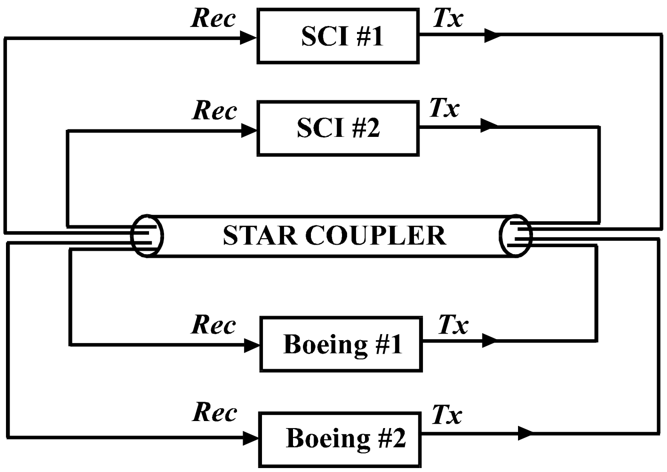

Figure 6: Block diagram of flight experiment.

B. *Experiment Design and Operation*

The electrical and optical portions of the experiment were designed to simulate how the DR1773 system may be utilized in an actual spacecraft design.

1) Overall System Design

Figure 7 is a block diagram that shows both the electrical and optical portions of the experiment design. The electrical portion of the circuit is mostly contained within an Actel A1280A Field Programmable Gate Array (FPGA) [20] which was packaged by Space Electronics Inc. in a RadPack™. The decision to use an FPGA was based on an effort to minimize the physical size of the electrical design in order to accommodate the board dimensional constraints. The FPGA circuit is divided into five major circuits: a data generator, a state machine, a total word counter, an error counter and a comparator circuit. Outside of the FPGA circuit exists the peripheral support electronics (not shown) and the optics. The data generator generates an electrical data word in the Manchester encoded format and transmits the data word to the enabled transmitting device. The transmitting device converts the electrical signal to an optical signal and transmits the data word over the optical link. At the receiving end, the enabled receiving device converts the optical signal back to an electrical signal and transmits the data to the comparator circuit in the FPGA. The comparator circuit then compares the generated data word with the received data word. If a transmission error occurred, the state machine increments the error counter corresponding to the receiving device involved. The state machine then increments a total word counter and the process repeats. Each generated data word is different from the previous words. There is a transmission over an electrical signal path for each transmission over the optical link. This electrical path provides an electrical reference for the experiment. The state machine also supplies all control signals for the experiment. Additional experiment details are available in [21].

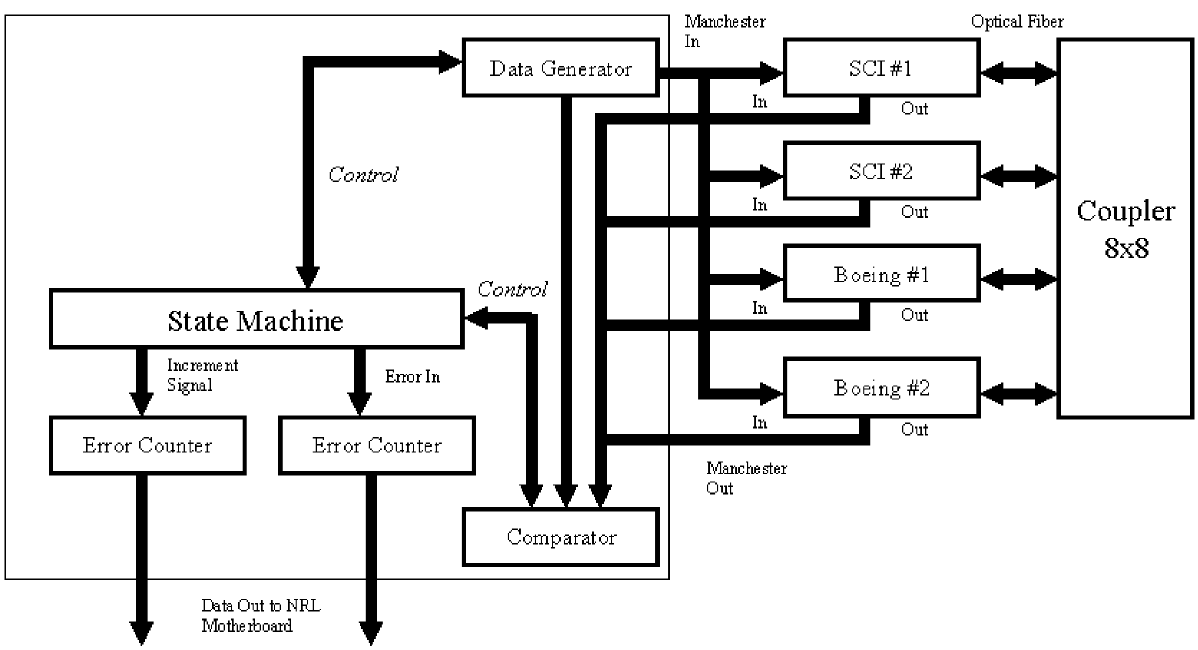

Figure 7: Data Flow Diagram for DR1773 Experiment.

2) Optical Design

As seen in figure 6, the optical coupler is an 8x8 star coupler with the additional attenuation added to simulate the insertion loss of a 32x32 star coupler (15 to 20 dB). In the DR1773 experiment, there are four DUTs. In an AS1773 fiber optic system, there can be as many as 32 FO transmitters and 32 FO receivers per bus. Hence, a 32x32 coupler would be ideal to simulate a real system. Due to cost, fiber availability, and dimensional (board size, volume) constraints an 8x8 coupler was utilized in place of the 32x32. The 8x8 star coupler is manufactured by Canstar.

The optical fiber used in the experiment is the Spectran 100/140/170 hermetic polyamide-coated fiber with 24 gauge Tefzel tubing [22]. The 100/140/170 specification denotes the outer diameters of the core, cladding and coating, respectively. This fiber is radiation hardened.

The fiber terminations are the M29504 Amphenol/Bendix termini. It would have been preferable to use SMA 905 connectors since they provided a worst case scenario for connector insertion losses, but board weight constraints prohibited this option. The Amphenol/Bendix connectors reduced the weight of the board by 70 to 100 grams and required less total board space.

IV. DISCUSSION

As expected, the receiver diode was the most sensitive portion of the DR1773 transceiver from the SEE perspective. However, it was not as sensitive as expected. At 1 Mbps operation, and based on the models by Marshall, et al [18], we had expected an approximate two orders of magnitude decrease in error cross section in changing from the Si PIN photodiode in the SEDS 1773 modules to an InGaAs diode employed in the Boeing devices. The decrease was greater than one would expect based simply on a photodiode model: approximately five orders of magnitude decrease in sensitivity to ionizing protons versus the original SEDS 1773. The number of expected radiation-induced spaceflight BERs would decrease proportionally. It should be strongly noted that the model does not take into account the filtering measures included in the Boeing electrical design. Hence, the several orders of magnitude improvement is a measure of the highly successful multi-stage filtering designed into the receiver. This is true for both 1 and 20 Mbps operation.

When operating at 20 Mbps, these devices also surpassed model predictions and we observed error cross sections that were two to three orders of magnitude lower than expected for a receiver with no special filtering. This bodes well for spaceflight utilization where BERs of less than 1E-9 are required. To place this in perspective, as a worst case, one *might* observe a bit error during the peak of a large solar proton event, whereas the previous SEDS 1773 modules could see hundreds!

The very low error cross sections and angle insensitivity are consistent with the bit errors being caused by proton-induced nuclear reactions. This possibility has not yet been investigated sufficiently to draw any conclusions at this time.

As mentioned previously, in order to make the original SEDS 1773 robust for the space radiation environment, a protocol feature entitled “bus retries” was enabled. Essentially, when a bit error occurs, the system is smart enough to automatically resend the same message. The probability of two consecutive failed messages was very small (1 per 7 years) for the first space flight usage, the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX). However, bus retries reduce available bandwidth to the user by ~50% (i.e., the overhead of requiring that bandwidth be available for each message attempt reduces a 1 Mbps bus to an effective 500 kbps bus). The retry scheme might not be required for the Boeing transceiver due to its inherently low proton BER. This would allow a more effective and higher utilization of the system bandwidth.

TID testing, though limited, showed no signs of failure for dose levels that cover most Polar and low earth orbits. Further TID testing is recommended for missions requiring a long lifetime such as a geosynchronous communications satellite.

It is unfortunate that the SCI/UNM transceiver design is not physically realized in terms of a fully functional IC. Ground irradiation tests will be performed on this device when it becomes available.

V. Summary

The MPTB DR1773 experiment along with an established ground test program of the DR1773 devices is providing valuable data on this emerging fiber optics data bus technology. Utilizing the ground SEE test results as well as typical NASA radiation requirements, the low predicted BER for the Boeing DR1773 transceivers meets the specification for most spaceflight missions. The low on-orbit BER prediction which is based on our ground based testing, indicates that the Boeing DR1773 transceivers meet the specification for most NASA spaceflight missions. The MPTB flight experiment, provides an opportunity to validate our ground test and on-orbit prediction models. This is especially true because on the detailed on orbit TID and particle flux dosimetry which will be made available to the experimenters. The MPTB orbit provides a severe radiation environment and will help to validate the use of the DR1773 bus in future NASA and other spaceflight missions.

Acknowledgments

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