MicroSD Operational Experience and Fault-Mitigation Techniques

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ABSTRACT

Xiphos has been supplying SD equipped processors to spacecraft developers in low-earth orbit applications since 2006. Despite early successes, some failures have occurred resulting in fallback to redundant hardware. Although rarely documented in the literature, other small/COTS spacecraft developers have encountered failures with SD cards on-orbit. This has led to an understandable concern on the part of end-customers and spacecraft integrators in the use of these devices.

Xiphos has executed many different test campaigns during the past decade to determine the best manner to replicate on-orbit error behavior and to establish mitigation techniques. Each failure event is unique, but a common symptom is an increase in continuous/standby current consumption. The level is on the order of twice the maximum expected current, but substantially less than a latch-up event.

Test campaigns at TRIUMF's Proton Irradiation Facility have shown resilience to data loss in biased conditions with total dose of greater than 20 krad. Recent testing with energies between 13 and 105 MeV have shown similar "low-current latch-up" behavior but without the apparently permanent damage witnessed on-orbit.

Xiphos is confident that rapid event detection techniques, along with several other robust design elements can permit long-term and reliable use of microSD on-orbit.

INTRODUCTION

The history of development of NAND flash for terrestrial use has lead to many features that are beneficial to spacecraft payload developers. The method of connecting NAND cells serially allows for a denser implementation in silicon when compared with NOR flash [1]. NAND is much faster for writing than NOR flash; up to 166 Mbytes/s versus up to 1.5 Mbytes/s respectively [2].

The bit error rate of NAND flash, immediately after production and during operational use, is higher than NOR flash; on the order of 10^{-8} [3][4]. The higher bit density leads to a higher component error rate. To increase yield, manufacturers need to develop methods to correct single bit errors present after manufacture and developed during operation [5].

Alongside each page of data memory is a spare area where external hardware can store error correction codes (ECC) associated with the data. There are different implementations, but in general the data areas and spare areas can be accessed independently.

The ECC block codes allow an external user of the data to correct multiple bit errors within a single data page. Some common codes are Hamming, BCH and Reed Solomon [6].

The bit error rate for a given page increases with the number of erase cycles it has performed. This relationship is device dependent, but it is typical for devices to perform 10,000 or 100,000 erase cycles before the bit error rate increases significantly [7]. Applications that use flash memory need to ensure that the erase events used on the device are spread through out the address range (a process referred to as “wear leveling”).

Flash Translation Layer

The requirements for ECC and wear-leveling can place a significant burden on application developers. To help reduce this, many platforms use a “Flash Translation Layer” (FTL) to implement these features and provide the application developer with a standard interface [8].

The implementation of these services can be provided entirely in software (for example BCH ECC and UBI devices in Linux [9][10]. These functions can be accelerated through programmable logic cores within FPGA [11].

It is also common to be implemented on a purpose built ASIC and incorporated with NAND flash dies within a multi-chip module such as eMMC or Secure Digital (SD) cards [12].

COTS Leverage

In the past decade, the quantity of NAND flash chips shipped for the terrestrial market has increased by more than an order of magnitude [13]. Of the NAND devices shipped, the majority are integrated with dedicated FTL hardware (i.e. embedded SSD and Flash Cards).

It can be inferred that even a small fraction of the production cost dedicated to developing fault-tolerant techniques would be considerable. This process must provide a reliable product in the presence of bit errors in a terrestrial environment. All of these features make modern COTS flash memory an attractive option for high capacity and high data-rate storage for modern spacecraft payloads.

SD Cards in Space

Although COTS NAND flash for terrestrial use must operate in the presence of bit-errors, the space radiation environment adds other potential fault sources. There are three main components to an SD card that need to be considered with regards to radiation tolerance

1. The core NAND flash components
2. The FTL controller
3. Configuration memory used for the FTL controller

In this discussion the core NAND flash refers to the susceptibility for the individual bits to change in the presence of ionizing radiation. The FTL controller is an active device (i.e. ASIC or micro-controller) that can malfunction due to an upset. Finally the firmware and/or configuration memory used by the FTL controller (e.g. bad block list, NAND hardware information) could be corrupted.

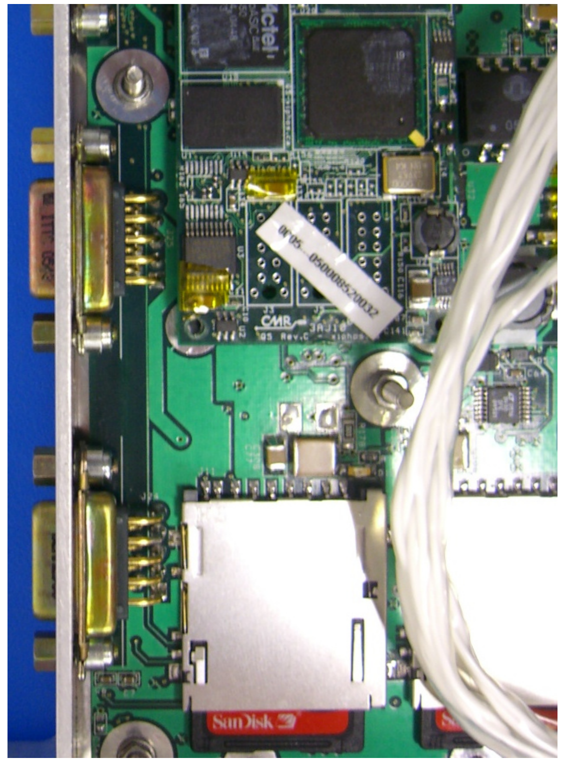
The implementation of these features is specific to each manufacturer's design. For example, the configuration and firmware may be stored within the NAND device, NOR flash or a factory programmed ROM [14].

XIPHOS SD FLIGHT EXPERIENCE

Xiphos Systems has used SD and MicroSD cards for several on-orbit applications.

Genesis-1, Genesis-2

Launched in 2006 and 2007, Xiphos supplied SpaceQuest and Bigelow Aerospace with camera systems that included 2GB SanDisk Secure Digital memory cards. These were used to store image data and telemetry.



Both systems operated successfully for the duration of the mission which included acquisition and downlink of several thousand images. No errors were detected.

The payload processor was a Xiphos Q5 card that used embedded NOR flash for firmware and operating system storage.

SpaceQuest AIS Data Recorder

Since 2008, Xiphos has provided several payload processing systems to SpaceQuest Ltd in support of their space-based Automatic Identification System (AIS) for ship tracking. These have used a variety of processors and flash storage configurations. The earliest used SD cards similar to that used for the Genesis flights, and the latest using microSD cards from several different manufacturers.

To date a total of 32 flash cards have been launched; comprising 12 SD cards and 20 MicroSD. Several of these have experienced failures that render them unable to operate as required.

The symptoms of the failures, in terms of the responses their controllers return, are slightly different in each case. They are generally able to respond to queries for Card Information and Card Status registers, but the values appear to be corrupted. Feedback from one vendor suggested that the controller's firmware had been corrupted and the device was reverted to a factory configuration.

The common feature has been a rise in power consumption of approximately 100 mA at 3.3V. This is roughly twice the expected peak current during SD write operations but much lower than the threshold required to trip standard latch-up protections. This has become known by the misnomer "low-current latch-up".

These failure identifications will be discussed in more detail later in the paper.

International Space Station

The latest Xiphos developed hardware to be launched with MicroSD card was a health sciences experiment sent to the International Space Station. The payload monitoring and network gateway functions was provided with a Xiphos Q6 card. All of the Q6 logic, firmware, and software were stored on redundant microSD cards. No errors were detected with the flash memory during this mission.

XIPHOS SD RADIATION TEST EXPERIENCE

Xiphos has executed a number of tests using the Proton Irradiation Facility (PIF) at TRIUMF to characterize the failure modes of SD and MicroSD cards.

2004 Test Campaign

Prior to operation on Genesis-1, Xiphos exposed five unpowered SD cards to varying dosages of 105 MeV protons. Each of the cards was preloaded with image files and checksums recorded. The cards were exposed to 5, 10, 15, 20 and 25 krad respectively. The data on the cards were checked approximately one week after exposure and no corruption was detected.

2011 Test Campaign

As part of the development of Xiphos' Q6 card, a set of Total Ionizing Dose (TID) experiments were done to find potential weak points in the design. The Q6 device uses MicroSD for firmware storage (logic bitstream, operating system and application software).

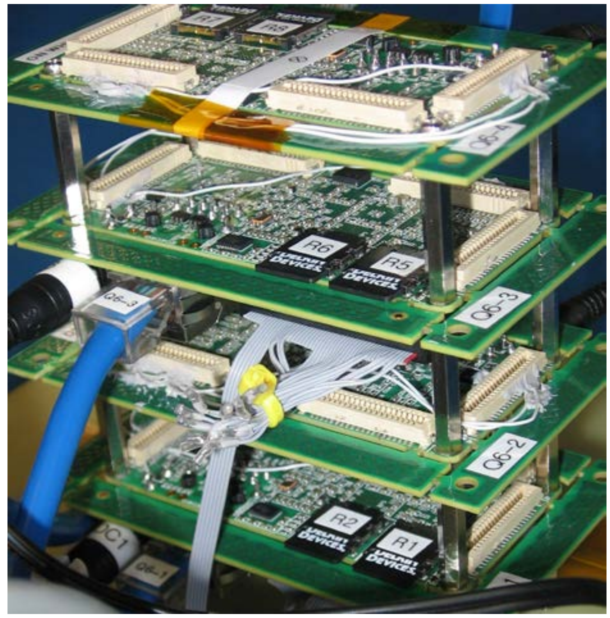


Figure 1: Placement of MicroSD cards within Stack

Four Q6 devices were arranged in a stack configuration and exposed to the proton beam as shown in Figure 2. Two of the devices were powered during exposure and two were unpowered. The stack was irradiated with incremental doses of 2, 3, 5 and 10 krad. After each increment, the MicroSD cards were removed from the devices and tested for corruption of stored data and correct operation.

A total of eight microSD cards were irradiated. All were fully operational at doses up to and including 20 krad. Data corruption, manifesting itself as the loss of data blocks, occurred at 2 krad for card R7 and at 5 krad for card R3. Transient write errors occurred at 20 krad for card R3.

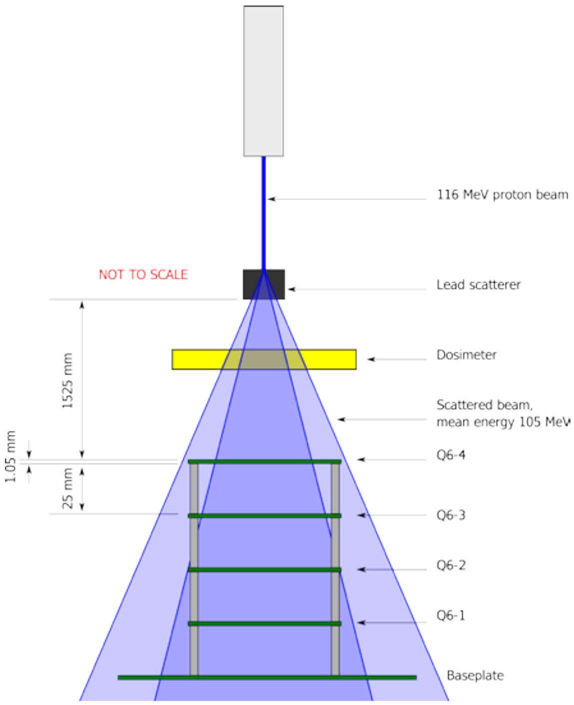


Figure 2: Radiation Exposure Configuration

The test continued with cards irradiated until failure or until beam availability finished. Table 1 presents the test configuration and the maximum dose each card was subjected to. Note that four cards were powered, and four were not.

Table 1: MicroSD Card Test Set-up

Card	Bias	Dose	Location
R1	NO	30	Card 1 (Bottom, farthest from beam)
R2	NO	30	Card 1 (Bottom, farthest from beam)
R3	3.3 V	30	Card 2
R4	3.3 V	30	Card 2
R5	NO	40	Card 3
R6	NO	40	Card 3
R7	3.3 V	30	Card 4 (Top, closest to beam)
R8	3.3 V	40	Card 4 (Top, closest to beam)

Only minor problems were detected and except for one card they were temporary:

- R3: multi-sector data corruption after irradiation to 5 krad.
- R7: multi-sector data corruption after irradiation to 2 krad, failure after 30 krad.
- R3: transient write I/O errors after irradiation to 20 krad.

It was reported that the biased microSD cards reached high temperatures during irradiation and were too hot to touch. Their temperatures probably reached at least 60 °C, and may have been well above their rated operating temperature range. This may also be a cause of the failure of R7.

2012 Test Campaign

In 2012, Xiphos executed a test campaign for an updated Q6 configuration with enhanced reliability features for spacecraft use (Q6S). One of these features is a robust storage mechanism implemented entirely in software as a Linux kernel module, xdm_replicate, which provides, via the Linux device mapper framework, a robust virtual block device by combining a number of non-robust devices. A user space tool, xdmrtool, is provided for low-level formatting. A block device testing tool, srwt, was used to exercise the block device.

The Q6S has two on-board microSD card slots and the Q6S carrier board has two additional microSD slots. Previous tests by Xiphos have demonstrated that doses as small as 2 krad are able to corrupt the contents of microSD cards provided they are powered on. However no tests where the microSD was powered and being actively used had been conducted. A redundant storage mechanism has therefore been developed to mitigate against data loss or corruption. The intent of this test was to determine the behaviour of active operation of microSD cards under a proton beam and to ascertain how efficient the redundant storage mechanism is at mitigating radiation induced errors.

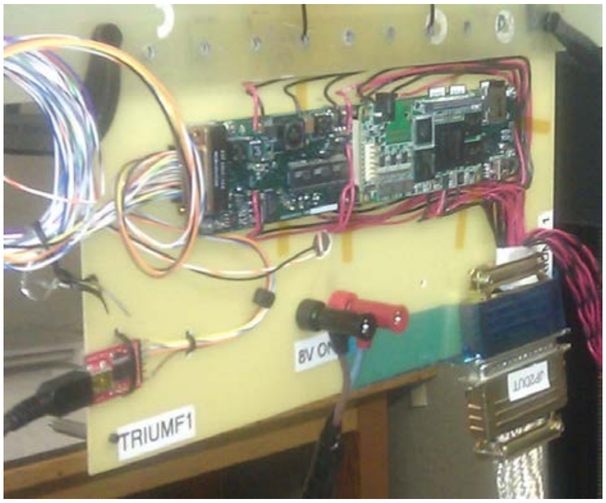


Figure 3: Q6S with Carrier Board at TRIUMF

When the microSD cards were irradiated while I/O was actively being performed, terminal (i.e. causing termination of the test) I/O errors occurred after 6544, 1271, 6900, 3433 and 1600 Measurement Counts (MC), for a mean of 3950 MC, and the cards would no longer properly operate. For some scale, at 2nA and 105MeV, a value of 217267 MC is equivalent to 2 krad(Si) TID. With errors occurring at such low dosages, it is reasonable to assume that they are caused by soft errors.

The cross section for I/O errors is therefore 2.75e-10 cm2 for the two devices combined. It is assumed that these are due to upsets in the FLASH controllers integrated in the microSD cards.

Only four damaged sectors out of 4 copies of 46600 data and 5825 checksum sectors were noticed and this occurred in a single event. If these were upsets in the FLASH memory on board the microSD cards, which is unlikely, this would give a cross-section of 4.20e-14 per bit after the error correction performed by the microSD cards. The ECC scheme used by the microSD cards is unknown and manufacturers are generally unwilling to disclose that information. These sectors were most likely damaged by an upset in the microSD controller.

The damaged sectors were detected and repaired by the robust storage software and no malfunctions were noticed.

SD CARD FAULT MITIGATION TECHNIQUES

As described earlier, the two most common symptoms of SD failure in orbit from Xiphos Q-card experience are corrupted flash controller firmware and higher than expected input current. Xiphos has considered methods to respond to each of these events in COTS flash devices.

Flash Controller Firmware Corruption

The user of COTS flash devices is often presented with a black box presenting the standard SD card interface. Information about the internal implementation of the device is proprietary and difficult to obtain when the expected quantity to be used for a single small satellite program is often much less than 100 units.

Recent efforts by the computer security community have helped us peer inside the box and revealed that some MicroSD card controllers implement firmware update facilities through non-standard SD commands [15]. Xiphos' inquiries to vendors revealed that many use extra pins for programming that are used before the final enclosure is encapsulated.

If a COTS MicroSD could have the onboard controller firmware modified "in the field", it may be possible to refresh a failed card. Xiphos' Q-cards use custom logic and software to communicate with MicroSD and can be easily modified to support non-standard commands and procedures. However, this is not feasible without support from vendors. Compared to terrestrial markets, the numbers of microSD that might be used for small satellite applications are insignificant and make negotiation difficult. Xiphos has had a positive response from one manufacturer and is presently considering this technique for future flights.

Low-Current Latch-Up Protection – Q6S

The low-current latch-up failure mode allows external detection and has been a recent focus of work from Xiphos. On the most recent flight of Q6S as part of SpaceQuest AIS data recorders (AprizeSat-9 & AprizeSat-10), the supply current to a pair of MicroSD cards are individually monitored and controlled. This flight has also included industrial COTS SLC microSD devices from four different manufacturers (Delkin, Apacer, ATP and SwissBit). All previous flights with MicroSD have used Industrial SLC parts from Delkin.

As this paper is written, no low-current latch-up events have been detected on the monitored devices.

Low-Current Latch-Up Protection – Q7

In 2014, Xiphos released the latest revision of their spacecraft processor, the Q7. The Q7 features onboard NOR flash for firmware and software storage as well as two microSD slots for mission data. The power supplied to each microSD card is monitored in hardware. Values above 100 mA trigger an automatic shutdown. This protection circuit is described in Figure 4.

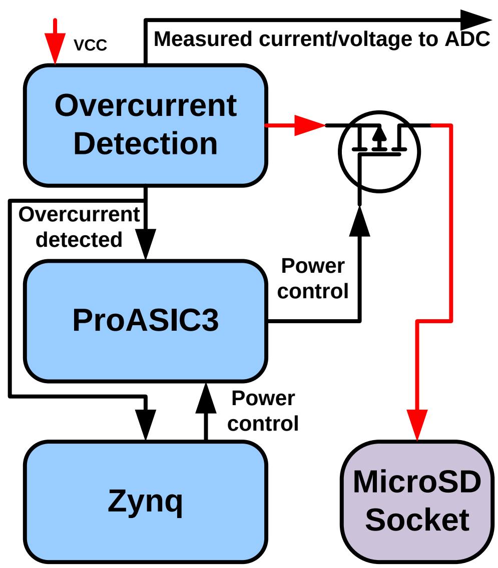


Figure 4 Q7 MicroSD Over-Current Protection

This feature was tested in December 2014 at the TRIUMF PIF.

2014 Test Campaign

The tests were performed on MicroSD cards from three different manufacturers and at energies and currents between 13 MeV @ 0.1 nA and 63 MeV @ 6 nA. The high-speed, low-threshold over-current protection was triggered successfully on all cards at different energies and currents. The cards were functional following a reboot of the system outside of the radiation beam.

Figure 5Q7 MicroSD Proton Target

A single MicroSD card was tested for each event. The card was isolated from the Q7 as shown in Figure 5. The 2012 test campaign demonstrated that a high-energy, high-flux proton beam could generate errors at a rate impossible to mitigate. Although efficient for rapidly accumulating total dose, it is difficult to accurately represent an operational scenario where devices might experience one single-bit event per day.

Part of the test effort was put toward finding a set of proton energies and fluxes that would generate a single event every 100 seconds.

For each test, a series of write and read operations was executed with a resulting activity duty-cycle of approximately 30%. The MicroSD supply current was monitored at 50Hz.

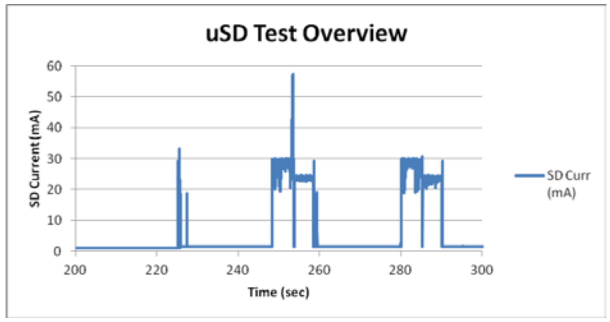


Figure 6 MicroSD Current Consumption

The current consumption of an Apacer 2GB SLC Industrial MicroSD card is shown in Figure 6. The period of zero current is due to the generation of randomized test data and the accompanying MD5 checksum. The higher current consumption occurs during the write activity, which is followed immediately by read activity.

A total of 15 separate tests were executed with beam energies varying between 13.5 MeV and 62.9 MeV at currents of between 0.1 nA and 6 nA.

Useful data was obtained on tests of 4 different MicroSD cards from three different manufacturers (Apacer, Delkin & ATP).

The initial testing used an Apacer Industrial SLC MicroSD and tested several energies at 0.1 nA beam current: 14, 27, 35, 49 and 63 MeV. No errors were detected during each 3 minute test. The beam current was increased for each following test to 0.2, 0.4, 1 and 3 nA. No errors were detected during these higher current tests.

When the beam was configured for 63 MeV at 6 nA, errors were detected within the first 100 seconds of exposure. The Q7 logic reported detection of over-current and subsequent shut-down of power to the MicroSD.

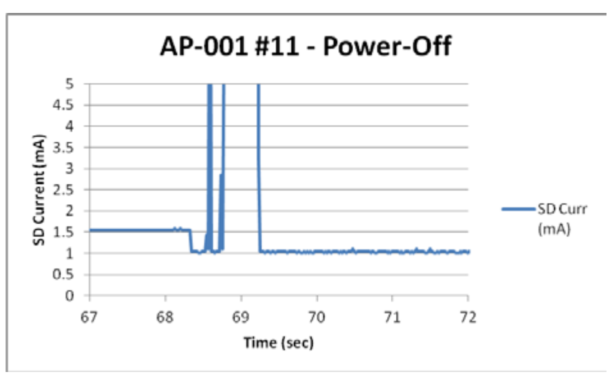


Figure 7 Q7 MicroSD Overcurrent Response

The Q7 FPGA responds to the overcurrent event in less than a microsecond. As such, the 50 Hz current measurement was unable to capture these transient events though the difference in quiescent current is apparent after the event as shown in Figure 7.

CONCLUSIONS

Modern small satellite payloads (e.g. hyperspectral imagers) are capable of generating massive quantities of data. COTS flash memory developed for terrestrial markets offer features that are attractive for deployment in these applications. Xiphos' on-orbit and proton radiation testing leads to the following recommendations for optimal use of MicroSD in space:

1. Provide separate power monitoring and control for each card;
2. Store critical firmware and software in redundant, error-corrected NOR flash;
3. Store payload data to redundant MicroSD cards; and
4. Keep MicroSD cards unpowered when not in use.

References

1. Micron Technical Note TN-29-19: NAND Flash 101
2. Spansion Application Note, Flash Memory: An Overview
3. The Inconvenient Truths of NAND Flash Memory, Jim Cooke, Micron, Flash Memory Summit, August 2007
4. NAND Flash Solid State Storage for the Enterprise: An In-depth look at reliability, Jonathan Thatcher et. Al., Solid State Storage Initiative
5. NAND Flash FAQ, Eureka Technology, Application Note 5_87
6. Spansion, What Types of ECC Should Be Used on Flash Memory?, Application Note, Revision 02, March 30, 2011
7. ST Microelectronics, Wear Leveling in Single Level Cell NAND Flash Memories, Application Note AN1822, Version 2.0, November 12, 2004.
8. Micron Technical Note, Bad Block Management in NAND Flash Memory, TN-29-59, Revision H, April 2011
9. Micron Technical Note, Enabling Software BCH Error Correction Code (ECC) on a Linux Platform, TN-29-71, Revision B, April 2012
10. http://www.linux-mtd.infradead.org/doc/ubi.html
11. Mir, I, McEwan, A.A. and Perrins, N., "A High Performance Reconfigurable Architecture for Flash File Systems", Communicating Process Architectures 2012
12. http://www.hyperstone.com/en/S6-SecureDigital-SD-and-MultiMediaCard-MMC-Flash-Memory-Controller-263,434.html
13. Decad, G., Fontana, R. and Hetzler, S., "The impact of Areal Density and Millions of Square Inches (MSI) of Produced Memory on Petabyte Shipments for TAPE, NAND Flash, and HDD Storage Class, Storage 13, 23 September, 2013.
14. 3D Plus SA, Data Sheet 4GB uSSD Memory Module 3DSS032G16VB2354, Revision 1, July 2011
15. Bunnie, Xobs, "The Exploration and Exploitation of an SD Memory Card", Chaos Communication Congress 2013