Next Generation Big Data Storage For Long Space Missions

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***Abstract*. This paper presents the results of the HELIOS (Hardened Extremely Long Life Information Optical Storage) mission on the International Space Station (ISS) which tested a unique solution for the long-term storage and retrieval of data in space. For this mission Creative Technology (CTech) developed test media—termed WORF (Write Once, Read Forever)—to validate whether this patented technology will survive all critical parameters for harsh space-based environments including microgravity and ionizing radiation. The HELIOS experiment confirmed that the WORF media is impervious to ionizing radiation, microgravity, solar (plasma) eruptions, and the stress from 8 Gs of the launch including extreme temperature exposure. The principal results indicate that there has been no discernible degradation of the media after 8 months on the ISS as compared to a control set of media stored on the ground. This data validated the media's survivability for harsh space environments for long-term and deep space missions. In addition to the space environment, we are confident that WORF technology can be used for data storage where space-related and other long-term or archival integrity is critical such as: geospatial collections from satellites; space weather archives; past, ongoing, and future space mission media and documentation files; the deep space Gateway program; as well as Big Data applications such as the Vera C. Rubin astronomical observatory (formerly the LSST). WORF technology for the HELIOS experiment uses a proven archival media, redesigned, re-purposed and patented by CTech to store digital data for long periods, measured in decades and possibly centuries. The media stores standing waves embedded in a substrate that capture the precise colors or wavelengths projected onto the media. The colors represent numerical data, with each data location storing multiple superimposed wavelengths, which facilitate the storage of multiple data bytes (rather than just zeros and ones); advanced mathematical permutations allow for extremely large data density equal to or greater than contemporary data storage devices. These colors cannot fade or degrade over time since the standing waves are physically stabilized (fully oxidized) metallic silver; no dyes are embedded for this storage system, and silver ions resist micro-bacterial and fungal contamination.**

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INTRODUCTION

There is a scene in *2001 A Space Odyssey* where astronaut Dave disables the spacecraft's main system computer, the HAL 9000. He disables it by removing core parts of the computer's software and memory, which is housed on pieces of glass. Whoever advised filmmaker Stanley Kubrick for that film did a far better job of imagining the future than most futuristic science fiction films.

The HELIOS project [1] provides a unique solution for the long-term storage and retrieval of data in space — *e.g.*, on the ISS, for lunar and Mars probes, etc. There have been several instances where a spacecraft has had some interruption in the operation of the vehicle due to corruption of the system software. Traditional electronic based memory systems (like solid state memory) are subject to damage from galactic cosmic rays and solar particle events. Having a fail-safe, incorruptible storage solution for core flight software could salvage a space craft, saving multi-billion dollar missions and possibly the lives of future deep space explorers.

Project goals and objectives were to provide a permanent, immutable data storage solution impervious to such environments. We proposed that our HELIOS media would be impervious to ionizing radiation, static electricity, electromagnetic (RF) interference, power surges and shorts, molecular and particle contamination, microgravity, magnetic fields, solar (plasma) eruptions, and stress from 8 Gs of the launch including extreme temperature exposure.

The results presented in this report indicate that there has been *no discernible degradation of the HELIOS media* after 8 months on the ISS as compared to a control set of media stored on the ground. This validated the media's survivability for harsh space environments for long-term, deep space missions.

The decision was made to actually fly the media in space to test vs. a ground-based radiation facility due to the mixed results of testing memory devices compared to actual experience in space. Early ground-based tests of small solid state memory cards used in cameras seemed to indicate they would not be viable for use in space. While actual experience using a camera with a small Secure Digital (SD) memory card on the ISS have indicated no issues from radiation damage, memory in computers and camera sensors, routinely are contaminated by space radiations. The sensor pixels are permanently destroyed while the memories, if not destroyed, have to be continually refreshed.

In addition to the space environment, we propose that the HELIOS technology can be used for data storage wherein space-related and other long-term or archival integrity is critical, such as: geospatial collections from satellites; space weather archives; past, ongoing, and future space mission media and documentation files; and crewed lunar and mars exploration programs.

The next NASA steps to test HELIOS will be to send the media with actual ISS program experiment data, along with a space-certified CTech HELIOS media reader, to the ISS.

1. THE HELIOS MEDIA

The technology for the HELIOS experiment uses a proven, archival media that can store digital data for long periods measured in decades and possibly centuries.[1] CTech has re-purposed and patented[2] this technology, applying contemporary COTS components, for long-term storage.

The HELIOS optical media stores standing waves embedded in a photosensitive. silver halide (AgX) emulsion coated on a substrate. [3] These immutable standing wave structures are physically stabilized (fully oxidized) metallic silver which embed the precise wavelengths of an image projected onto the media [2].

This methodology was first demonstrated over 130 years ago for color photography; extant photographs have stood the test of time showing no degradation to the present day. Unlike modern color films, no dyes are used so the colors cannot fade. Silver based photographs over 170 years old have shown little degradation to the present day. Moreo-

[1] While the patented name of this archival technology is "Write Once Read Forever," or WORF, for the purposes of this NASA ISS experiment it has been code-named HELIOS for "Hardened Extremely Long Life Information Optical Storage."

[2] US Patent No. 9,330,706.

[3] Details on the media process and the technology applied for writing and reading are in R.J. Solomon*, et. al,* "WORF (Write Once, Read Forever) Next Generation Archival Big Data Storage," submitted in this conference in Session 7.02, *Peripheral Electronics, Data Handling, and Interconnects for Space Applications*.

ver, silver is an anti-microbial, resisting bacterial and fungal attacks, unlike other optical media which degrade under such adverse attacks [3] [4]

CTech redesigned, re-purposed and patented this technology for data storage with the standing waves representing numerical data. While this special emulsion may be coated on rigid or flexible substrates, for the HELIOS mission we used conventional microscope glass plates for experimental convenience and handling in our processing labs and analytic devices; this substrate size and material will not be a constraint for future production devices since the planar dimensions for data storage are agnostic.

Being optical, the waveforms are detected directly via a simple and open source spectroscopic imaging device, as described by the waveform analysis in Sect. 4, "Spectroscopic Reading Procedure."

3. THE WORF TECHNOLOGY

Rapid Parallel Processing

One of the key attributes of the media's application of optical standing waves is that they can be superimposed. Therefore, each memory storage location can store *multiple data states* using *M*-ary arithmetic.

High Data Density.

Unlike legacy *bin*ary storage media, where a 256-bit byte would require 8 data locations, multiple data states permit one data location to store multiple bytes depending on the number of wavelengths that the media can embed. Data density can be further dramatically increased by combining data locations into matrices, drawing from larger wavelength palettes, and applying advanced permutation formulae.[4]

Data Transfer Speeds.

Since the data is stored as an optical pattern, whereby data locations can be read in parallel, extremely high speed data processing and analysis for *massively parallel Big Data* applications are feasible, equal to or faster than conventional, serial-access data storage techniques. *No movement is required* for these sensors to detect the colored patterns *in parallel*, as opposed to disks or tape where optical or magnetic data must be read *sequentially and in motion*.

Archival Features.

The HELIOS archival media resolves the long-standing dilemma of how to conserve tenuous digital archives without continuous network authentication, labor-intensive cyclical refreshing, and using the lowest possible energy inputs.

High energy efficiency—All current magnetic and optical digital media are unsustainable for long-term data storage due to their excessive energy requirements, inherent environmental deterioration, stiction, and the wear and tear of highspeed moving parts. In contrast, the long-term stability of microscopic metallic silver particles used for HELIOS standing wave data storage is well recognized.

Immutable &, Hack Proof—Error checking is inherent to each location so there is no necessity to read any other location to retrieve data; furthermore there is no need — nor is it possible — to rewrite or change any data point during the read process.

Human Readable—Since the media is optical, human-visible text and images are possible on the same media (Fig. 1). This permits ready identification, decoding and cataloging should for any reason the media be misplaced or retrieved some point in the future when the access formats are forgotten or lost. If necessary, metadata, indexing codes, and instructional text can be incorporated on the media along with numerical data.

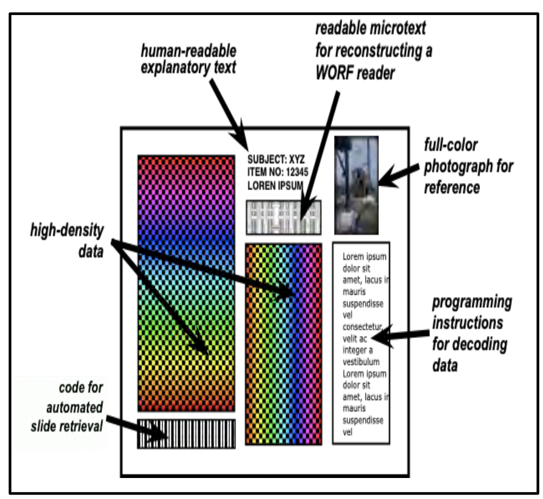


Figure 1. One example of WORF media consisting of multiple readable information.

[4] See discussion of permutation mathematics for increasing data density in the Appendix in our Session 7.02 paper, cited in fn. 3 above.

4. HELIOS RESEARCH PROCEDURE

WORF Media

CTech fabricated media specifically for the purposes of the HELIOS ISS space test. The test media was formulated with 8nm silver halide grains embedded in a 2-4µ (micron) thick hardened emulsion, applied to a dimensionally stable glass substrate, 75mm x 26mm (3″x1″), 1 mm thick (Fig. 2). Unlike most conventional storage media, no power or supervision was required for HELIOS storage on the ISS, reducing the astronaut work load.

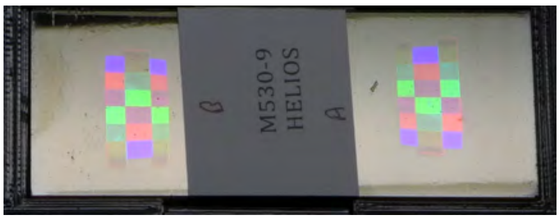


Figure 2. Sample HELIOS media tested on the ISS, showing colored test patterns.

Media Processing—During the research and development phase, we isolated and identified more than 15 potential variables in the exposure process and chemical development of the media. Through extensive experimentation, we gathered data from these variables to refine unique process controls to optimize the media. The key media write controls included input wavelength selection, exposure variables, and processing technique in order to get consistent results and to maximize the media's data storage capacity.

Media Preparation for HELIOS Experiment—Test patterns instead of encoded data were used for the HELIOS mission, because: 1) colored patterns were easier to analyze for any performance degradation; and, 2) sending data or actual information to the ISS on the media would have required further approval under international export regulations, potentially delaying the project.

Delivery to NASA.

The ISS case was delivered to NASA Johnson Space Center (JSC) in Houston on December 18, 2018, by CTech personnel via Amtrak, avoiding possible radiation contamination from air travel. The case, along with a NASA supplied radiation monitor (RAM), was launched to the ISS on May 3, 2019, on Space-X CRS-17 from the Kennedy Space Center. An identical radiation monitor was stored with the ground control case (Fig 3).

Figure 3. Opened ISS case showing two cassettes holding HELIOS test media.

25 HELIOS media in the sealed case were on the station for 246 days. The HELIOS case splashed down off Long Beach, CA, on January 7, 2020, from Space-X CRS-19 (Fig. 4), and was delivered by ground transport to JSC. After receiving the case from JSC in Houston on February 18, 2020, the sealed, unopened case was escorted by train to CTech's labs in Pennsylvania, arriving on Feb. 22, 2020. No physical degradation of the ISS media was detected — no cracks, scratches, abrasion, etc.

Figure 4. SpaceX CRS-19 splashdown off Long Beach, CA, carrying the HELIOS case on Jan. 7, 2020.

Media case decontamination—Both the ISS and ground control media cases went through a biological test and decontamination process before opening. The HELIOS case from the ISS was swabbed using a sterile swab moistened in distilled water prior to swabbing the case. The swab was then spread over a sterile, agar-prepared Petri dish, cover removed, and held with cover side down to prevent airborne contamination. The Petri dish was then covered, labeled, and set aside in 85ºF for three days. The Petri dish was then inspected for bacterial growth.

As shown in Fig. 5, there was no growth in the Petri dish from the ISS. In comparison, the same procedure was used to detect microbial contamination on the CTech ground case, which showed bacterial contamination (Fig. 6). The sterile swab was preserved for later DNA analysis if the ISS HELIOS case bacteria requires identification of the contaminant.

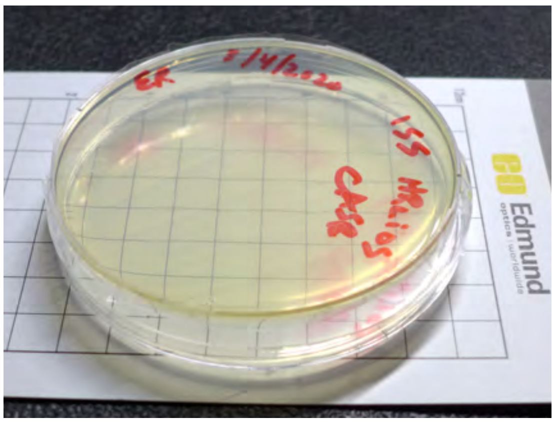


Figure 5. Culture from swab of HELIOS case after return from ISS to CTech's Labs.

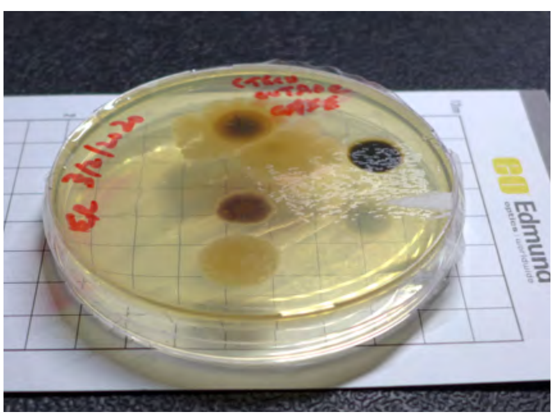


Figure 6. Culture from swab of control case kept at CTech's Labs.

Spectroscopic Reading Procedure.

The ISS and ground control media were read using a CTech designed and fabricated semi-automated spectroscopic reader (Fig. 7) to determine if there were any signs of degradation in the ISS test patterns compared to the ground control set. Using this controlled process, all media, ISS and ground, underwent the same test procedure. As noted, no discernible degradation between the ISS and control media colored test targets has been detected.

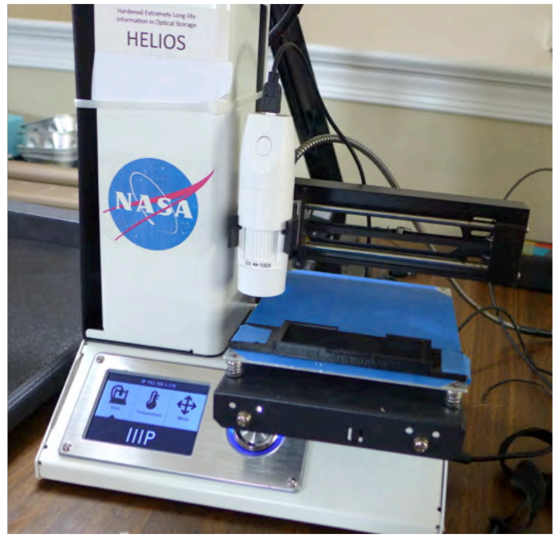
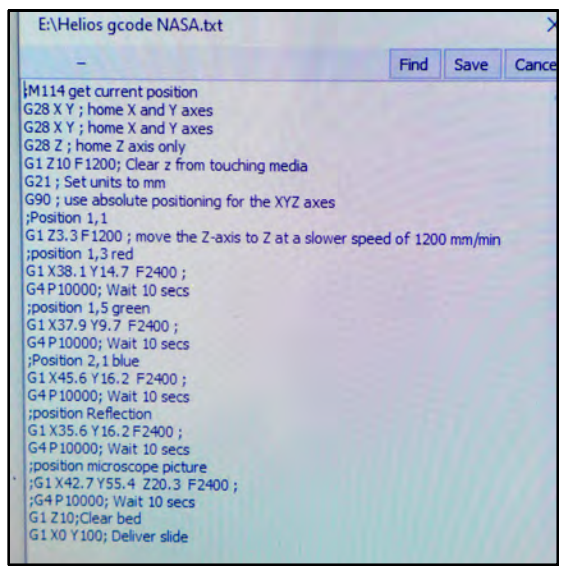


Figure 7. CTech designed and fabricated semi-automated spectroscopic reader for HELIOS media built on a modified 3D printer.

The automated system was programmed with custom Gcode (Fig. 8) running on Pronterface Printrun software (v.20140406) on a PC over USB.



E:\Helios gcode NASA.txt

Find Save Cance

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M114 get current position
G28 X Y ; home X and Y axes
G28 X Y ; home X and Y axes
G28 Z ; home Z axis only
G1 Z10 F1200; Clear z from touching media
G21 ; Set units to mm
G90 ; use absolute positioning for the XYZ axes
;Position 1,1
G1 Z3.3 F1200 ; move the Z-axis to Z at a slower speed of 1200 mm/min
;position 1,3 red
G1 X38.1 Y14.7 F2400 ;
G4 P10000; Wait 10 secs
;position 1,5 green
G1 X37.9 Y9.7 F2400 ;
G4 P10000; Wait 10 secs
;Position 2,1 blue
G1 X45.6 Y16.2 F2400 ;
G4 P10000; Wait 10 secs
;position Reflection
G1 X35.6 Y16.2 F2400 ;
G4 P10000; Wait 10 secs
;position microscope picture
;G1 X42.7 Y55.4 Z20.3 F2400 ;
;G4 P10000; Wait 10 secs
G1 Z10;Clear bed
G1 X0 Y100; Deliver slide
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Figure 8. GCode program for controlling CTech's semi-automated spectroscopic HELIOS media reader.

Spectroscopic Analysis—Another 3D printer was modified by CTech to act as a robotic mechanism for positioning the spectrometer illuminator and probe to the identical positions of red, green and blue areas of the test patterns recorded on each HELIOS media. The robotic mechanism included a USB microscope camera to capture an image of each test pattern on each HELIOS media to detect and document any physical anomalies of the media (Fig. 9).

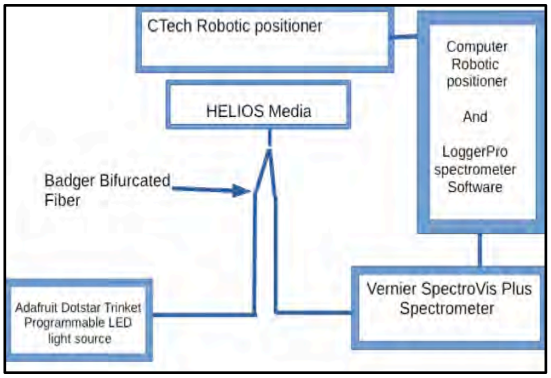

Figure 9. Functional test setup for spectroscopic measurement of HELIOS media.

Spectroscopic measurements were made using a Vernier SpectroVis Plus spectrometer with a custom designed and 3D printer fabricated cuvette, modified for fiber optic excitation. The SpectroVis Pro was connected to a MacBook Air via USB. Software was Vernier LoggerPro (v. 3.15) under MacOS 10.13.6. Spectrometer sensitivity was set to 32 ms per scan, 6 scans per reading, and averaging set to 1. Spectral range was set to 400nm to 700nm, with a color spectrum strip at the bottom (X-axis) of the graph.

5. CONCLUSIONS.

ISS vs. Ground Control Results.

The graph in Fig. 11, from one example of the sets of HELIOS media,[5] overlays two test patterns from one ground control run with one ISS run from the same processed and exposure batch. The curves represent the red-green-blue wavelength intensities (the X-axis is the wavelength in nanometers; the Y-axis the relative intensity), as captured by the spectroscopic analysis process. The RED curve is the ground control media and the BLUE curve is the ISS in all the graphs.

[5] See Final Report, Ref. [1] for other graphs from the HELIOS experiment.

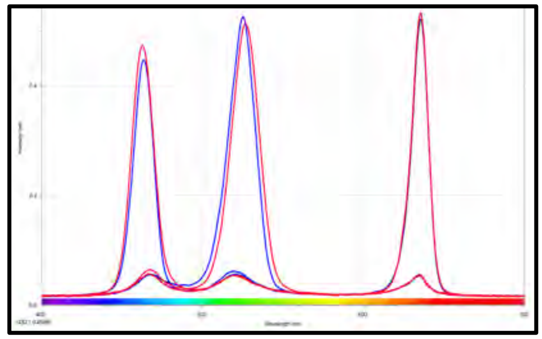

Figure 10. Spectra graphed via Logger Pro software, comparing ground control media (RED) intensity curves with ISS (BLUE) curves. Overlaps indicates no degradation due to ISS media exposed to space radiation.

The slight differences in the curves are well within expected nominal values due to minor variations in exposure and manual processing techniques. Further, the curves show that the test patches' SNR are well within parameters for robust reading.

Radiation Exposure.

Two Radiation Area Monitors (RAMs) were assembled and delivered on November 27, 2018, by the Space Radiation Analysis Group at NASA/JSC in support of the HELIOS Payload. One RAM was designated to fly on the ISS, while the other was to be used as a control for ground radiation exposure measurements during shipping and transportation (Fig. 12). The RAMs included two different types of thermoluminescence dosimeters (TLD), TLD-100 (LiF:Mg,Ti); and TLD-300 (CaF2:Tm); with a total of 20 TLDs for each RAM.

Figure 11. The HELIOS Radiation Area Monitor units as delivered for Space X-17

The ground exposure RAM (S/N 3078) measured a total dose of 0.62 ± 0.02 mGy for a 521 days exposure. The ground exposure results confirmed no contamination to the signal from X-ray sources (*i.e.,* the RAMs were inside lead-lined bag for transport, and thus protected). The flight RAM (S/N 3079) was exposed for 248 days in space and 273 days on the ground. Since the RAM can measure only the cumulative mission dose, the final RAM flight dose has been corrected by the ground exposure dose rate. The HELIOS RAM total mission dose on ISS was 221.5 ±5.7 mGy (Table 1).

Table 1. Summary of RAM Results.

Location	RAM S/N	Duration (days)	RAM Mission* Dose (mGy)	RAM Dose Rate (µGy/day)
Ground Exposure (CTech Lab) Dec 16, 2018 – May 1, 2020	3078	521	0.62 ± 0.02	1.19 ± 0.03
ISS Exposure May 4, 2019 – Jan 7, 2020 *Dragon Vehicle* (May 4 -7, 2019) *ISS NOD2* May 7 - Jun 6, 2019 *ISS* Jun 6, 2019 – Jan 5, 2020	3079	248	221.5 ± 5.7	892.2 ± 23.1

The next steps for NASA:

- Testing HELIOS technology containing actual program experiment data, along with a space-certified CTech HELIOS media reader, to the ISS.
- Crewed lunar and Mars exploration, including key precursor missions and return vehicle (Artemis Program).
- A ground-based writer-system with reader at the station, or a writer/reader system, with media processing on the ISS.
- Process for writing NASA ISS program data.

Additional aerospace applications

Long-term storage of data for astronomical extended-term analysis:

- Data captured by high powered radio and optical telescopes, such as the Rubin LSST telescope under construction in Chile [5].
- Solar data.
- Space weather.

BIOGRAPHIES

Richard J. Solomon *is a Visiting Scholar in University of Pennsylvania's School of Engineering and Applied Science, and Creative Technology's Chief Scientist researching wave-based imaging and human vision. Formerly, Associate Director of the Research Program on Communications Policy at the Massachusetts Institute of Technology, working on the MIT/Polaroid/Philips HDTV camera for NASA and DARPA, and on advanced telecommunications implementations. Prior, Research Fellow in Harvard's School of Engineering and Applied Science researching telecommunications technology and regulation.*

Eric Rosenthal*, CEO/CTO of Creative Technology, LLC, formerly Adjunct Professor/Scientist in Residence at New York University's Interactive Telecommunications Program, teaching Master's classes in electronics and digital imaging. Over 40 years experience in electronics technologies including advanced, wave-based imaging for US DoD and NASA, low-cost spectrometric sensors, a novel 3D video system, and micro-miniature directional microphones. Formerly, VP Advanced Technology Research at Walt Disney Imagineering Research and Development, and General Manager Systems Engineering for the Disney/ABC TV network.*

Rodney Grubbs *began his career as a co-op motion picture photographer at NASA's Marshall Space Flight Center while a student at the University of Alabama. He is currently the NASA Imagery Experts Program Manager and Chairs an International Space Agency Imagery Standards Group. He is responsible for the NASA video distribution architecture including NASA TV and internet video distribution. He has been a Principal Investigator for flights of High Definition Television (HDTV) and Digital Cinema cameras and related experiments on the Space Shuttle and International Space Station (ISS), including the first ever live HDTV program from a spacecraft and the first ever Ultra High Definition program from a spacecraft. He is currently a Principal Investigator for the National Lab's Red Digital Cinema camera on the ISS and is working on the imagery architecture for NASA's Artemis program to land the next man and first woman on the Moon.*

Brian Solomon *is CTech's photo-chemistry and emulsion expert. He has 30 years experience in photographic laboratory techniques and methods including automated processing machinery. BA, Rochester Institute of Technology.*

References

[1] Final Report, "Hardened Extremely Long Life Information Optical Storage (HELIOS)," is at: http://www.creative-technogy.net/CTECH/Papers_files/NASAreport.pdf

[2] Further details of the WORF process and technology used for the HELIOS media are in the following papers:

a) R.J. Solomon, M. Buchman, C. Johnson , E. Rosenthal, & J. Smith,, "Toward a 'Digital Noah's Archive' (DNA)", *Proc. IS&T Archiving 2019*, Lisbon. DOI: 10.2352/issn.2168-3204.2019.1.0.15

b) R.J. Solomon, M. Buchman, C. Johnson , E. Rosenthal, & J. Smith, "Write Once, Read Forever (WORF): Low-energy storage in perpetuity of high-density, multi-state data," *Proc. IS&T 2014 Archiving Conference*, Berlin, Society for Imaging Science and Technology, 5:118-122.

c) R.J. Solomon, M. Buchman, C. Johnson , E. Rosenthal, & J. Smith, "Write Once, Read Forever (WORF): Proof-Of-Concept Demonstrated For Archival Data Storage Using Interference Spectra," *Proc. IS&T Archiving 2015 Conference,* Los Angeles, Society for Imaging Science and Technology, pp. 92-97.

d) R.J. Solomon, M. Buchman, C. Johnson , E. Rosenthal, D. Carlin, & W. Butterfield, "Test Data Reader for Write Once, Read Forever (WORF) Interference Spectra Archival Media," *Proc. IS&T 2016 Archiving Conference*, Washington.

[3] R. Belly & G. Kidd, "Silver Resistance In Microorganisms," *Dev. Ind. Microbiol*., **23** (1982) pg. 567 fn.

[4] X. Bosch, "Fungus eats CD—Spores bore holes in compact disks, rendering them useless," *Nature*, doi:10.1038/news010628-11 (2001).

[5] https://www.lsst.org [accessed 6 Sept. 2020].