March 22, 2017

How to get the most out of your flash memory cards

By both choosing the best type of memory card for your application and following some simple best practices for use, you can maximize the capacity, lifetime and performance of the memory cards you use in your Nanometrics instruments.

Remember, for maximum reliability, flash media should be treated as a component that wears out over time (i.e., it should be replaced regularly)!

How flash memory works

Flash memory is available in varying sizes, speeds, reliabilities and lifetimes. In order to choose the best card for your application, it's helpful to understand a bit about how flash memory works. Digital devices typically store and record data using removable flash memory devices such as Compact Flash (CF) or Secure Digital (SD) cards. Flash memory stores an electrical charge in a memory cell, which is retained even when the device is not powered. Each cell represents one bit of information. If the amount of charge is below a certain threshold, then the cell is considered to store a '0'. Conversely, above the threshold, it is a '1'. This is called a single-level cell (SLC). To provide higher capacity cards, it is possible to store more than one bit in a memory cell. The charge threshold is 4 levels, providing 2 bits of storage. This is called a multi-level cell (MLC). To provide even higher capacity, the threshold can have eight levels, providing three bits of storage. This is called a triple-level cell (TLC).

The cost (as measured by price per GB) is higher for SLC, because more memory cells are needed to provide the same storage capacity as MLC or TLC. TLC is the least expensive because it's the most dense format, storing three bits per cell. TLC requires fewer memory cells than MLC or SLC to support a given capacity.

SLC cells (with just two levels) are the fastest type, and TLC cells with eight levels are the slowest. That is because the more levels in a cell, the more accuracy is required and the more time it takes to read and write the memory cell.

The different types of memory cells

Memory technology	Lifetime (number of write cycles)	Speed	Cost (cost per GB)
Single-level cells	100,000	fastest	most expensive
Multi-level cells	10,000	moderate	moderate
Triple-level cells	3,000	slowest	least expensive

Memory cells are organized into blocks for writing and reading efficiency. This means that when modifying a single byte on the card, the entire block that contains that byte is erased and rewritten. The block sizes are typically between 4MB and 32MB.

What can affect the capacity of a memory card?

The capacity or actual usable free space on a card is always somewhat less than the advertised size of the card, due to the overhead of the file system and other system information that occupies a portion of the raw memory.

What can affect the lifetime of a memory card?

The lifetime of a memory cell. The lifetime of a memory cell is measured in the number of write cycles. For each write cycle, the cell is erased and programmed with a new value. Each read and write of the memory cell causes some damage to the cell. Over time, this damage reduces the accuracy with which the voltage can be measured, which leads to the memory cell becoming unreliable and the value read from the cell no longer matches the value written to the cell. Because of their increased capacity, the lifetime of multi-level cells and triple-level cells (as measured in the number of write cycles) is less than the lifetime of single-level cells.

Write amplification. Access to the memory cells is organized into blocks for efficiency, but this means that when modifying a byte on the card, the entire block that contains that byte must be erased and written Thus, writing many small chunks of data to the card causes a large number of write cycles (called write amplification). Because memory cells have a limited number of write cycles, write amplification accelerates the aging of the card, so it's best to write data to the card in large chunks.

In addition, the effect of write amplification is significantly higher on Nanometrics instruments compared to common consumer devices that use SD cards (cameras, for example) due to the relatively low rates at which data is written to the card. The instrument writes continuously in small chunks to ensure there is no significant loss of data in the event of a power loss.

Spare block pool exhaustion. Each card has a reserve pool of spare memory blocks, which are used to replace any memory blocks that become bad due to excessive write cycles or other aging issues. Once all the spare memory blocks have been exhausted, then the card can no longer be written to.

Wear levelling. Each memory card uses a microcontroller to interface with the device and manage access to the memory cells. The controller firmware also contains proprietary algorithms for maximizing performance and increasing lifetime. One way the controller does this is by ensuring that writes to the card are spread across all the memory cells in the card. This is called wear levelling. Vendors of memory cards can specialize and optimize their proprietary algorithms for wear levelling in order to maximize the lifetime of their cards.

Temperature. Memory cells are affected by temperature. Low temperatures cause increased wear on the cell for each write cycle, so as the card is operated in low temperatures, the lifetime of the card is shortened.

High temperatures cause the charge in the memory cell to decay faster. As the charge decays, the value stored in the cell becomes more difficult to read accurately, eventually becoming unreliable. Cards operated in high temperature environments have a much more limited retention time span.

Corruption. In the event that the device loses power during operation, there is a possibility that the card could become corrupted. There are two types of corruption that can occur on the card: corruption of memory blocks and corruption of the file system.

Memory block corruption can occur when a power loss happens while a block is being erased or written. It is possible that the block is left in a state where it is no longer usable. In this case, it would be added to the "bad blocks list". The data in that block would be lost, and a replacement memory block is taken from the spare blocks pool. If this occurs frequently, the spare blocks pool is exhausted and the card is no longer usable. This is another area where the controller firmware can be optimized to prevent or reduce the corruption that occurs due to a loss of power.

Corruption can also occur in the file system on the card. In this case, the blocks themselves aren't damaged, but the data within the block is corrupt, which can cause file system errors. If the error is within the key file system allocation and directory tables, then the entire file system could become unreadable. File system repair utilities may be able to repair file system corruption with some loss of data (some files may be truncated or deleted). Formatting the card would restore full functionality, however, all data on the card would be lost.

Bad blocks. Each block of memory cells on a card maintains some cells for error-correcting code (ECC). The ECC enables correction of a small number of misread bytes, and detection of any number of misread bytes. If a block with an uncorrectable amount of errors is detected, then it's no longer used by the controller for writing data. It is added to the "bad blocks" list and a block

from a reserved pool is used instead. As the card ages, and more blocks are added to the bad blocks list, eventually the reserved pool is exhausted and the card is no longer usable.

What features or specs should I look for when choosing flash memory?

The most important factor in choosing a flash memory card is getting the maximum reliability for the capacity required. **One way to ensure you get the maximum reliability, performance and lifetime from your card is by opting for industrial-grade cards over consumer-grade cards. Consumer-grade cards are sold to consumers for use in consumer devices, such as digital cameras or smart phones. Industrial grade cards are sold for use within industrial equipment, such as medical devices. Industrial-grade cards are designed to be more reliable, have a longer lifetime and be less susceptible to corruption as well as less vulnerable to temperature extremes.**

Consumer-grade cards are designed primarily to maximize capacity per dollar at the expense of lifetime and reliability. They generally use TLC technology and less advanced controller firmware that's optimized for speed rather than lifetime or corruption resistance. TLC should also be avoided due to its significantly shorter lifetime.

We strongly prefer industrial grade cards **because they're designed to maximize reliability. They have controller firmware that's designed to provide a longer lifetime and better resistance to corruption. Industrial cards also operate in a wider temperature range. Also, industrial-grade cards use SLC or MLC technology. We recommend industrial-grade SLC or MLC due to its robustness and longer lifetime.**

Consumer-grade vs. industrial-grade cards		
	Consumer	**Industrial**
Cost	**Less expensive**	**More expensive**
Capacity (GB)	**Larger**	**Smaller**
Flash technology	**TLC**	**SLC and MLC**
Lifetime	**Shorter**	**Longer**
Corruption	**More likely**	**Unlikely**
Operating temperature	**Narrow range**	**Wide range**

What can I do to get the best out of my card?

Ensure there is enough free space. It is critically important to ensure there is enough free space on a removable media card so that it does not fill up between site visits to exchange cards or before the experiment concludes. The actual usable free space on a media card is always somewhat less than what's advertised size of the card, due to the overhead of the file system and other system information that occupies a portion of the raw memory. Always check the available free space reported by the computer or instrument that the card is in.

Formatting ensures the card is truly empty and there are no hidden files occupying space. It is best to format the card before using it in an instrument. Formatting can be done on the instrument, although that can take longer than formatting in a computer.

A rough estimate for space required for typical seismic waveform data is approximately 1.5 GB for 3 channels at 100 samples/second for 30 days. More channels and higher or lower sample rates change this proportionally. This also assumes typical compression rates using Steim compression. Continuously active or noisy signals could reduce compression, requiring more space.

Use care when deleting files. If you use a computer to delete files to free up space on an unformatted card, be very sure to use the appropriate "safe eject" procedure on the computer before physically removing the card. If the card is pulled from the computer without ensuring it is "safe to remove," the file system on the card may be corrupt or files may not have been deleted properly.

Remember the effect of temperature. When operating at very low or very high temperatures, it's important to remember that the lifetime is reduced and therefore replacement should be more frequent.

Replace the card before its useful life is exhausted. A rough rule of thumb for industrial grade MLC cards is to record no more than the equivalent of 15 times the capacity of the card before replacing it, more frequently if operating in more extreme conditions.

How can I get a card that I know will work for my instrument?

It's best to procure flash memory cards directly from Nanometrics. There are many different brands and models of memory cards, and not all cards behave in the same way. Our comprehensive testing process ensures the cards we offer are very reliable.

Nanometrics selects and qualifies specific SD and CF flash cards for use with Nanometrics instruments such as Centaur, Meridian, TitanSMA and Taurus. We select an industrial grade card using SLC or MLC, with a wide temperature operating range. We use the card in our test bed of Nanometrics instruments, comprised of dozens of Centaurs, TitanSMAs, Meridian Compacts and

others. The instruments are operated in various configurations of sample rates, archiving and streaming. After two months of operation, the cards are checked for the completeness and correctness of the data.

During our testing of various candidate models and types of cards we have seen a variety of failure modes that would disqualify a particular model. One type of failure is due to flaws in the card's controller firmware so that the card does not always respond correctly to read/write requests. Cards with failures like these tend to fail immediately upon use.

Other card types have severely shortened lifetimes. The controller is not efficiently managing the wear levelling of the memory cells resulting in lifetimes of less than one year.

Some card types failed after many weeks of continuous usage due to bugs in the controller firmware that caused the entire card to become unreadable and unwritable. Formatting the card did not restore the card to usability.

Once we have tested and confirmed that a particular model and brand of card is reliable, we ensure that that exact model number of card is used. Any changes to the electronics or firmware of the card cause us to go through a full test regime again.

What if I want to buy the cards myself?

If you don't want to purchase cards directly from Nanometrics, we can supply the manufacturer and specific part number for the memory cards we have qualified, so that they can be procured directly.

If you opt to procure memory cards on your own, keep in mind that not all cards labelled as "industrial grade" have the required characteristics for successful operation.

- **The memory technology should be SLC or MLC and not TLC.**
- **The controller should protect against abrupt power loss or the user pulling the card during write operations.**
- **Wear-levelling algorithms should be designed for long-term reliability and not speed. Temperature rating should be considered.**

Once you select a new model of memory card, you should make sure it functions properly within the specific instrument model(s) it is to be used in. Prior to deployment, we recommend continuous recording for at least one month, then verifying all the data was properly recorded to the card.

We strongly recommend against using consumer-grade cards. **While they may have impressive read/write speed performance benchmarks, they are not designed for being written continuously for months and years, have little protection against corruption on sudden power failure or if the**

card is removed without being properly dismounted by the operating system. In addition, their memory technology, electronics and controller firmware change frequently within the same model number, so that two cards with the same model number might not perform the same. These cards may be sufficiently reliable for applications such as digital video or photography, but are not suitable for unattended continuous write usage in harsh environments. They will often function correctly in limited testing (and appear reliable), but are prone to failure when subjected to the extended recording and harsh usage that consumer products are not designed for.

We recommend only using consumer-grade flash media only when no other option is available, and then only for very limited usage, such as demos or in-lab testing of instruments.