Commercial Off-The-Shelf (COTS) Graphics Processing Board (GPB) Radiation Test Evaluation Report

George A. Salazar  
Johnson Space Center, Houston, Texas

Glen. F. Steele  
Johnson Space Center, Houston, Texas

National Aeronautics and Space Administration  
Johnson Space Center  
Houston, TX 77058

December 2013
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA’s STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.**
  Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.**
  Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.**
  Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.**
  Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- **SPECIAL PUBLICATION.**
  Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.**
  English-language translations of foreign scientific and technical material pertinent to NASA’s mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at [http://www.sti.nasa.gov](http://www.sti.nasa.gov)
- E-mail your question to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Information Desk at 443-757-5803
- Phone the NASA STI Information Desk at 443-757-5802
- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320
The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802
Abstract

Large round trip communications latency for deep space missions will require more onboard computational capabilities to enable the space vehicle to undertake many tasks that have traditionally been ground-based, mission control responsibilities. As a result, visual display graphics will be required to provide simpler vehicle situational awareness through graphical representations, as well as provide capabilities never before done in a space mission, such as augmented reality for in-flight maintenance or Telepresence activities. These capabilities will require graphics processors and associated support electronic components for high computational graphics processing.

In an effort to understand the performance of commercial graphics card electronics operating in the expected radiation environment, a preliminary test was performed on five commercial off-the-shelf (COTS) graphics cards. This paper discusses the preliminary evaluation test results of five COTS graphics processing cards tested to the International Space Station (ISS) low earth orbit radiation environment. Three of the five graphics cards were tested to a total dose of 6000 rads (Si). The test articles, test configuration, preliminary results, and recommendations are discussed.
Table of Contents

Abstract ......................................................................................................................................... 1
Table of Contents .......................................................................................................................... 2
List of Figures .................................................................................................................. 2
List of Tables ................................................................................................................................. 2
Acronyms ...................................................................................................................................... 3
1.0 Introduction ............................................................................................................................. 4
2.0 Testing .................................................................................................................................... 4
  2.1 Test Article Description ........................................................................................................... 4
  2.2 Test Approach ......................................................................................................................... 5
  2.3 Test Results ............................................................................................................................ 7
3.0 Conclusion and Recommendations ...................................................................................... 10
  3.1 Conclusions ....................................................................................................................... 10
  3.2 Recommendations ............................................................................................................ 10
4.0 References ............................................................................................................................ 11

List of Figures

Figure 1  GPC Radiation Test Setup ............................................................................................ 6
Figure 2  Graphics Processing Card Jig .......................................................................................... 7
Figure 3  Motherboard and support Components Radiation Shielded ........................................... 7
Figure 4  Windows Startup Display Screen .................................................................................. 8
Figure 5  Example Graphic Failure Display Error ......................................................................... 8

List of Tables

Table 1 Graphic Processing Unit Key Specifications .................................................................... 5
Table 2 Radiation Screening Results ............................................................................................ 7
Table 3 Mean Time to Functional Interrupt Results ...................................................................... 9
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEO</td>
<td>Beyond Earth Orbit</td>
</tr>
<tr>
<td>CAT 5</td>
<td>Category 5</td>
</tr>
<tr>
<td>CLK</td>
<td>Clock</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial off the Shelf</td>
</tr>
<tr>
<td>FI</td>
<td>Functional Interrupt</td>
</tr>
<tr>
<td>GPC</td>
<td>Graphics Processing Card</td>
</tr>
<tr>
<td>HD</td>
<td>High Definition</td>
</tr>
<tr>
<td>HDMI</td>
<td>High Definition Multimedia Interface</td>
</tr>
<tr>
<td>IUCF</td>
<td>Indiana University Cyclotron Facility</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>MTTFI</td>
<td>Mean Time to Functional Interrupt</td>
</tr>
<tr>
<td>PCI-e</td>
<td>Peripheral Component Interface-extension</td>
</tr>
<tr>
<td>Pwr</td>
<td>Power</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>TID</td>
<td>Total Ionizing Dose</td>
</tr>
<tr>
<td>VGA</td>
<td>Video Graphics Array</td>
</tr>
</tbody>
</table>
1.0 Introduction

NASA is investigating deep space mission concepts and the systems necessary to support those missions. Large round trip communications times for deep space missions will require more onboard computational capabilities as the space vehicle is required to take on more of what used to be mission control responsibilities. Architecture concepts under development require the use of graphics processing hardware to enable increased situational awareness of the vehicle through high resolution graphics. Additionally, applications targeting the maintenance of astronaut health, both psychological and physiological, will be necessary (i.e. Telepresence/Telemedicine and augmented reality for just-in-time training or maintenance). However, no known radiation test of graphics processing cards (GPC) has been identified to understand how well they would work in the space environment.

To obtain initial radiation test data of electronic components found in commercial GPCs, five commercial off-the-shelf (COTS) GPCs were tested to the International Space Station (ISS) low earth orbit (LEO) radiation environment. The testing occurred at the Indiana University Cyclotron Facility (IUCF). It should be understood that COTS GPCs were not designed or intended to operate in the space environment—they were designed to operate in an ambient terrestrial application. However, the radiation testing served to get an initial rough assessment of how well these specialized processing cards would operate if their design were deployed in a space application.

This report is organized as follows. First, the test articles description is presented, including specifications. The test setup is described along with the methodology used to test the cards. Then, the test results are disseminated. Finally, the report concludes with a brief summary of the test results and recommended future GPC testing.

2.0 Testing

2.1 Test Article Description

Five COTS GPCs were acquired to perform a limited GPC radiation test evaluation. The selection of the GPCs was based on immediate availability and cost. However, at least one of the five was required to be a high performance GPC. Table 1 shows the GPCs that were selected along with their key performance specifications. Note that the GTX 650 has a high speed core and memory clock frequency as well as a large number of processing graphics cores. It also scored the highest/best based on the 3D Mark 11 benchmark program. The 3D program is used to assess performance of a graphics card 3D rendering and CPU workload processing capabilities.

All cards had a Peripheral Component Interface-extension (PCI-e) bus to a computer. In addition, all cards have a High Definition Multimedia interface (HDMI). HDMI was used to transmit the output of the graphics card to a display monitor located in the control room to view anomalies during the irradiation of the card. The lowest performing card based on the 3D Mark 11 benchmark was the GE Force 8400 GPC.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSI HD6450</td>
</tr>
<tr>
<td><strong>Chipset Mfg.</strong></td>
<td>AMD</td>
</tr>
<tr>
<td><strong>GPU</strong></td>
<td>Radeon HD 6450</td>
</tr>
<tr>
<td><strong>Core Clock</strong></td>
<td>625 MHz</td>
</tr>
<tr>
<td><strong>Memory Clock</strong></td>
<td>1333 MHz</td>
</tr>
<tr>
<td><strong>Memory Size</strong></td>
<td>1 GB</td>
</tr>
<tr>
<td><strong>Memory Interface</strong></td>
<td>64-bit</td>
</tr>
<tr>
<td><strong>Memory Type</strong></td>
<td>DDR3</td>
</tr>
<tr>
<td><strong>OpenGL</strong></td>
<td>OpenGL 4.1</td>
</tr>
<tr>
<td><strong>RAMDAC</strong></td>
<td>400 MHz</td>
</tr>
<tr>
<td><strong>Max Resolution</strong></td>
<td>2560 X 1600</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Fan</td>
</tr>
<tr>
<td><strong>Pwr Requirement</strong></td>
<td>Min. 400 Watt Power Supply</td>
</tr>
<tr>
<td><strong>Processors/CUDA Cores</strong></td>
<td>160 Stream Processors</td>
</tr>
<tr>
<td><strong>3D Mark 11 Score</strong></td>
<td>480</td>
</tr>
</tbody>
</table>

### 2.2 Test Approach

Resources and time limitations resulted in performing a coarse rather than a fine test of each GPC. This meant that the entire card was irradiated rather than selective shielding of the different sections of the GPC to determine what components were susceptible to radiation.

All five GPCs were first evaluated by an initial irradiance screening to determine how much fluence each GPC accumulated after at least six (6) data points of failures occurred. The top three (3) performers were selected to continue irradiating them until they reached a Total Ionizing Dose (TID) of 6000 rads (Si). A demo graphics benchmark program called Tropic from Unigine Corporation was launched, the entire card irradiated, and the output of the GPC viewed on a display and recorded.

Figure 1 shows the setup used for testing each GPC. The chamber room contained the motherboard that connected to the GPC via a PCIe extender cable. In addition to the motherboard, a hard disk and power supply that powered the motherboard and GPC were co-located on the test table. The hard disk contained the Windows Operating System files and the graphic card benchmark program used to run the GPC.

Four 100-foot cables ran from the control room to the system in the chamber: Category 5 (CAT 5) Ethernet, Video Graphics Array (VGA), High Definition Multimedia Interface (HDMI) and a 2-wire remote switch. The CAT 5 Ethernet cable was used to send keyboard commands from the
laptop to the motherboard. The VGA cable provided output status of the motherboard to a display in the control room. The HDMI cable provided the output of the graphics card device under test (DUT) to another display in the control room. An HD camera was used to record the GPC display and capture any anomalies that occurred.

![Diagram of GPC Radiation Test Setup](image)

**Figure 1 - GPC Radiation Test Setup**

Since the test objective was to irradiate the GPC and not the electronics that drove the card, a GPC test jig was developed to permit radiation to reach the GPC DUT but protect the motherboard from the beam. Figure 2 shows a block diagram of the test jig used to separate the motherboard and associated support components and the GPC via the PCIe extender cable. Figure 3 shows the motherboard and associated support components shielded with lead bricks and boron impregnated plastic.
The 100-foot 2-wire cable was used to provide a remote power switch function to control power to the motherboard in case of a latch up or other hardware problem. In the event of a hard failure, a momentary push button could be depressed to power cycle the motherboard and GPC. The motherboard power supply contained over voltage/power and short circuit protection.

2.3 Test Results

Screening all five GPCs resulted in selecting the top three performers. All the failures that occurred were functional interrupts (FI) where the program stopped working and required a reboot or power cycle to regain control of the system. Table 2 shows the results of the screening and the top three winners highlighted in red.

<table>
<thead>
<tr>
<th>Graphics Card</th>
<th>Impregnated Boron</th>
<th>Lead</th>
</tr>
</thead>
</table>

The top three GPCs were each tested until the card reached a TID of 6000 rads (Si). Though the cards had several failures, none of the cards experienced a permanent failure.
Initially, the plan was to use the graphic card benchmark program while the card was irradiated. However, it became evident from the number of reboots/restarts and time to do the reboots/restarts (due to FIs) that running the benchmark program was not the best approach. Hence, rather than run the benchmark program, a decision was made to use the Windows startup screen as seen in Figure 4 as the test case for the radiation test. This provided a simpler and faster way of testing the GPCs. The reasoning was that since the graphics card displayed the Windows startup screen, radiation upsets to the card would result in the screen displaying anomalies.

Figure 5 is a representation of some of the display output anomalies captured with the video recording. Also, during the irradiation, the mouse was moved around the screen. If the mouse stopped moving, it suggested that the graphics card stopped operating. Typically, when the graphics card stopped responding or output became corrupted, a common failure message that Windows operating system outputted was “D3D11 Appwindows.swap()device remove” which suggested the card became unstable and timed out. However, there were a few times where the screen went blank as well. A power cycle regained control of the system.

![Figure 4 - Windows Startup Display Screen](image)

![Figure 5 - Example Graphic Failure Display Errors](image)

The Mean Time to Functional Interrupt (MTTFI) of each card including the two that did not make the final selection is shown in Table 3. The MTTFI calculation is computed using the Bendel A method.
### Table 3 - Mean Time to Functional Interrupt Results

<table>
<thead>
<tr>
<th></th>
<th>MSI HD6450</th>
<th>Diamond HD 5450</th>
<th>PNY GE force GTX 650 Ti</th>
<th>MSI GE force GT 640</th>
<th>EVGA GE Force 8400</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTTFI (Days)</td>
<td>43.1</td>
<td>15.5</td>
<td>15.7</td>
<td>19.6</td>
<td>14.8</td>
</tr>
</tbody>
</table>
3.0 Conclusion and Recommendations

3.1 Conclusions

Several design factors affect a system or card’s MTTFI performance which includes the inherent radiation tolerance of the components, operating voltages, and radiation single event effects mitigation strategies. Commercial card manufactures are not interested in designing for the radiation environment – that market is small compared to the commercial market (i.e. gaming). The radiation test levels environment for LEO these cards were subjected to is benign (earth’s magnetic shielding and spacecraft shielding) compared to Beyond Earth Orbit (BEO) where places like the moon or MARS have little to no magnetic shielding.

Though the radiation test of the five GPCs did not meticulously test the board, it did provide preliminary data regarding use of commercial GPCs operating in the LEO environment. However, because each board was entirely irradiated, it is not known what component(s) caused each board’s failures. Further detailed testing would be required to determine that.

Based on the GPCs specifications and the MMTFI results, no correlation appears between high performing GPUs and radiation tolerance. The 6450 faired the best with respect to MMTFI of 43.1 days though it was not the highest performing GPC when measured against the 3D Mark 11 benchmarking program it was tested to by the vendor. The highest performing GPC (GTX 650) scored near the bottom with respect to MTTFI performance. The lowest 3D Mark 11 benchmark performing GPC was the GE Force 8400 which also scored the lowest in MTTFI performance. However, the performance of a HD 6450 may suffice depending on the LEO space application.

3.2 Recommendations

Based on the results of the testing, some recommendations are presented:

1. To identify/understand radiation-susceptible parts on the HD 6450 GPC, further testing should include more detailed pre-test planning that includes x-raying each board, identify components used on the board, and determining beam positions/shielding out components not of interest in the beam position.

2. Since the testing was performed to the LEO radiation environment, it is unclear how well the best performing board would operate in a BEO environment. Extrapolating the LEO results from LEO to BEO results is not possible. Therefore, performing heavy ion testing is the only way to understand BEO performance of the candidate GPC.
4.0 References


