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Physics 4900 Senior Project

Final Report

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Microcontroller Survivability in Space Conditions

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Introduction

The Utah State University (USU) Materials Physics Group (MPG) is interested in the performance of Commercial Off the Shelf (COTS) microcontrollers in space conditions. Microcontrollers are commonly used on CubeSats, small relatively inexpensive satellites that are flown in Low Earth Orbit (LEO) at altitudes of ~160 km-2000 km. There is a large area of interest in COTS microcontrollers because they provide a more cost-effective on-board computer for CubeSats. This experiment focused on the functionality of an ATmega328 microcontroller on an Arduino Uno board inside the MPG's Space Survivability Test (SST) Chamber. A diagnostic program was used to try to detect radiation effects on the microcontroller, including both soft errors and permanent failures. ArduSats is the coined term for CubeSats that use Arduino boards for space flight [1]. Though ArduSats are typically used for educational purposes, the results from this research and proposed related tests could shed light on a CubeSat's (particularly an ArduSat's) ability to pursue extended space missions into more radiation intensive environments such as Geosynchronous orbits and lunar missions.

Space Environment and Effects

The main component of space environments examined in this experiment was radiation exposure; however, the test was performed in vacuum. Different orbits expose satellites to various levels and types of radiation. The LEO dose level is about 2 krad/yr. This is relatively low compared to the Medium Earth Orbit (MEO) (~100 krad/yr at 2000 km-35000km) and GEO (~50 krad/yr above 35000 km) [2]. These values could be assuming some minimal amount of shielding. As seen in Figure 1, some regions of space have a high electron flux, such as LEO, but the energy of these electrons is relatively low. This means that the microcontroller can be protected from a large portion of these electrons with very minimal shielding.

Microprocessors can experience failures ranging from soft errors to total system failure due to radiation effects. A soft error, also known as a single-event upset (SEU), is when radiation causes enough of a charge disturbance to alter the state of a memory bit. These are called

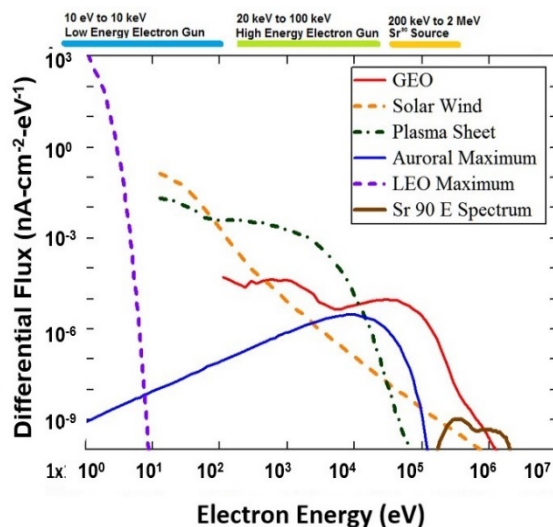


Figure 1: Electron flux versus electron energy in various space environments (Sr⁹⁰ source is ~200keV~2MeV) [3].



Figure 2: SST chamber with CubeSat setup.

soft errors because they are repairable, and the system is still functional after an SEU. There are both multibit upsets and single bit upsets, but the latter is more common [4]. A single-event effect (SEE) happens when high-energy particles in the space environment strike the components of the microcontroller circuit [5]. An SEE can cause a range of damage including, no observable effect, a transient disruption of circuit operation, a change of logic state, or even permanent damage to the device or integrated circuit (IC) [5].

The microelectronic circuits in this experiment are particularly susceptible to radiation because of their physical size. They are small enough that an energetic particle can change the device state or destroy a trace. In some cases, these high-energy particles can even destroy portions of the microcontroller's memory. Beta radiation hits these circuits with electrons, causing the SEE's. The long-term damage done by radiation in space environments is typically due to the total ionizing dose (TID), which is the total amount of radiation an object is exposed to.

Chamber Capabilities

The SST chamber (Figure 2) contains ~100 mCi Sr^{90} beta radiation source (Figure 3) that provides a dose rate of ~0.1 krad/hr at a 30 cm distance over a 15 cm diameter sample area [3]. This dose rate provides an upper bound approximation of the dosing rate in GEO with minimal shielding. To expedite the testing process, the distance to the radiation source can be decreased; this relationship is shown in Figure 3. Since the dose rate was only important as it related to the total ionizing dose (TID), the Arduino board with dimensions of ~7cm x ~5.5 cm was moved to ~9 cm from the source, increasing the TID rate to ~0.991 krad/hr, but decreasing the diameter of a uniform dose to ~4.5 cm. The ATmega328 chip was centered under the source since this experiment was focused on the microcontroller. There are many instrumentation cabling feedthroughs available on the SST chamber, including both USB and D-pin serial adapters, able to accommodate a maximum voltage of 100 V and a maximum current of 1 A.

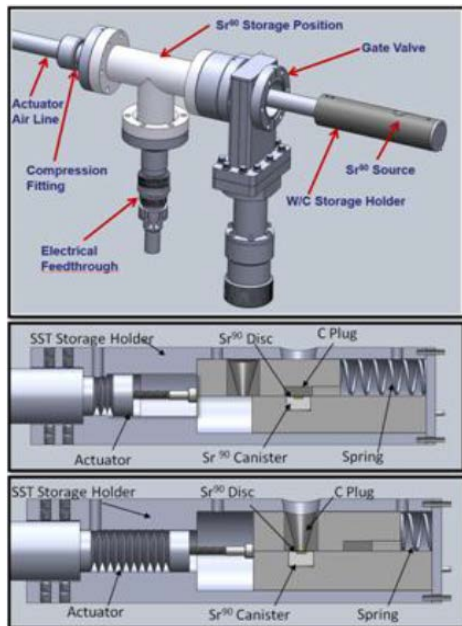


Figure 3: Sr^{90} source. (a) Exterior view. Cutaway views while in the (b) closed and (c) exposure positions [3]. respectively. [2]

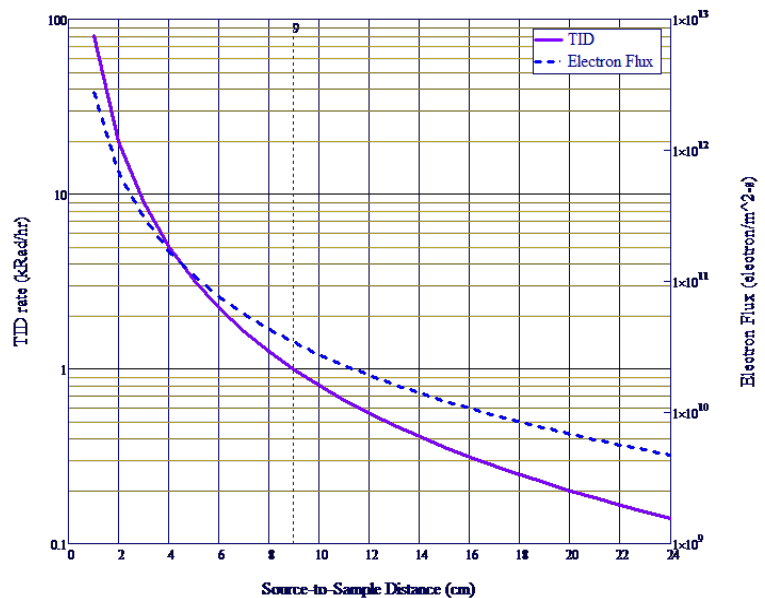


Figure 4: TID versus Source-to-Sample Distance (~9 in. for this test).

Table 1: Specifications of the types of memory in the ATmega328 microcontroller.

Memory Name	Memory Type	Size (kB)	Number of Transistors (~2/byte)	Transistor Density (Transistors/mm ²)
Flash	Non-volatile	31.5 Application/ 0.5 Boot Loader	~64000	~8410
SRAM	Volatile	2	~4000	
EEPROM	Non-volatile	1	~2000	

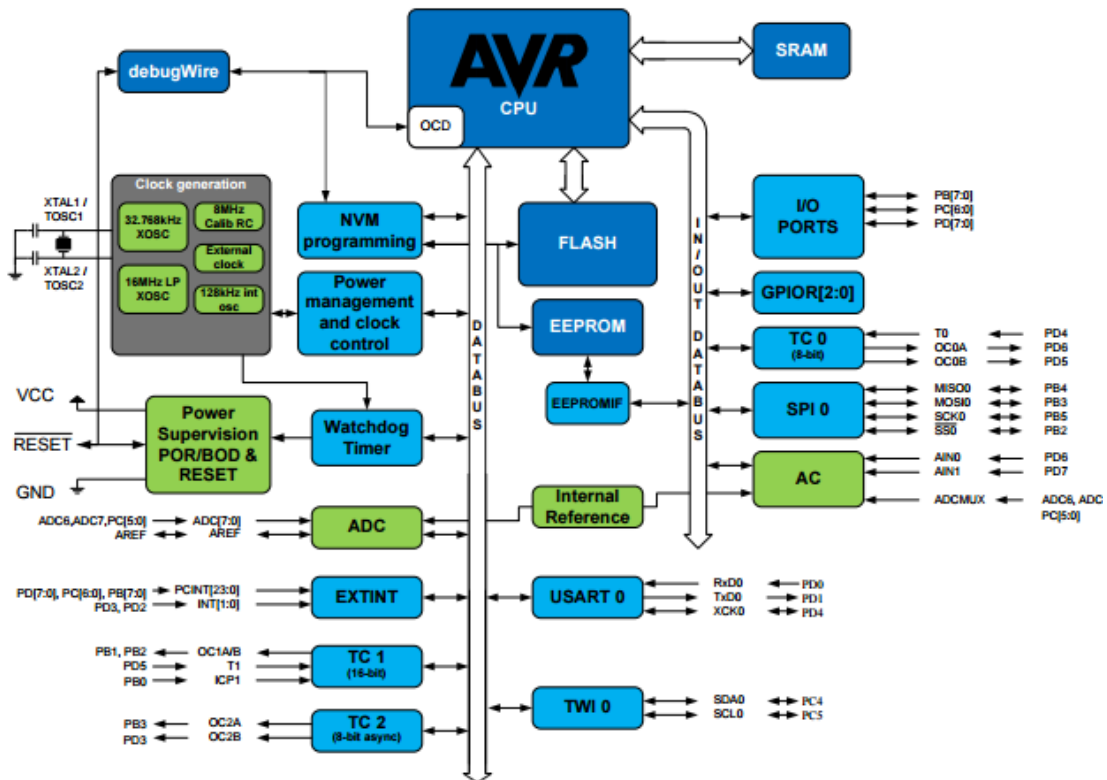


Figure 5: ATmega328 microcontroller block diagram [6].

Microcontroller Design

The microcontroller used in this experiment was an ATmega328 on the Arduino Uno development board (Atmel, ATmega328/P). There are three types of memory associated with this microcontroller: Flash, SRAM, and EEPROM (Table 1). As can be seen in Figures 5 and 6, the Flash memory is physically the largest memory portion of the chip, which makes it the most susceptible of the three memory sections to radiation damage. The Flash memory is where the program is uploaded and stored in the microcontroller. This memory is divided into two physical regions: the Boot Loader and Application section [5]. The Boot Loader section contains firmware that aids in programming the microcontroller when using the *Arduino Integrated Development Environment (IDE)*. This leaves the Application section to store any program that is written to the microcontroller [6]. Flash memory is non-volatile memory which means the information stored there remains even when the power is turned off. Static Random Access Memory or SRAM is the portion of memory used by the program to create and manipulate variables. Unlike the Flash memory, the

SRAM is volatile memory, meaning that all information stored there is deleted every time the microcontroller is turned off. Lastly, the electrically erasable programmable read-only memory (EEPROM) is dedicated space to save long-term information, making it non-volatile memory.

Since there is a high volume of open source Arduino code on the internet, code was taken and modified for the purposes of this experiment. The bulk of this code was left unchanged from what was found online. The original code was created by Terry King and can be found at arduino-info.wikispaces.com/Arduino_Test. The program used assumes that pins 0, 1, and 13 work if the program can be uploaded and if the on-board LED can blink, therefore this program does not test these pins. Digital pins 2-12 and analog pins A0-A5 each had 220 Ω resistors connected to each other in parallel. These resistors were then connected in series to the 5-Volt power supply and the ground through 100 k Ω resistors (see Figures 7 and 8). The circuit design created a voltage divider that provided each of the common points with 2.5 V when the pins were set to high input. The code runs a total of three types of tests to ensure that all the pins were functioning properly.

The first test uses the first analog pin (A0) to see if the common points are at anything besides 2.5 V, which would indicate that a pin was stuck in a High or Low state or is not properly set to either state. The next type of test sets pins 3-A5 to the High or Low state and setting pin 2 to the opposite state. Each of the pins are individually tested against pin 2 and must be able to sink or source the proper amount of current to pass the test. The last type of test verifies that the analog pins read out the correct voltages when supplied with various voltages. If any failures are detected by the program, they are then summed and a read out of how many failures occurred during the test is displayed at the end of the print out. A delay function is at the end of the code to allow the user to run the code at whatever the desired frequency is. This program takes ~2 seconds to run through all the tests and output the data. This code is named *King_Olsen_Diagnostics.ino* and can be found in the raw data compressed file given separately.

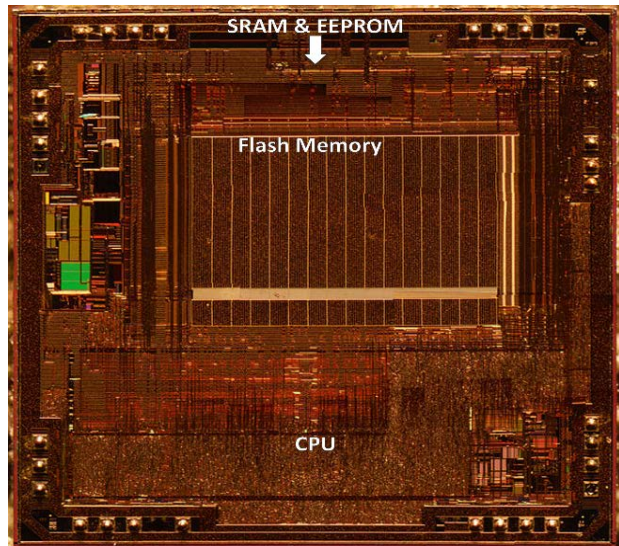


Figure 6: Atmega328 microcontroller die [7].

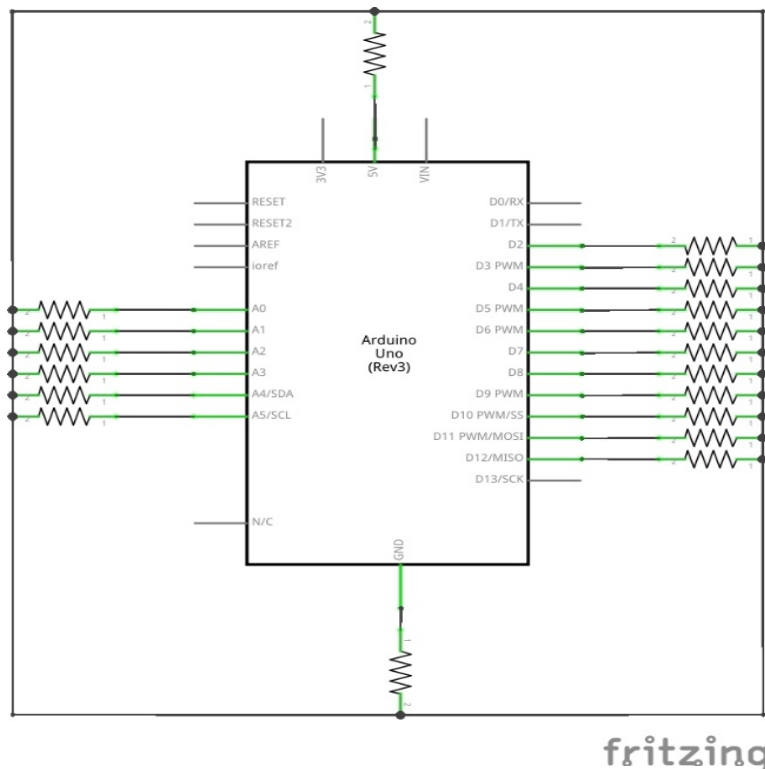


Figure 7: Schematic of the diagnostics testing setup

The Arduino IDE was the code writing environment used in this project. Although Arduino IDE allows programs to output data to the Serial Monitor, the output is not archived anywhere. Therefore, the only way to save information from the Serial Monitor is to copy and paste the output into a text file once data is acquired. This is not the most reliable way to save the data because if the Serial Monitor is closed for any reason during the test, all that data is lost. Therefore, the Serial Monitor was only used for quick checks to ensure that the program was performing properly and another program called *CoolTerm* from www.freeware.the-meiers.org was used to save the data. *CoolTerm* allowed for the user to record the data to a text file and monitor the program at the same time. Another necessary feature for archiving the data was parallel serial monitoring. The Arduino IDE only allows for one Serial Monitor window to be open at a time while *CoolTerm* allowed the user to run, watch, and save data from two different setups at once. This feature was important because while an Arduino was being tested in the chamber (referred to as the “test Arduino”), an identical setup was being tested outside the chamber without radiation exposure (referred to as the “control Arduino”) and both of their data needed to be recorded. The control Arduino provided information about how the microcontroller performed of an extended period without radiation exposure. *CoolTerm* also allowed all of the data to be timestamped as it was being saved into a text document.

How frequently the diagnostic code is running is directly related to the probability of recording a soft error. As previously mentioned, SEU’s are temporary failures in the system being tested, which makes them more difficult to test. Simply taking more data helps in the detection of these soft errors. If the test is running less frequently, then the SEU could occur and the affected bit could go back to normal before the program is run again. The program was set to run every fifteen minutes and it took 2 seconds to complete. Therefore, the Arduino was only being tested 8 secs/hr or 1/450 of the testing duration.

Testing

The chamber Arduino was placed on top of a large beaker with a piece of Kapton-insulated graphite inside the SST Chamber (Figure 9) to increase the TID rate to ~1 krad/hr. Because the main objective was to test the microcontroller, the Arduino was positioned so the ATmega328 chip was centered under the radiation source. The Arduino communicated with the computer via a ~58 cm USB type B cable (Figure 10) designed for this experiment. The high vacuum compatible cable was made of four Kapton-insulated wires that were braided into two wire pairs to minimize ground loop noise and put inside a coaxial copper braided sleeve. The end of the cable opposite to the Arduino had pins sockets that connected to the vacuum electrical feedthrough pins inside the chamber. On the outside of the chamber, a ~185 cm standard USB type A cable with four pins was connected to the computer and the corresponding pins on the outside vacuum electrical feedthroughs.

The diagnostic code was tested with a 1 second delay while the vacuum chamber pumped down to a pressure of $\sim 1.7 \times 10^{-7}$ torr and the radiation source was not in place. The delay was then changed to 10 seconds with the closed source inserted into the chamber. The source was then opened and the Arduino was

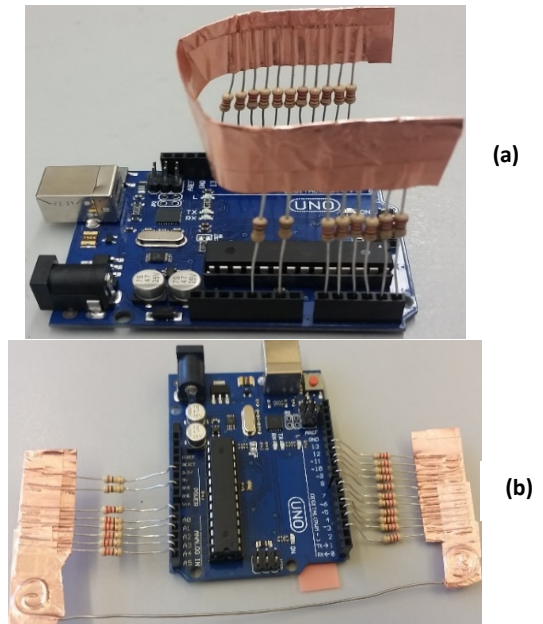


Figure 8: Diagnostic setup. (a) Control setup. (b) Chamber setup.

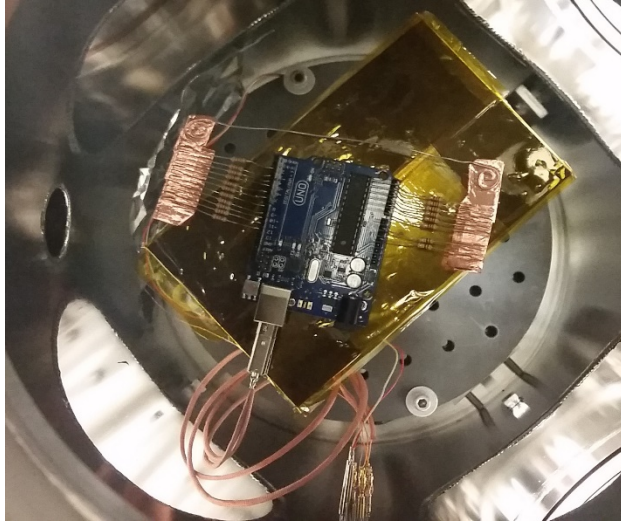


Figure 9: The test Arduino placement inside the SST chamber.



Figure 10: USB type B cable with an enlarged view of the sockets used for the cabling feedthrough.

monitored in this configuration for 35 minutes. Finally, the delay was set to run once every 15 minutes, to keep the amount of data to a reasonable amount, presumably until a failure was observed. A control Arduino outside the chamber followed these same configurations for the entirety of the test.

Results

After ~188 hours of exposure (~186 krad), the diagnostic code had not detected any pin failures while running in 15 minute intervals. In an attempt to detect SEU's, it was proposed to reupload the program with a shorter delay. The 15 minute delay was replaced with a 10 second delay. However, when trying to upload the adjusted code, an error message was produced. This error message read “avrdude: verification error; first mismatch at byte 0x133f 0xea != 0xe6; avrdude: verification error; content mismatch; avrdude: verification error; content mismatch”. An error such as this indicates an issue in either the memory or communications with the computer. The same error message was produced with each attempt at uploading any sort of code to the test Arduino. Also, the diagnostic code was successfully uploaded to a third Arduino. These exercises ruled out a communications issue, leaving a failure in the memory. The location of the mismatched byte is given in the message as 0x133f, 4927 in decimal. From examining the memory maps of

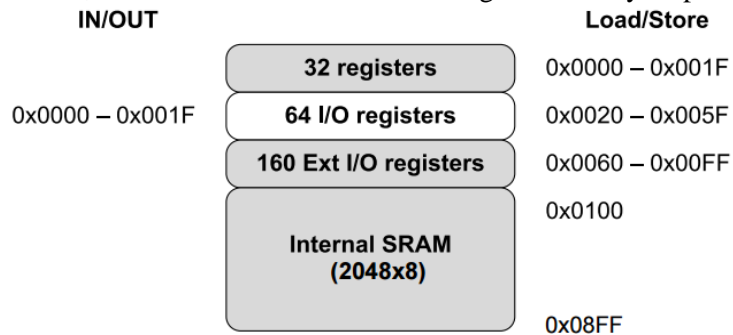


Figure 11: Memory map of the SRAM [6].

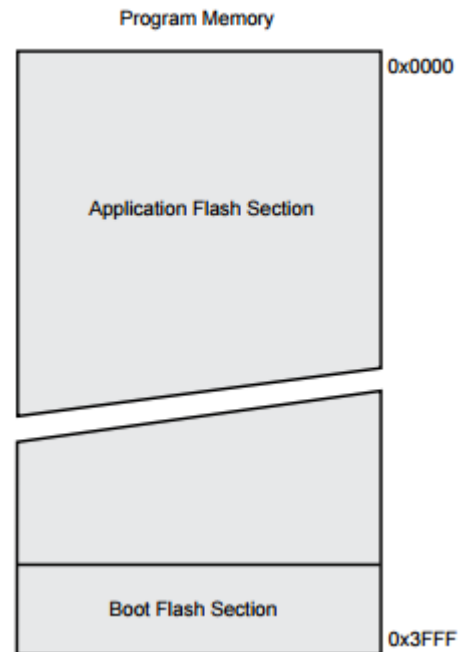


Figure 12: Memory map of the Flash memory [6].

the SRAM (Figure 11) and the Flash memory (Figure 12), the location of this error can be narrowed down even further. SRAM contains addresses ranging from 0x0000-0x08ff, 0-2303. This range is not large enough to contain the location of the problem byte. Flash memory contains addresses from 0x0000-0x3fff, 0-16383. The EEPROM is left for the user to store data, so a program does not use this memory unless it is written into the code, which was not the case for this program. Therefore, the mismatched byte must be in the Flash memory. It makes sense that an error would occur here because of the physical size of the flash memory. The portion of the error message that says “0xea != 0xe6” is indicating that the bootloader found binary 1110 1010 instead of 1110 0110. This means that two bits are in the wrong state. Since the error was identical every time the program was uploaded, it can be assumed that these bits were permanently stuck in the wrong state.

The program continued to run a diagnostic test at 15 minute intervals until the Arduino stopped writing to the computer after ~263 hours (~260 krads). The diagnostic program did not show a single pin failure throughout the entire test, however errors did occur.

Conclusions & Future Work

In conclusion, the diagnostics program never indicated pin failures although the TID from this test was on the same order of magnitude of the TID during a year in MEO. However, an error did arise when trying to upload code to the Arduino after ~186 krads of exposure. This error was caused by two bits in the Flash memory being stuck in the wrong state. Also, the Arduino stopped writing to the computer after being exposed to ~260 krads. Although the pins seemed to still be operational in the MEO and GEO ranges, the memory was affected and further investigation into the consequences of these effects would be pertinent to CubeSat flights.

This test was just a starting point for a larger variety of radiation testing on microcontrollers. Further investigation into memory tests, such as running a continuous checksum program on the Arduino could help identify SEU's in the Flash memory. Also, trying to periodically upload new code would help narrow down the TID at which the Arduino can take before code can no longer be uploaded to it. Another area in need of testing is radiation effects on memory cards and their ability to interface with Arduinos in space environments.

Sensors could also be used to detect SEU's. The configuration shown in Figures 13 and 14 could be used in conjunction with a magnet and LED inside the chamber to monitor for SEU's. These sensors should be durable under radiation exposure, but the

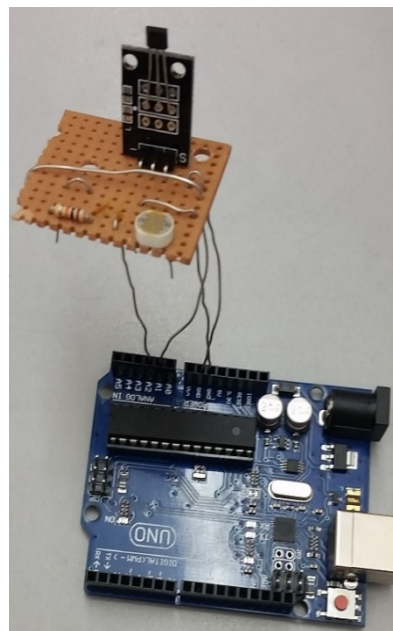


Figure 13: Sensor setup.

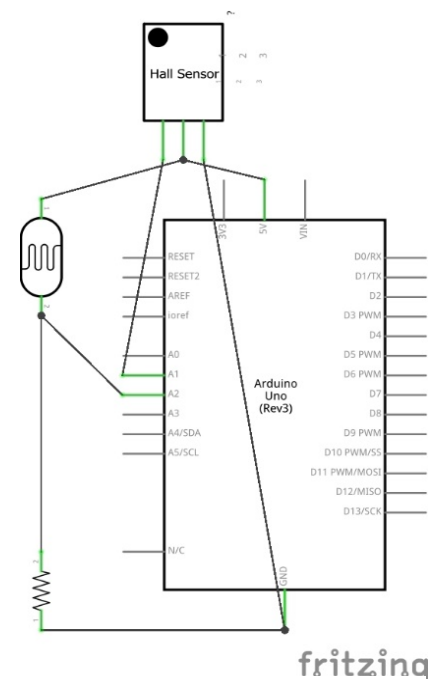


Figure 14: Schematic of a sensor

calibration could be affected by space conditions. So, another valuable test would be to calibrate the sensors before putting them in the SST chamber and then examine how well calibrated they are after their time in the chamber. A set of identical sensors should be used for the duration of the test outside the chamber to rule out calibration changes due to aging.

Performing tests with shielding would help weigh the benefits and costs of putting shielding on the microcontroller. Shielding can stop some high-energy particles, but a particle can hit the shielding and then scatter, cascading onto the electronics. Therefore, more testing on microcontrollers with and without shielding could prove valuable to future CubeSat flights.

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