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THE USE OF SPACE QUALIFIED COTS DATA HANDLING EQUIPMENT FOR THE ESA INTERMEDIATE EXPERIMENTAL VEHICLE (IXV) MISSION

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ABSTRACT

In recent years there has been a trend towards the wider use of COTS (Commercial Off The Shelf) equipment in space missions. This trend has been mainly driven by the restrictions in R&D budgets and a growing demand for shorter design cycles. Funding Agencies are encouraging designers of spacecraft systems to identify and overcome the obstacles that previously prevented the use of COTS products for space missions.

This paper discusses the design and development of a COTS data handling and recording equipment solution on board the IXV (Intermediate Experimental Vehicle) spacecraft for the European Space Agency. The IXV is a flying test-bed for the development and testing of the technologies and critical systems for Europe's future autonomous controlled re-entry missions from low Earth orbit. The data handling system in the IXV spacecraft was developed using COTS equipment from Curtiss Wright. The IXV spacecraft was successfully launched on a VEGA rocket, re-entered and recovered on the 11th February 2015 and all on-board data was recovered for analysis by ESA.

INTRODUCTION

Functional requirements for data acquisition and recording equipment for space flight tests are very similar to those for aircraft flight tests. It therefore seems to be an obvious choice to use proven COTS aircraft flight test equipment in a space mission. However, the differences between spacecraft and aircraft flight environments require a different methodology in developing a solution with COTS equipment in order to meet all requirements.

The impact of radiation effects on aircraft flight test equipment is minimal due to the relatively low altitude and short duration of the flight. However, when considering space vehicles including launchers, satellites, orbiting platforms and re-entry vehicles, the tolerance of on-board electronics to radiation effects becomes one of the most challenging tasks. As the risk of equipment failure due to the radiation effects increases with the altitude and flight duration, the tolerance to radiation effects becomes the crucial criteria for selecting the on board equipment. More information on the complex challenges of the harsh space environment that designers of spacecraft equipment face can be found in [1], [2] and [4].

Designers of spacecraft systems have been encouraged by funding Agencies to identify and overcome the obstacles that have prevented the use of COTS products for space missions in order to make better use of limited budgets while still meeting the overall Mission Assurance requirements. The approach taken by Curtiss Wright designers focuses on the characterization of existing commercial technologies and their modification and optimization for use in space environments and is called Space COTS Qualification.

The first step in this approach involves the analysis and tests required to determine the performance of COTS products in relevant space environments, a step called Space COTS Characterization. This step is followed by the assessment of product characteristics against mission requirements, a step called Space COTS Mission Mapping. Identified shortcomings are then addressed by an appropriate system design and minor modifications with the objective to lower any potential risks to acceptable levels and this step is called Space COTS Adaptation.

RADIATION ENVIRONMENT EFFECTS

Semiconductor components are essential building blocks of modern spacecraft electronics, including data handling equipment. As radiation interacts with a semiconductor it produces ionization which effectively increases the conductance of the material. As a result, ionizing radiation creates tiny spikes of electrical current in the material. Cumulatively, these current spikes cause degradation of material characteristics and are known as Total Dose Effects. Individually, they can temporary or permanently disturb the function of a device, a phenomena known as Single Event Effects [2].

Total Dose Effects

The amount of radiation dose, i.e. the amount of energy deposited in the material, that results in ionization is called Total Ionizing Dose (TID). Historically, in the field of space environment effects, the total ionizing dose uses *Rad* units, where 1 Rad represent any kind of radiation which deposit 0.01 Joule per kilogram of material. The total dose accumulated during a space mission depends on orbit altitude, orientation and duration of the mission.

Ionization of a semiconductor material typically causes very small leakage currents, which can lead to long-term consequences. Electron-hole pairs created by ionization do not simply recombine, but drift under the influence of any internal electrical fields. These displacements alter the structure of the component and can affect its function. The total dose effects cause a slow degradation of a component's performance, such as threshold voltage shift or decrease in switching speed, and eventually lead to component failure.

Single Event Effects

The increased density of integrated circuits has resulted in the size of the elementary semiconductor structures shrinking to the level where a spurious current spike produced by a single particle can interfere with the operation of the circuit. These disruptions are commonly known as Single Event Effects (SEE), the three classes of which are [2]:

- *Single Event Upset (SEU)* - occurs when a radiation-induced current causes a memory structure to change its state. This results in a temporary error in device output or its operation and is commonly referred to as "soft error". The device is not damaged and will function properly in the future, but the data processed by the device can be corrupted.
- *Single Event Latchup (SEL)* - occurs when a radiation-induced current activates a parasitic structure (e.g. transistor), which forms an undesired low-impedance path in the semiconductor structure. The circuit typically remain latched up until it is powered off and afterwards it may continue function properly.
- *Single Event Burnout (SUB)* - occurs in power MOSFETs when the current pulse forward biases the source of the device. If the drain-to-source voltage exceeds the breakdown voltage of semiconductor material, the device can burn out due to the large current that will flow.

Sensitivity of an electronic component to SEE in a given environment can be quantified by the Linear Energy Transfer (LET) threshold. The LET is a measure of the energy transferred to material and the LET threshold represents a minimum critical energy that is necessary in order for an SEE to occur.

ENVIRONMENT MODELS AND EQUIPMENT CHARACTERIZATION

Space Environment Models

When designing electronic equipment for a spacecraft it is essential to have a good understanding of the environment the spacecraft will operate in. This includes an understanding of anticipated total dose as well as the density and energy of particles that may cause SEE during the mission.

There are three naturally occurring sources of radiation in space - the trapped radiation belts, galactic cosmic rays and solar particle events [2]. Due to the nature of these sources, the level of radiation experienced by the equipment on-board spacecraft depends on spacecraft trajectory and the time and duration of the mission as well as the epoch in which the mission occurs due to the cyclical patterns of the natural radiation sources.

One of the tools available to designers in their analysis of space environment is the Space Environment Information System (SPENVIS). The SPENVIS was developed by the European Space Agency with the intention to facilitate the use of space environment models in a consistent and structured way [7]. Tools such as SPENVIS can be used to calculate the anticipated TID as well as the flux of particles for a given spacecraft trajectory and mission time and duration and epoch.

Equipment Characterization

In order to quantify the level of radiation tolerance of COTS equipment in a given environment it is necessary to obtain the radiation tolerance characteristics, such as TID and LET threshold, of all critical components used in the design. In practice these characteristics are rarely available for industrial grade components used in COTS equipment. Moreover, the values of both maximum TID and LET threshold of a single component can vary significantly from one manufacturer lot to another and even between batches from the same manufacturer.

While the outlined analytical method provides a logical approach for quantifying the radiation tolerance of electronic equipment, it often needs to be complemented by a test. There are two basic approaches to the radiation testing. The first approach is concerned with the characterization of each component by measuring its maximum TID, LET threshold and SEU rate. The outcome of this test forms an input to the above analytical method that determines the level of radiation tolerance for the analyzed equipment.

The second approach is based on regression tests where the entire equipment or equipment's sub-elements are exposed to a radiation environment representative to that of the space mission. While it is non-trivial to create a representative environment and execute such a test, it is often the only way to characterize COTS equipment and justify it suitability for a space mission. The following section provides practical details of such a test.

DESIGN AND QUALIFICATION OF IXV DATA HANDLING EQUIPMENT

Mission Overview

The European Space Agency (ESA) undertook work on a space mission with important implications for the future of space transportation in Europe. After being launched into space, the Intermediate eXperimental Vehicle (IXV) returned to Earth as if from a low-orbit mission, testing new European atmospheric re-entry technologies. As indicated by its name, the IXV was designed to be the "Intermediate" element of European program for in-flight verification of re-entry technologies. The mission builds on earlier achievements and forms a significant step toward future developments. It is essential for further development of critical technologies required for future European manned and unmanned space missions.

The IXV was launched on 11 February 2015 from Europe's spaceport at Kourou in French Guiana using the new VEGA launcher. The duration of the mission was 102 minutes. After re-entering the Earth's atmosphere the vehicle descended by parachute and landed in the Pacific Ocean to await recovery and post-flight analysis.

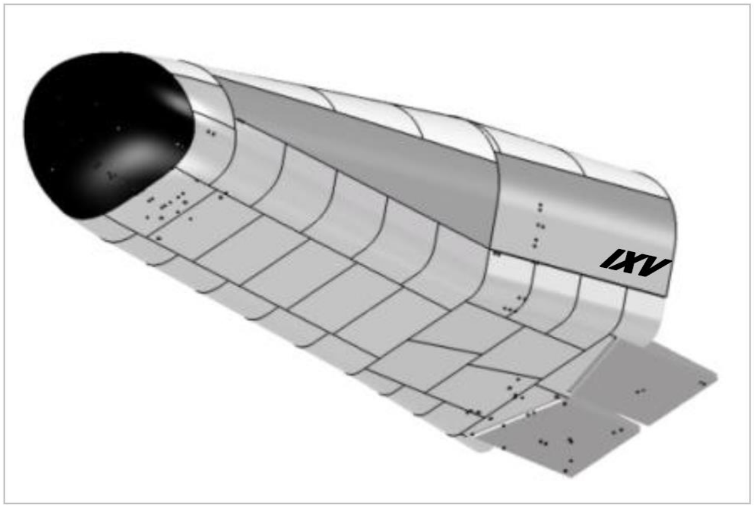

Figure 1: The Intermediate eXperimental Vehicle (Courtesy of ESA)

One of the IXV mission success criteria was the collection and recovery of exploitable flight data and this objective was the driving factor behind requirements for the IXV data handling subsystem. The on-board data acquisition and recording system was designed using COTS equipment manufactured by Curtiss-Wright.

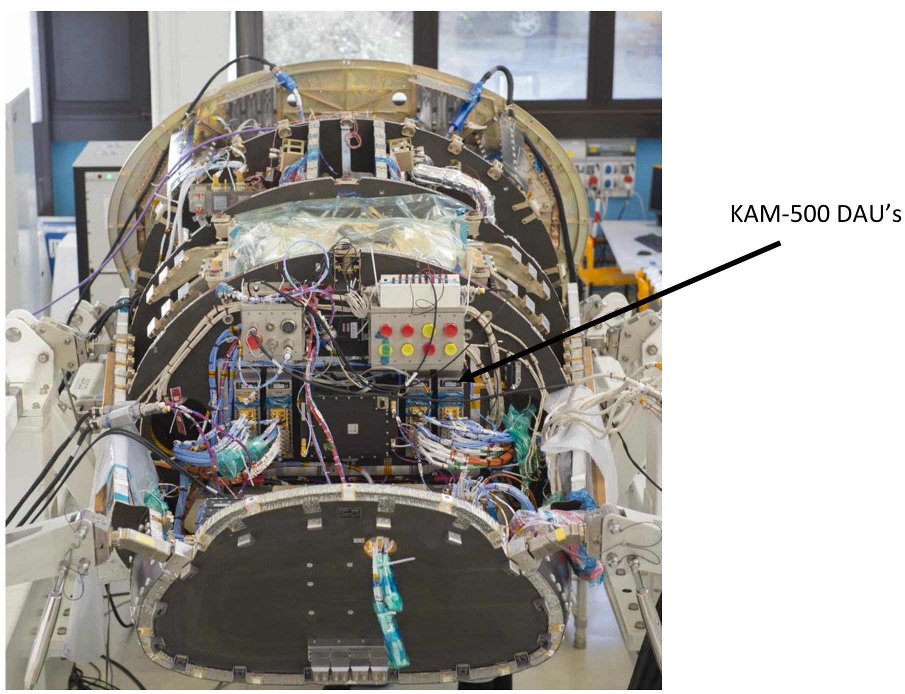

Figure 2: *Curtiss Wright KAM-500 COTS DAUs integrated on the IXV Spacecraft (Courtesy of ESA)*

System Design

Figure 3 shows a block diagram of the data acquisition and recording system for the Experimental layer of the IXV Data Handling System. The system was designed using COTS equipment originally developed for Flight Test applications. The system features four types of network devices - Data Acquisition Units (DAUs), a Network Switch, a Network Gateway and two Recorders.

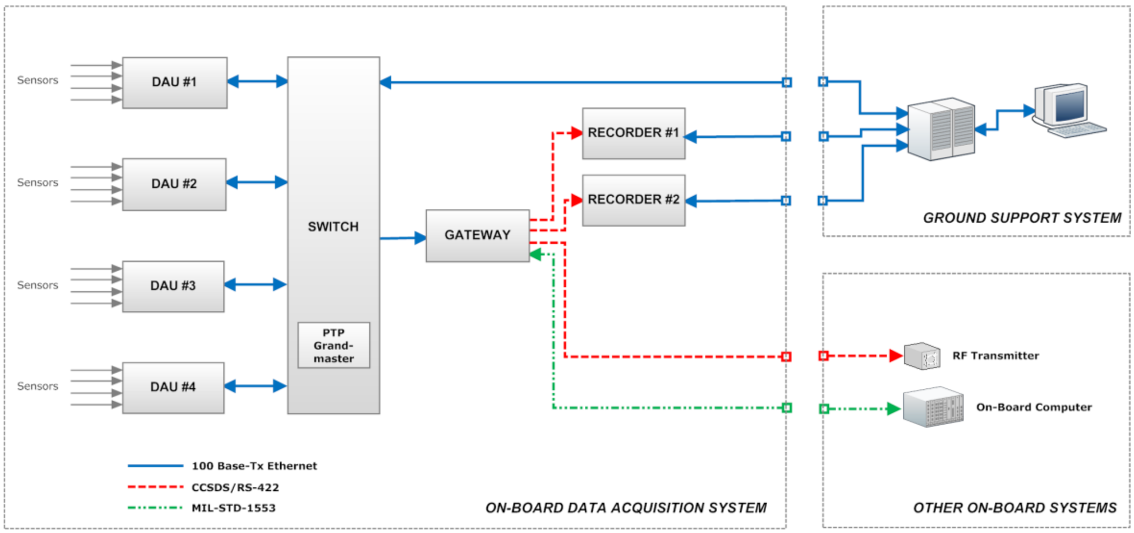

Figure 3: IXV Data Acquisition System

Each of the four DAUs acquires data from a number of sensors. The acquired data is encapsulated into data packets and delivered to the Network Gateway via the Network Switch. A single Ethernet 100Base-TX data link is used for all required network services - data transfer, synchronization, configuration and management. In order to simplify the qualification testing and integration, all DAUs are identical and fully interchangeable.

The Network Switch connects the DAUs to the Network Gateway and ground support system. It was selected from the range of COTS NET-500 switches from Curtiss Wright. It features 8 Ethernet ports and an integrated IEEE 1588 Precision Time Protocol (PTP) Grandmaster.

The Network Gateway receives data packets generated by the DAUs and encapsulates them into CCSDS transfer frames. The gateway creates three copies of CCSDS streams, one for each of the two recorders and one for the RF transmitter. At the data link level the Gateway is connected to the Recorders and Transmitter via an RS-422 link. Additionally, the gateway acts as a MIL-STD-1553 Remote Terminal, extracting predefined parameters from the received data packets and makes them available to the On-Board Computer via a MIL-STD-1553 bus. Like the DAUs, the Gateway is based on a COTS KAM-500 data acquisition system from Curtiss Wright.

The data recording part of the system is dual-redundant. Each of the two Recorders is used to store a copy of CCSDS stream generated by the Gateway. The IXV Recorder was selected from the range of COTS SSR-500 recorders from Curtiss Wright. Because the CCSDS stream at bit-stream level is identical to the PCM stream, a standard network recorder with IRIG-106 PCM interface can be used. The data is stored in Packet CAPture (PCAP) files to a removable CompactFlash® card using the FAT32 file system. During the pre-flight and post-flight operations the ground support system can download recorded data from the recorders using the Trivial File Transfer Protocol (TFTP).

Radiation Qualification

The radiation environment of IXV mission was modelled using SPENVIS tool [7]. The worst-case TID and LET thresholds for the mission were determined by considering the IXV trajectory and time and duration of the mission. The TID qualification limit obtained by the analysis was 100 Rad. The equipment's tolerance to total dose effects in IXV mission environment was verified by TID test (4.3.1). The specified LET threshold qualification limit was 20 MeV. Components with known LET threshold greater than 20 MeV were considered radiation insensitive.

As the COTS equipment had components with LET threshold lower than 20 MeV, a test in a representative radiation environment was required at equipment level in order to characterize the equipment tolerance to SEE as this approach incorporates the mitigations of components operating in-situ. The representative environment for the duration of the mission was modelled using protons with energy of 200 MeV and fluence of 3,500 protons/cm^2. The equipment's tolerance to single event effects in this environment was verified by SEE test (4.3.2).

Total Ionizing Dose Test

A total ionizing dose test was carried out on a representative configuration of KAM-500 Data Acquisition Unit. The test was performed at the European Space Research and Technology Centre in Noordwijk, the Netherlands.

The Device Under Test (DUT) was irradiated using Cobalt 60 gamma rays with a constant dose rate of 39.6 Rad (Si) per hour. The DUT was fully operational during the test and its performance was continuously monitored by real-time data analysis software. The aim of the test was to establish the TID level at which the DUT fails to be fully functional. Figure 4 shows the layout of the Cobalt 60 gamma ray facility.

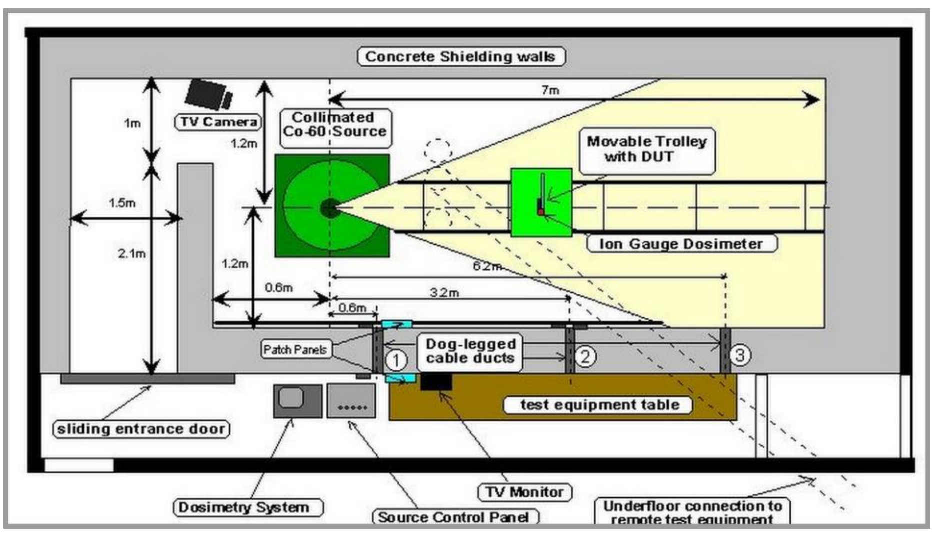

Figure 4: Cobalt 60 gamma radiation facility (Courtesy of ESA)

The first performance degradation was detected after 197.3 hours, when one of 47 monitored acquisition channels showed an incorrect reading. The test was terminated shortly after the failure occurred.

At the rate of 39.6 Rad/hour the DUT accumulated the total ionizing dose of 7,813 Rad before the first failure was detected. This measurement exceeds the IXV TID qualification limit with a significant margin of more than two orders of magnitude.

Single Event Effects Test

A single event effect test was carried out on a representative critical sub-element of the IXV data acquisition system. The KAD/BCU/140, a KAM-500 backplane controller with Ethernet interface, was selected as a representative design of the four network devices used in the IXV system. Two samples of KAD/BCU/140 were used as the Device Under Test (DUT) for this investigation.

The test was carried out at the Proton Irradiation Facility of Paul Scherrer Institute in Switzerland. During the test the DUT was exposed to a high-energy proton beam. The performance of the DUT was continuously monitored by the real-time analysis of data received from the DUT and by measuring DUT’s power consumption.

The data generated by the DUT was analysed with the intention to detect potential Single Event Upsets (soft errors) caused by interaction of high-energy protons with the components on the DUT. In order to detect a SEU caused soft error the input data stream was compared bit for bit with the output data stream from the DUT. In the order to detect Single Event Latchup, the current drawn by the DUT was continuously monitored. A protection circuit was used for switching the power off if the current exceeded the nominal current by 15%. The nominal current of the DUT was 300mA and the threshold for switching off the power was set to 345mA. Figure 5 shows the test setup with two DUTs positioned in the front of proton beam.

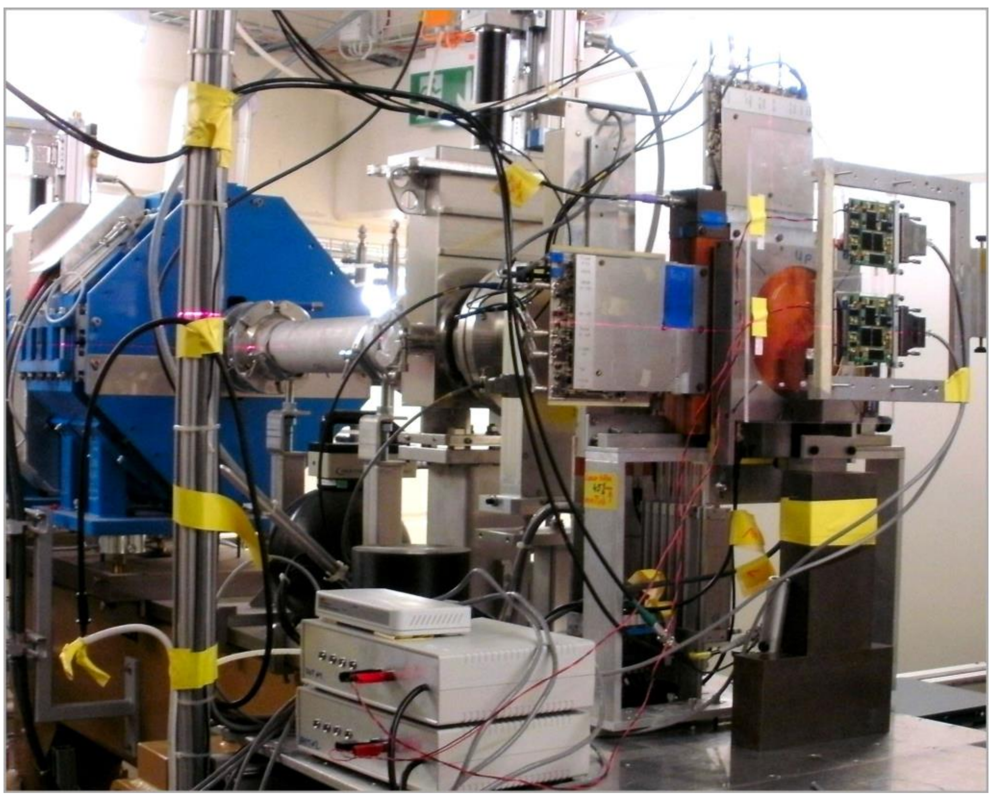

Figure 5: DAU controller module in the front of high-energy proton beam

Multiple irradiation tests were carried out with each DUT. While the energy of protons was kept at 200MeV, the proton flux was incrementally increased until an event was observed. Table 1 summarises the test results.

Flux [p.cm^{-2}.s^{-1}]	**Elapsed Time [s]**	**Fluence [p.cm^{-2}]**	**SEU Detected**	**SEL detected**
200	17.5	3,500	No	No
200	175	35,000	No	No
2,000	175	350,000	No	No
20,000	175	3,500,000	No	No
100,000	417	41,700,000	No	Yes

Table 1: Summary of SEE radiation test

No single event upsets were detected during the test. The first latchup event was detected at the total fluence of 41.7 x 10^6 p.cm^{-2} which was the equivalent of approximately The latch-up event caused an increase in the current drawn by the DUT, which activated the power supply protection and the power was switched off. After the power was re-applied the DUT continued to function properly. The test was repeated four times with similar results. The current measured during the test and its increase caused by the irradiation is shown in Figure 6.

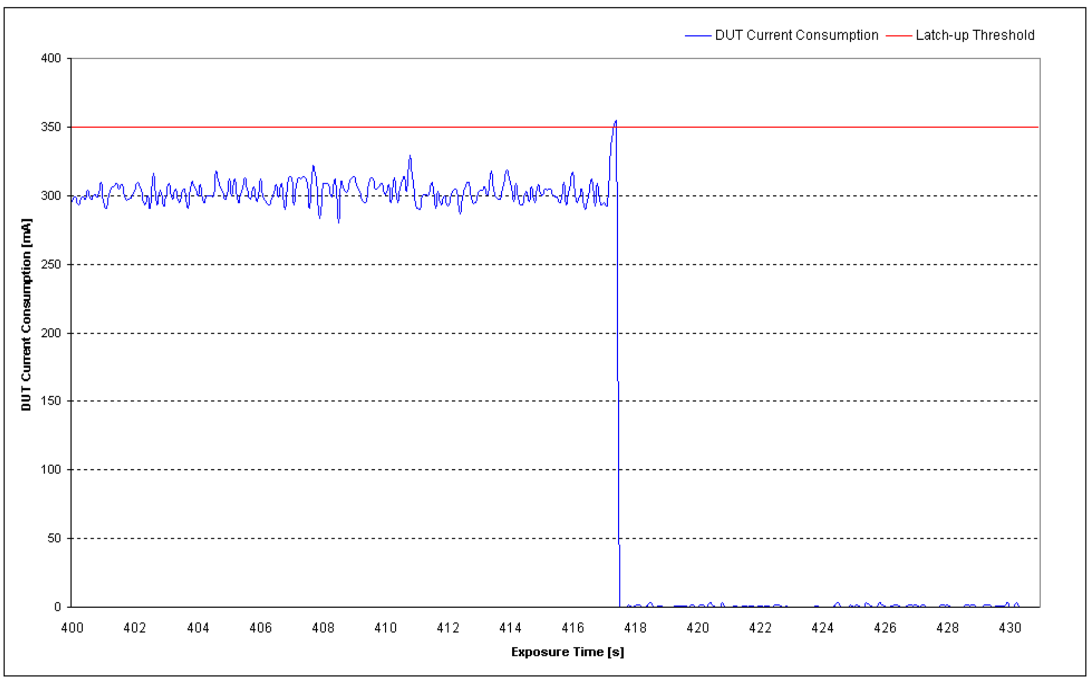

Figure 6: Current consumption during high-energy proton test

The results of SEE test illustrate a relatively high level of radiation tolerance of the COTS design. The events were not observed with fluence levels representing the IXV mission environment (3,500 p.cm^{-2}). Moreover, the fluence at which the events were detected exceeds the IXV SEE qualification limits by four orders of magnitude.

MISSION DATA SAMPLE

The data displayed in Figure 7 is actual temperature data from a single Thermocouple sensor acquired using Curtiss Wright COTS equipment on-board the IXV spacecraft during the re-entry phase of the mission.

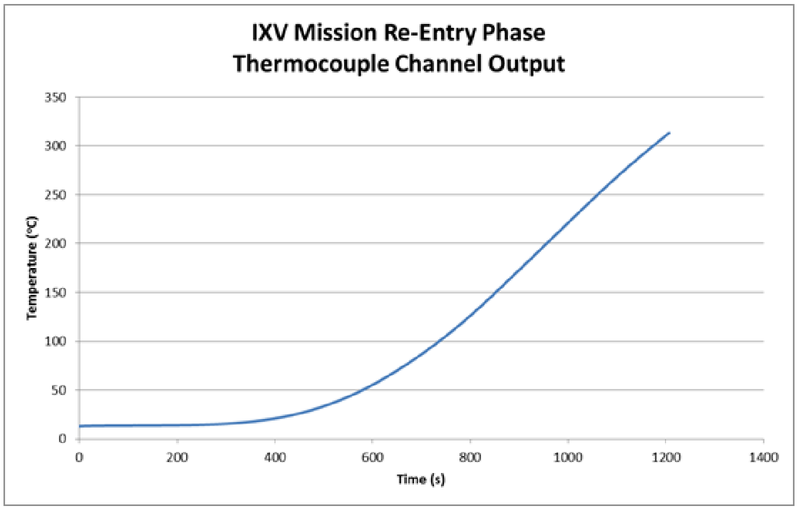

Figure 7: Thermocouple sensor data from IXV Mission

CONCLUSION

This paper outlined the challenges associated with the use of COTS equipment in space missions. Specifically the impact of radiation effects caused high energy particles present in the space environment on electronic equipment was discussed.

It was proposed that concerns about application of COTS equipment in radiation environment can be addressed through test in a multi-step process called Space COTS Qualification. The practical use of this approach was demonstrated by the radiation qualification tests performed on COTS data acquisition and recording equipment from Curtiss Wright, originally tasked for use in aircraft flight test and then used successfully as the on-board data handling system for ESA's IXV re-entry spacecraft.

The test results achieved and the success of the IXV mission using the Space COTS Qualification methodology demonstrates that COTS equipment can be used to replace costly highly specialized equipment and that Curtiss Wright Space COTS equipment provides a reliable and cost-effective solution for a wide range of space missions.

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