SEDS MIL-STD-1773 Fiber Optic Data Bus: Proton Irradiation Test Results and Spaceflight SEU Data

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ABSTRACT

We present proton test and space flight single event effect data for NASA's first fiber optic data bus. Bit error rate predictions based on a new proton direct ionization model agree well with flight data for proton belt and solar flare effects.

I. INTRODUCTION

The Small Explorer Data System (SEDS) was launched in July of 1992 as part of the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) mission. The SEDS utilizes NASA's first MIL-STD-1773 Fiber Optic Multiplexed Data Bus (or 1773 bus) to communicate with other spacecraft subsystems in the space environment. The 1773 bus is the fiber optic version of the MIL-STD-1553 Data Bus, a electronic wire bus used in many avionics applications. Due to the successes based on ground radiation test results and the spaceflight SEU data, the 1773 bus has been baselined for several additional NASA missions (X-ray Timing Explorer, Tropical Rainfall Measuring Mission, Far Ultraviolet Spectroscopic Explorer, et al...) as well as generating great interest in the DoD community.

A detailed series of proton irradiation ground tests were performed that allowed an understanding of the Single Event Upset (SEU) mechanism and accurate space flight predictions. Previous work detailed heavy ion test results[1]. Additionally, this paper discusses the SEUs seen in space during the first months of the SAMPEX mission including a solar flare from October 30 through November 6, 1992, their impact, and comparison to predicted SEU rates. SAMPEX is a three year mission with an inclination of 82 degrees and an average altitude of 615 km (slightly eccentric orbit). This paper extends previous preliminary analyses of proton test results[2] and flight data analysis[3].

II. SEDS MIL-STD-1773 FIBER OPTIC DATA BUS AND SEUs

Fiber optics provides a significantly reduced weight and power solution to spacecraft subsystem interfacing, while providing EMI/RFI immunity to the cable harness. The 1773 bus is a master/slave, 1 MHz bandwidth means of passing telemetry and commands between spacecraft subsystems. The 1773 bus has enhanced reliability due to its use of redundant busses (i.e., A and B sides). The 1773 bus transfers messages of up to 32 words between subsystems encoded with Manchester coding (i.e., each bit has a mid-bit transition). The receiving subsystem responds with a short status packet to tell the system controller whether or not the transfer was successful. This data transfer includes parity and other error checking means to control the error flow. Additionally, if an error occurs, the 1773 bus has the option of automatically retrying the same data transfer (an entire data packet of up to 640 bits) that failed either on the side that failed or the redundant side, thus reducing the effective error rate. The number of optional bus retries is set by the system designer.

Each subsystem contains a 1773 optical terminal consisting of two of each of the following: Honeywell HFD3801-002 TTL Integrated Fiber Optic Receiver (Si PIN diode and bipolar IC), Honeywell HFE4811-014 TTL Integrated Fiber Optic Transmitter (GaAlAs LED and bipolar IC), and a radiation-hardened ASIC from LSI Logic. The optical terminal provides the interface between the user's electronics and the optical fiber bus utilizing a 850 nm wavelength.

A SEU on the 1773 bus typically manifests itself as a transient seen by the receiver as a non-valid Manchester signal. During the SAMPEX mission, SEU rates are tracked by the bus retries that occur; i.e., each bus retry is caused by an SEU on the 1773 bus. The SEU test methodology has been detailed previously[4].

III. PROTON TEST RESULTS

Testing was performed on both the optical terminal (a system level test) and on individual Honeywell devices (generic test). Figure 1 is a block diagram of the 1773 system test set utilizing a PC-based Bus Controller (BC) and the Devices Under Test (DUTs) configured as 1773 Remote Terminals (RTs). The generic test set was designed to capture and count transients as with a typical Bit Error Rate (BER) test set. Many factors were explored including error rate dependence on proton energy, proton flux, beam incident angle, and data rate, as well as the 1773 system error handling capabilities and total proton fluence related degradation. Measurements are in error cross-section as defined by:

$$\text{Error Cross-Section in cm}^2 = \text{N errors} / \text{Proton Fluence in particles/cm}^2 \quad (1)$$

This paper presents results of monoenergetic proton testing to determine the system level response to protons incident on either the transmitter (TX) or the receiver (REC). The University of California at Davis Cyclotron Proton Facility was utilized.

The test results will be divided where appropriate into 1773 and generic results. Transient error rate measurements were made in each case on at least two devices and in most cases on four. The error cross-section for the TX was determined during testing to be several orders of magnitude smaller than for the REC. Therefore, the REC tests were emphasized.

A. ENERGY DEPENDENCE - 1773 REC

Two 1773 RECs were tested with proton energies incident to the DUT package (39.2 and 63 MeV). Minimal variance was seen between results at the two energies. To the first order, the measured error cross-sections for the detected errors did not depend on proton energy over the range of 39.2 to 63 MeV. This was verified at three data rates: 78, 161, 471 kbits/s. This is illustrated in Figure 2.

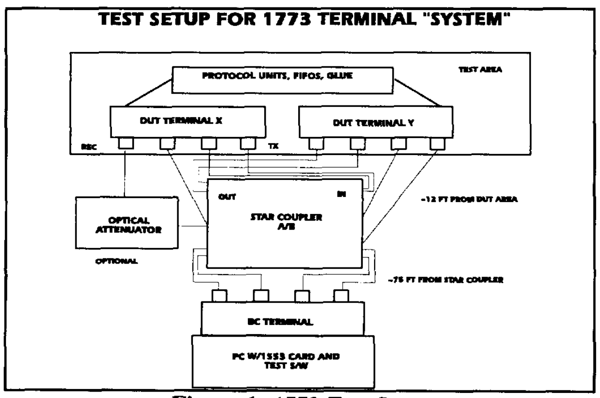

Figure 1 1773 Test Setup

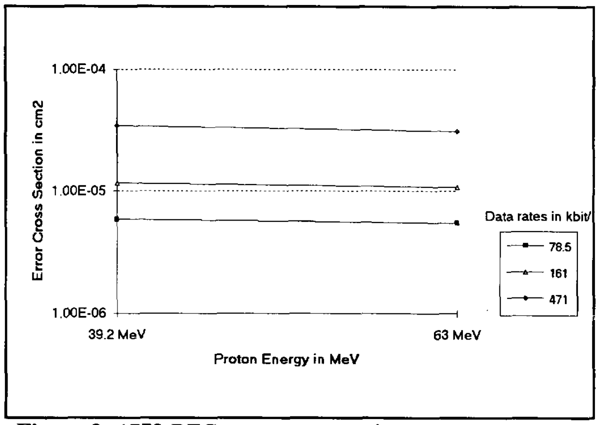

Figure 2 1773 REC error cross-section vs. proton energy for each data rate

B. FLUX DEPENDENCE - 1773 REC

This test was only performed on the 1773 setup and only for system level tests with bus retries enabled. This data is illustrated in Figure 3. Tests were performed at several fluxes. Test results were independent of the flux with the exception of when bus retries were enabled. This exception will be discussed later.

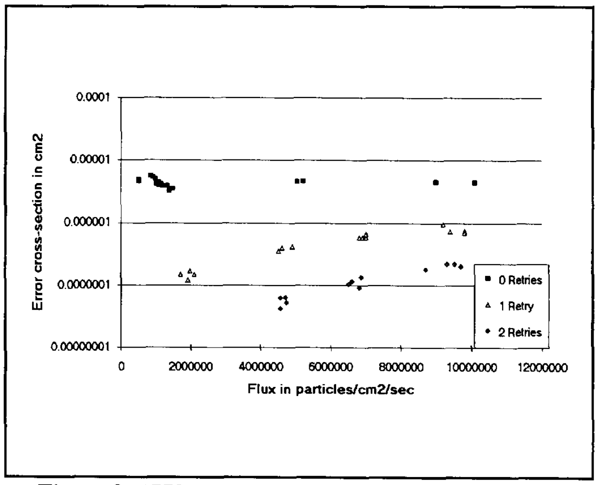

Figure 3 1773 error cross-section vs. proton flux for retries at 78.5 kbit/s

C. BEAM INCIDENCE ANGLE DEPENDENCE - 1773 REC

Normal incidence (0 degrees) corresponds to particle entry into the side of the disk-shaped Si photodiode. Figure 4 illustrates the sharp increase in the error cross-section as the beam angle rotates from the plane of the receiver's photodiode.

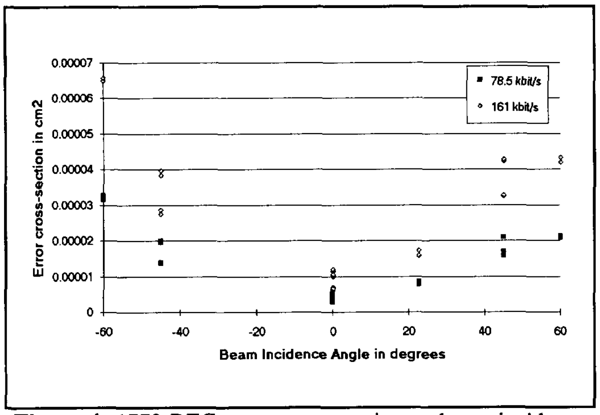

Figure 4 1773 REC error cross-section vs beam incidence angle (63 MeV)

D. DATA RATE DEPENDENCE - 1773 REC

Data rate is determined on the 1773 bus by the number of messages transferred each second, i.e., if 10 messages each containing 32 20-bit words were transferred each second, the data rate would be 6400 bit/s (32x20x10). Data rate is varied by changing the number of messages that occur each second. Since the 1773 has a fixed 1 MHz frequency, each transfer of message is of a fixed time period. Therefore, changing the message rate alters the duty cycle of the bus.

Figure 5 shows the measured dependence of the error cross-section as a function of data rate. The relationship seen here appears linear, i.e., as activity on the data bus increases, so does the error rate.

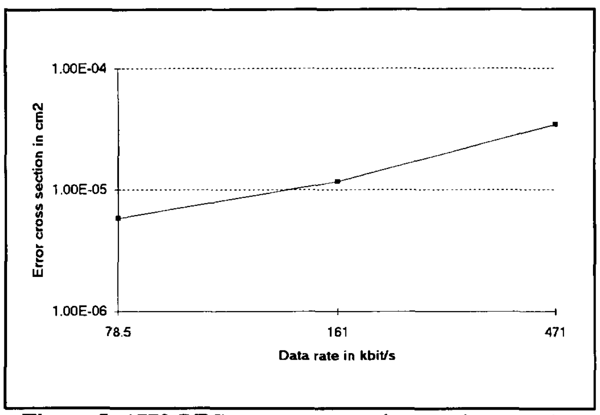

Figure 5 1773 REC error cross-section vs. data rate (no retries)

E. SYSTEM LEVEL RESPONSE - 1773 REC

Under the MIL-STD-1773 protocol, there is the option of retransmitting a failed message (i.e., a retry based on parity errors, non-valid Manchester signals, etc...). Multiple retries may be enabled as a system design consideration. If the last attempted retry fails, then an SEU is counted. If the retry is successful, no SEU is counted. This objective was to investigate the use of enabling the occurrence of retries (as it would be in a actual flight system) and investigating the results. Test data were taken on the 1773 test set with 0, 1, and 2 retries enabled.

Discussion of this data will be deferred until later in order to understand the interplay between data rate, retry options, and proton fluxes.

F. TOTAL PROTON FLUENCE - 1773 REC/TX

Further checks determined that the error cross-sections were not affected by 100 and 500 kRad(Si) proton exposure. The devices remained fully functional post-irradiation and, as a rule, became slightly less sensitive to SEUs. Error cross-sections dropped by < 30% for both RECs and TXs.

G. BEAM INCIDENCE ANGLE DEPENDENCE - GENERIC DEVICE-REC

The factor checked here is the beam angle rotation from the plane of the receiver's photodiode. All of the error cross-section data were taken using a test signal of 1 MHz frequency. Transient glitches of greater than 13 nanoseconds in duration were then counted as errors.

Figure 6 summarizes the data taken. This curve shows a similar shape to the data from the 1773 setup in terms of ratios to projected area. With the Si diode being an indirect band-gap material, it requires a depletion depth of approximately 40-50 microns to attain a reasonable quantum efficiency. The circular diode has a diameter of several hundred microns.

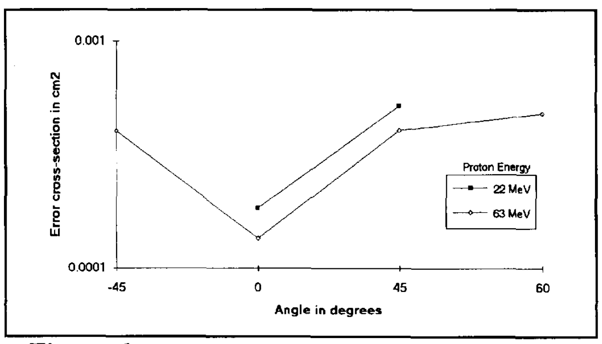

Figure 6 REC error cross-section vs. beam incidence angle

Given that a error cross-section of > 1E-5 cm^2 for normal incidence is approximately the same order of magnitude as the physical diode cross-section, this implies that nearly every physical proton strike was capable of causing a transient error. Additionally, the increased error cross-section with tilt angle scales roughly with proton projected area increase, further evidence of direct ionization events.

H. TOTAL DOSE DEPENDENCE - GENERIC DEVICES

Three levels of exposure were performed (50, 100, 200 krad) on the REC while two were performed on the TX (50, 100 krad). Both the lidded and delidded RECs were exposed with little variance between the two. Again, a slight decrease in SEU sensitivity was seen (<30%).

I. DATA RATE DEPENDENCE - 1773 TX

Data were taken at two data rates: 161 and 471 kbit/s. The results are seen in Figure 7. With only two data points, trends are hard to determine, but it is expected that the error cross-section will scale linearly as with the REC.

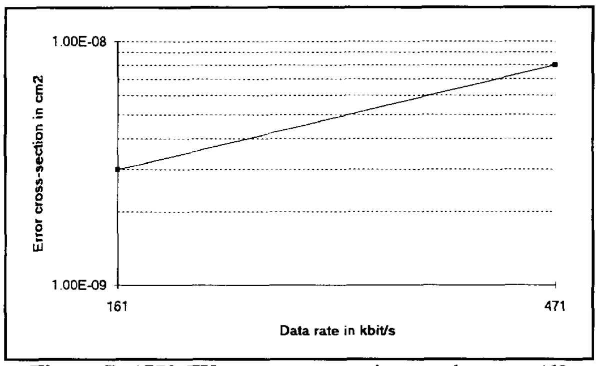

Figure 7 1773 TX error cross-section vs. data rate (63 MeV)

IV. MODELLING SYSTEM LEVEL DEPENDENCIES

Normal system operation anticipates the occurrence of bit errors, and the Manchester encoding scheme provides for easy error detection which, for the 1773 bus, provides bus retries. The above mentioned cross-sections measure the occurrences of these retransmissions. Measurements were made to demonstrate the robust ability of the 1773 system to transmit error free data in the presence of proton induced effects. Figure 3 shows the measured cross-section dependence on beam flux for 0,1, and 2 attempted retries, i.e. 1,2 or 3 sequential failures. The probability for such failures is obviously not a concern for natural proton exposure levels in orbit. A model of these effects assumes random proton arrival times and predicts the lack of flux dependence on single errors as well as the linear and quadratic dependencies for 1 and 2 retransmissions.

An alternate way of expressing error cross-section is

$$\sigma_S \equiv \text{Error cross-section for a single 1773 message error} = \text{Message Error Rate/Flux} = MER_S/\Psi, \quad (1a)$$

where MER_S is the number of messages in error per total number of messages transmitted. We further define

$$\sigma_N \equiv MER_N/\Psi, \quad (2)$$

where MER_N is the error rate for N 1773 message errors. Further, we define, P_N, the probability of losing N consecutive messages as

$$P_N \equiv MER_N/MR \quad (3)$$

where MR is given in number of 1773 messages transmitted per second. MR is analogous to a data rate as discussed previously. By substituting (2),

$$P_N = (\sigma_N \Psi)/MR \quad (4)$$

I.e.,

$$P_S = MER_S/MR = (\sigma_S \Psi)/MR \quad (5)$$

From the Binomial distribution, we get

$$P_N = P_S^N = (\sigma_S^N \Psi^N)/MR^N \quad (6)$$

By using (4),

$$P_N = (\sigma_N \Psi)/MR = (\sigma_S^N \Psi^N)/MR^N \quad (7)$$

or more appropriately by solving for the error cross-section,

$$\sigma_N = (\sigma_S^N \Psi^{N-1})/MR^{N-1} \quad (8)$$

For a typical 1773 bus system where retries are enabled, the design constraint for error rate becomes the error probability for 2 or more consecutive errors based on proton flux and system data rate.

Figure 8 verifies this point for one data rate (161kbit/s) by showing both the experimental and theoretical error cross-sections for 1, 2, and 3 consecutive errors as a function of proton flux. The results for other data rates were equally as effective in matching the theory to experimental data. Theoretical error-sections are scaled to the data for 0 retries.

Note the agreement between 2 and 3 consecutive errors (1 and 2 retries enabled) with the model, even though there is no independent scaling of the data. This illustrates the robustness of utilizing system level error handling approaches. Moreover, with a typical mission proton flux of 1E5 particles per cm^2

per second, the occurrence of lost data is highly unlikely.

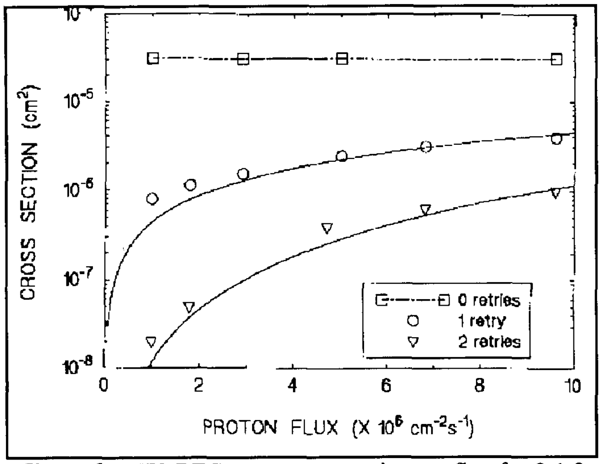

Figure 8 1773 REC error cross-section vs. flux for 0,1,2 retries

V. INTERPRETATION OF PROTON MEASUREMENTS

There are obvious similarities between the treatment of SEU effects in memories and the evaluation of BER effects in NASA's MIL-STD-1773 bus. However, the extension of the measured proton error cross-sections to predict data retransmission frequency in orbit requires a careful examination of the basic mechanisms involved. Several clues found in the cross-section data lead to a conclusion that direct proton ionization effects are involved, rather than nuclear reaction recoils as is typically the case.

The case for direct ionization effects is further supported by the strong dependence on tilt angle as shown in figures 4 and 8. Again, the fact that the error cross-section follows strong angle dependence suggests that the rate scales approximately with the projected photodiode area to the beam. This further establishes that the threshold LET is small since the circular diode has a diameter to thickness ratio of about 15. For these reasons, the flight predictions for retransmissions have been made with the assumption that all protons incident on the photodiode will be capable of affecting a bit if the arrival occurs during a sensitive time window. Therefore, a significantly different approach over existing SEU formalism is required.

VI. SEU RATE PREDICTIONS

Based on the direct ionization, error rate prediction was performed assuming every proton or energetic ion incident on the REC diode would cause a transient error. For SAMPEX the main areas of concern are passes through the South Atlantic Anomaly (SAA) of trapped protons, proton solar flare events, and cosmic ray exposure. Using the above data, environmental prediction and previous heavy ion data, the following SEU rate calculations were made by integrating the predicted SAMPEX radiation environment with the test data:

Heavy ion upset rates: 0.43 upsets/day
Trapped proton (SAA) upset rate: ~18/day.

It should be noted that SEU rates may increase during solar flare activity.

VII. COMPARISON OF SEU PREDICTIONS AND SPACEFLIGHT DATA

It should first be noted that no unsuccessful retries have occurred to date (i.e., all first retries have been successful). Thus the effective BER is zero. Figure 9 shows the number of bus retries for September 14th through April 15th 1993 with the predicted daily retry rates superimposed. The predicted data shows a close correspondence to the actual flight data. The overall daily retry average is 8 retries per day. Flight SEU levels are below the predicted on the average by a factor of two. A brief digression is needed to explain why the daily retry rates vary.

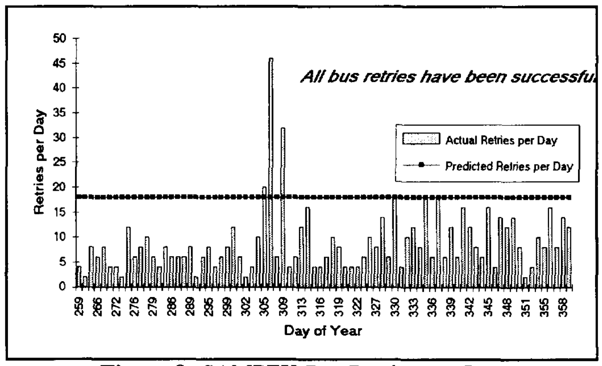

Figure 9 SAMPEX Bus Retries per Day

SAMPEX's orbit precesses. Therefore, the number of spacecraft orbits through the SAA per day varies, as does the proton fluxes per orbital pass (i.e., different areas of the SAA have varying proton flux densities).

Note the abrupt rise in bus retries during the period of October 30th through November 7th. This enhanced period may be correlated with proton flux data during that time period. In particular, the peak proton event occurred on November 2nd, which is the highest bus retry period. As is typical with large solar proton events, the trapped proton belts are enhanced for some time period post-event. This is confirmed by noting the higher post-event bus retry rates as compared to the pre-event rates. The pre-event average was 6, while the post-event was 9.

Figure 10 shows the abrupt rise in proton flux levels as recorded by the GOES-7 spacecraft during a solar proton event October 30th through November 7th, 1992, courtesy of NOAA, as well as the daily number of retries during that time period. On day 307 a > 100 MeV proton event occurred and, as one can see, correlates well with the daily retries seen during that day.

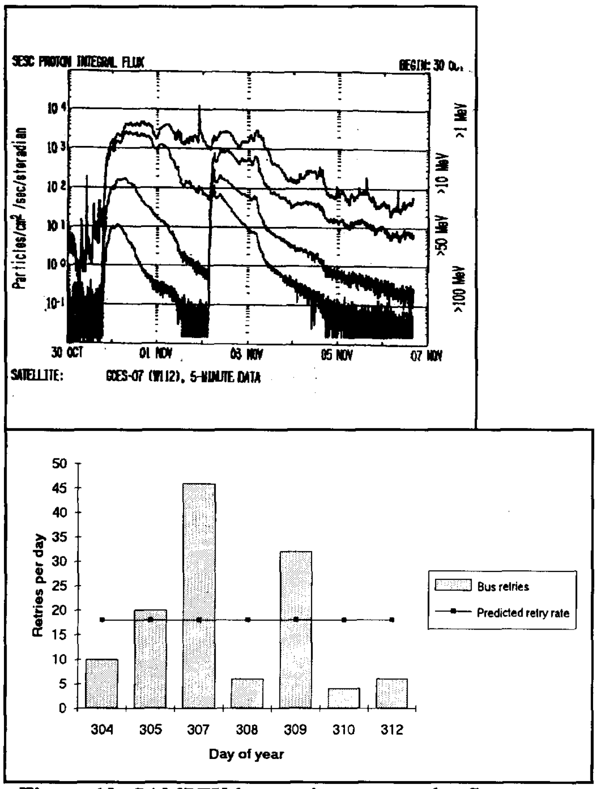

Figure 10 SAMPEX bus retries versus solar flare proton fluxes

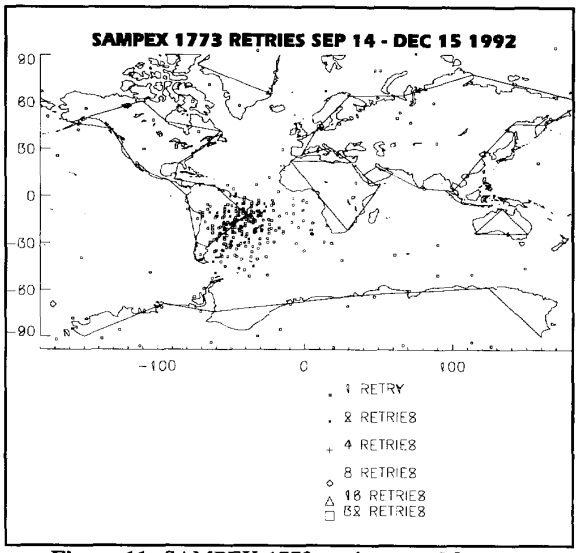

Figure 11 SAMPEX 1773 retries over Mercator projection

Figure 11 shows the bus retry data from September 14th through April 15th time period with the locations of the retries illustrated over a Mercator world map projection. This figure includes those retries that occurred during the solar flare time period. The SAA is well mapped in Figure 11 and will be mapped in its entirety with further time periods of data.

VIII. FUTURE EFFORTS

Due to the robust nature of the MIL-STD-1773 error tolerance approach using retries, there is little concern for information loss as was demonstrated during the October 1992 solar flare. It is worth mentioning that efforts under development for higher data rate busses are considering receiver approaches which minimize the need for system level handling. In Reference [5], several physical layer design choices are discussed which have the potential of lowering the uncorrected bit error rates by approximately five orders of magnitude.

Significant reduction in the error rates follow from minimizing the physical volume of the receiver's photodiode. In addition to selecting small junction diameters, this minimization includes using III-V direct band-gap detectors such as InGaAs at 1300 nm. The resulting thinner junctions significantly limit the numbers of long pathlengths, and therefore the direct ionization- induced photocurrents. Reference [5] also points out the advantages of operating with optical signal levels well above the noise margins and for using receiver approaches which do not latch transient pulses. Noise filtering approaches are also being investigated for lower data rate applications, where the temporal characteristics of the proton transient can differ significantly from the optical signal.

IX. CONCLUSIONS

The fact that the interpretation of test results leads to a flight model which assumes direct ionization effects suggests that the occurrence of retransmissions could be significantly reduced with design changes to the receiver. The paper compared the measured and predicted rates for the present implementation with those expected for a III-IV based detector. This comparison showed that improvements would follow from both a smaller physical cross-section, as well as greatly reduced particle pathlengths through a thinner direct band-gap detector. The latter would lead to a much smaller ionization pulse, and possibly results in a system which would not be sensitive to direct ionization effects. Assuming only nuclear reaction related effects would lead to a reduction in retransmissions of several orders of magnitude.

X. ACKNOWLEDGEMENTS

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XI. REFERENCES

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