Nuffield Research Project

Eternal Data Storage for a Digital Archive to be Stored on the Moon

Lunar Mission One Project

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Abstract

This literature review is an investigation into the most suitable medium for data storage over extended periods of time, in order to contain a digital record of human life in Lunar Mission One's Archive on the moon. Due to the conditions on the moon, and the great period it will have to maintain integrity over, special considerations will have to be given to radiation damage, direct physical damage and great variances in temperature. Radiation damage is especially relevant on the moon due to the lack of o-zone, however the time period brings with it another concern, neutron radiation from the surrounding material and radioactive isotopes in the moon soil itself. Direct physical damage is primarily from two sources, moon-quakes and meteorites, which would burn up Earth's atmosphere, however impact on the moon frequently due to its extremely thin atmosphere. The moon experiences great changes in temperature because it does not experience the greenhouse effect and rotates relatively slowly, therefore the medium will have to be able to withstand great ranges of temperatures. This review primarily focuses on the 5D data storage method.

What is the Lunar Mission One Project?

The Lunar Mission One projects has two main aims, to gain greater knowledge of the composition of the moon beneath the surface, and to leave a record of mankind behind, the archive[1].

Composition of the Moon

The main reason for looking at the composition of the soil under the lunar surface is to achieve a greater understanding of how the solar system and other celestial bodies formed – an area in which we have surprisingly little information. Up to this this point only surface samples of the Moon's soil have been taken, while Lunar Mission One plans to drill 20m – 100m beneath the moon's surface, taking out a series of cores 25mm in radius. The cores will be entirely analysed by the probe and the data sent back to earth to be processed, as sending another probe or shuttle to collect it would be far too expensive, as would giving the probe itself a method of returning physical material.

The Archive

The archive is intended to serve as a record of sentient existence on Earth. It will be split into two components, the public and private archives. The public archive will consist of files submitted by the general public in order to serve as a record of day-today-life, although it is mostly marketing to raise funds for the mission and to generate public interest. The private archive will be a curated record of mankind's science, culture, literature and technology. It is designed to be proof that sentient life once existed on Earth and will wait under the surface of a moon until it is recovered, by either exploration by an alien species, or by the redevelopment on earth. Although these are unlikely scenarios, and we will not live to see the result (as if we did it would be unnecessary), it is what we have been hoping to find during space exploration as proof of other sentient life; so now if something is looking, they have the archive to find.

Traditional Mediums of Digital Data Storage

Phase-shift (Rewriteable)

Phase-shift data storage is where data is stored by altering the state of a phase-shift material with a laser[2]. The laser alters the surface of the DVD by changing the state between crystalline and amorphous. When it is in its amorphous state, because the atoms are disordered, light does not pass

[1] https://www.LunarMissionOne.com – Accessed on 25/08/16
[2] http://www.explainthatstuff.com/cdplayers.html - Accessed on 06/08/16

through, while when it's in its crystalline state it is translucent. Phase-shift data storage is the most common type of consumer data storage due to its low manufacturing cost, and how most consumer electronics have the capacity to read/write to the medium. Electromagnetic storage is most commonly seen in the rewriteable variants of disks such as CDs, DVDs and Blu-Rays. The current expected longevity of consumer-grade rewriteable stored data is 4-5 years.

Organic

Organic data storage is where an organic film is placed over the surface of a disk, and then modified in a controllable way in order to store data. This altering is permanent, and as such cannot be rewritten without replacing the organic layer itself, thereby removing all existing information. As a result of this, the most common use is for data that is only meant to be read, and not altered. Examples of this are CDs/DVDs/Blu-Rays with movies or series on and software, most commonly operating system, install disks.

Inorganic

Inorganic data storage is where the medium is physically altered to store the data, this usually entails altering the surface of the material in order to make it interact differently with light. This method is far less commonly used as the data is not rewriteable, and usually a specialised system is required to read/write the data. Because of these constraints this method is most commonly used in industry and for physical back-ups of sensitive data; this most often practiced by websites storing personal information, such as Google and Facebook.

Femto Frequency Laser

Femto frequency lasers are a special type of ultrafast laser (also known as ultrashort frequency lasers). Ultrafast lasers are lasers which fire for a duration in the realm of $1x10^{-12}$ seconds or less, the femto frequency lasers fire for a duration of approximately $1x10^{-15}$ seconds (one femto second)[3], so the Femto frequency lasers are an ultrafast laser, but more specialised.

Uses in the Project

Femto Frequency lasers are used to record data in the most promising up-and-coming data storage method designed to last over extended periods, fused silica[4]. The laser need to use short pulses to record data to improve the read/write speed due to the way the data is stored.

The femto-frequency lasers used to write the data onto the fused silica uses a beam of very high intensity due to fused silica having such a high melting point.

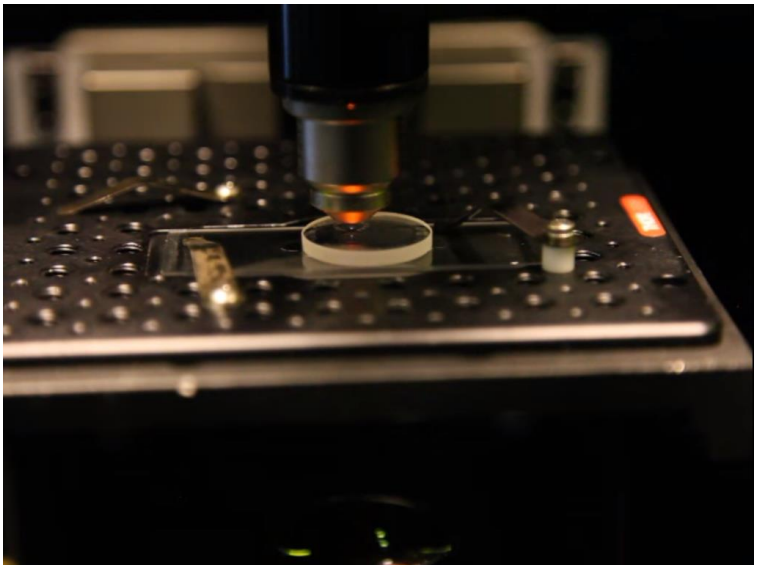

Figure 1 A femto laser building 5d optical storage
Source: http://www.southampton.ac.uk/news/2016/02/5d-data-storage-update.page

[3] https://www.rp-photonics.com/femtosecond_lasers.html - Accessed on 02/08/2016
[4] http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=2501563 - Accessed on 12/08/2016

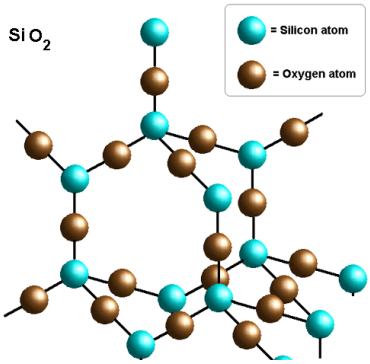

Figure 2: The structure of a fused silica crystal
Source:http://blog.nus.edu.sg/kyawthetlatt/files/2013/08/silicon-dioxide-lattice-12od3m7.gif

Fused Silica

Fused Silica (also known as fused quartz) is a "non-crystalline (glass) form of silicon dioxide (quartz, sand)"[5] most used for its near zero thermal expansion and relative chemical inertness over a great range of temperatures[6]. Fused Silica is a type of glass, except that it does not contain any other elements – the aim is for it to be as pure as possible. Most glass has "fluxes" added to it (most notably lead oxide)[7] in order to lower its melting point(1723°C) in order to reduce manufacturing costs, however these additions make the glass overall less chemically inert and expand more at higher temperatures.

Why a High Level of Purity is Necessary

A high level of purity is vital to the storage medium working primarily because:

- **Pure Silica withstands high temperatures very well.** The Silica functions similarly across a broad range of temperatures, which makes it particularly suitable for the mission to the moon, because the temperature on the moon in the Shackleton crater is very low. This is an improvement over most modern forms of storage which can be damaged due to contraction at very low temperatures, or just become brittle and then shatter to outside influences.
- **Silica Crystal is very resistant to damage.** The silica crystal is a giant covalent lattice, like diamond, and as such is similarly hard. Other substances being added to the crystal could provide weak points, which would make the silica more prone to cracks and chips, which would ultimately make the data more difficult to read.
- **Imperfections in the silica reduce data quality and could compromise data integrity.** The recorded data is spaced in the order of 10^{-6}m between dots[8], which means that even minor imperfections could corrupt the data.
- **"The fourth and fifth dimensions of data storage".** The slow axis orientation and strength of retardation both rely on a consistent medium to be readable; if there is a different substance present, even in small quantities, the differing refracting index and strength of retardation will increase the bit error rate to the storage medium becoming unreliable.

Why the 5D data storage method is so unique

The main reason the 5D data storage method is so unique is that the data has been stored in a material that is inherently inert and extremely resistant to physical damage, temperature and radiation. It also utilised a phenomenon(birefringence), previously only used in research, which will not degrade over time and does not negatively affect the storage medium, allowing for the data to be read an infinite number of times without degradation in the data quality. The scale of the estimated lifespan (13.8 billion years) is so many orders of magnitude removed from its only real competitor (the M-Disk) that is really a notable breakthrough in the field of digital data storage, and could later be put to use in many fields outside of the Lunar Mission One project.

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[5] http://accuratus.com/fused.html - Accessed on 03/08/2016
[6] http://www.southampton.ac.uk/news/2016/02/5d-data-storage-update.page - Accessed on 12/08/2016
[7] http://www.chemistryexplained.com/Ge-Hy/Glass.html - Accessed on 03/08/2016
[8] http://www.jlps.gr.jp/jlmn/upload/3035363f0d66bad8d782002dd3476606.pdf - Accessed on 02/08/2016

How the Data is Imprinted into the Crystal

The data is imprinted into the crystal using a femto frequency laser which focusses 600µm below the surface of the crystal to make a mark. This produces 5 "dimensions" of data storage. [9]

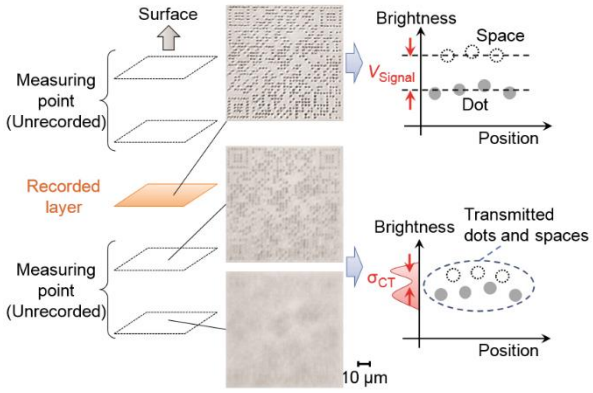

Figure 3: Data Imprinting by layer
Source:http://www.jlps.gr.jp/jlmn/upload/3035363f0d66bad8d782002dd3476606.pdf - Page 3

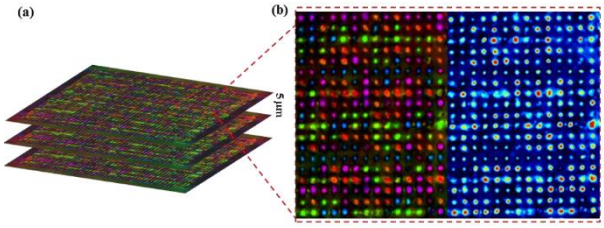

Figure 4 (a) Diagram Showing the arrangement of Layers. (b) The slow axis orientation for data stored.
Source:http://www.orc.soton.ac.uk/fileadmin/downloads/5D_Data_Storage_by_Ultrafast_Laser_Nanostructuring_in_Glass.pdf

1st, 2nd and 3rd Dimensions – Position

The first three dimensions are the simplest, they are the position of "dot" in the crystal along the x, y and z axes (*see figure 4*). These provide data storage in the standard method, although they have far more layers than most comparable mediums, DVDs usually only have 1-2 while the 5D crystals have been tested with 26. There is potential for an even greater number of layers, however there have been problems with spherical aberration[10], which is more difficult with a greater number of layers.

4th Dimension – Slow Axis Orientation

The slow axis orientation is one of the two ways in which that data is stored within the "dot" in the crystal itself, and is a method of data storage specific to birefringent materials[11], most commonly quartz crystals.2 bits can be stored in this manner, by two pairs of slow axis orientations each of which can be either a 0 or a 1, dependent upon where the light travels through slowest when polarised.

5th Dimension – Strength of Retardation

The strength of retardation is the second way in which data is stored within the "dot", and it can store 1 bit, as the "dot" is one of two possible strengths of retardation. The strength of retardation is determined by the intensity of the laser when the imprint is made. Lasers with a greater intensity create a greater strength of retardation by creating a deeper hole into the silica.

Birefringence

Birefringence [12]is a phenomenon that is the basis of the 5D storage medium, and is a property displayed only by certain form of crystal, most notably calcite and silica crystals. When polarised light enters the crystal it splits into two different beams, one horizontally polarised, the other vertically polarised, which exit at different points due to having different speeds. The different speeds are because of the skewed nature of the crystal, in which light polarised one way will collide

[9] http://www.orc.soton.ac.uk/fileadmin/downloads/5D_Data_Storage_by_Ultrafast_Laser_Nanostructuring_in_Glass.pdf - Accessed on 02/08/2016
[10] Jingyu Zhang *et. al*, JLMN-Journal of Laser Micro/Nanoengineering Vol. 9, No. 1, 2014
[11] http://www.edmundoptics.eu/resources/application-notes/optics/understanding-waveplates/
[12] http://iopscience.iop.org/article/10.1086/303542/pdf

with more bonds, slowing it down more than the light polarised the other way. The light that moves more slowly is referred to as the slow axis and the light that moves more quickly is referred to as the fast axis. The orientations of the axis can be a both altered and measured, allowing for a means of data storage such as that proposed by the 5d data storage method.

Crystalline Structure

Birefringence occurs in calcite and silica crystals due them being anisotropic, because of their atomic structure. The different strengths and orientations of the bonds in the crystal cause polarised light to diverge into two beams. This is done because the light interacts with these bonds differently depending upon its polarisation, slowing down the light at different rate, ultimately leading to different refractive indexes for light polarised in a different plane. This occurs because the Silicon bonds are all orientated in the same direction, while the oxygen bonds are all orientated in another.

The Readability of the Archive When Found

A major concern with using convention data storage methods is that, given other civilisations likely dissimilar culture and conventions from our own, they would not be able to read the archive, and particularly recover damaged data. Using the silica crystal 5D data storage method inherently solves two aspects of this problem.

Differing Conventions in Data Storage and Reading

The convention methods of data storage, most notably hard drives and disks, are built upon many previous iterations and are a product of our civilisation's specific rate and method of technological development. This would make the medium difficult to decipher for a civilisation alien to our own, particularly without a reference. The 5D data storage method solves this issue as it is neither an evolution of existing technology and it is utilising an easily observable phenomenon specific to its class of crystals, which would be able to be deciphered with relative ease even without instruction or reference.

Irretrievability of Damaged Data

Corrupted data is extremely difficult to recover, and is essential impossible if the software and file type is not known or understood, especially in the case of compressed files. This is still an issue in the case of using 5D data storage, although it is far less of an issue because of the physical method of data storage and high potential data density. The physical method of data storage means that physical damage to the storage medium is more easily repaired and can be corrected for without extrapolation of existing data. The high density helps prevent the compression issue as less of the data will need to be compressed, or it will at least reduce the compression level necessary.

The M-Disk

The Millennium Disk(M-Disk) was an attempt by Millenniata in 2009 to provide a method for long-term data backup in industry. It was modelled on existing DVDs, and improved upon them by replacing the commercial organic coating with one composed of minerals, which increased the projected duration of data integrity for the disk to approximately 1000 years. They functioned similarly to existing non-rewriteable DVDs, "Write once, read many times". This was done as their primary role was to replace existing methods of long-term data back-up. While the specific mechanics and materials of the M-Disk are still trade secrets, extensive testing has been conducted on the M-Disks.

Testing

In 2011 the first tests were sanctioned by Millenniata and conducted by the US Navy[13]. They were designed to compare the new M-Disk to existing DVDs. In these tests the disks were exposed to great amounts of light, moisture and high temperatures (*See Figure 5*). The tests quickly damaged the current DVDs, however the M-Disks retained 100% data integrity, even long after the DVDs were rendered completely unreadable.

Figure 5 Testing mechanism for the DVDs
Source:http://i.techweb.com/infoweek/byte/reviews/MDisc/discexposurerack.png

A conclusion on the suggested medium for eternal digital data storage in the archive

The 5D data storage method is a the most logical candidate for the medium of data storage in the archive. This is for several reasons, the main of which are:

- **The medium being physically robust**. The medium's inherent resistance to physical damage, radiation and heat increases the chances of the archive lasting for the required period of time and reduces the amount of required shielding from all of these potential forms of damage, which will in turn make the project cheaper, not only by the cost of the shielding itself, but also by making the probe lighter.
- **The lack of natural data corruption.** The medium does not degrade or decay naturally over time, unlike other storage mediums. This is what allows the archive portion of the project to have any real feasibility, as existing technology does not accommodate for data storage over such long periods.
- **The inherent ease of reading.** The utilisation of a natural phenomenon specific o the category of crystal used makes the project far easier to decipher.
- **The potential of the medium.** Research has not yet concluded on this method of data storage, and it looks promising to improve on itself greatly, especially in the data storage density.

[13] http://www.networkcomputing.com/storage/mdisc-review-thousand-years-storage/1130636931 - Accessed on 22/08/16