"Hardened Extremely Long Life Information Optical Storage" (HELIOS) with Creative Technology, LLC (CTech) • CAN No. 80MSFC18M0049 Supplement P00003[1]

Final Report, August 1, 2020

1.0. Executive Summary.

The HELIOS project 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.

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.

For the HELIOS mission we developed test media to validate whether the technology will survive all critical parameters for harsh space-based environments, including microgravity and ionizing radiation. Project goals and objectives were to provide a permanent, immutable data storage solution impervious to such environments.

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 the deep space gateway program.

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

2.0. Technical Merit and Feasibility of the HELIOS project.

This project explored whether HELIOS technology is a more robust solution for keeping data intact during long-term deep space missions.

The patented technology[2] for the HELIOS experiment uses a proven, archival media that can store digital data for long periods measured in decades and possibly centuries. The media was placed on the ISS so it would be exposed to a hostile space environment.

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1. Section 2.1.5.4, "Technologies Supporting Solar and Space Science and Applications - Advanced data archiving." https://techport.nasa.gov/view/94998.

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

(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.”)

We had proposed that this 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 experiment confirms that all these criteria have been met, and *validated the media’s survivability for harsh space environments for long-term, deep space missions*.

The data, discussed and illustrated in Sect. 3.6, show no discernible degradation of the media after 8 months on the ISS as compared to a control set of media stored on the ground under a normal ambient room environment at CTech’s Pennsylvania labs.

Since the HELIOS media is a passive storage system consisting of optically stable data elements, no power or supervision was required for storage on the ISS. Hence, the astronauts merely had to place and secure the test media contained in a sealed case, and remove the case for its return to Earth; no other astronaut participation was required during the mission.

3.0. Research Procedure.

CTech fabricated media specifically for the purposes of the HELIOS ISS space test. This media stores colored test pattern images, discussed in Sect. 4.0.

3.1. HELIOS Media. Five sets of media were processed for the test; each set having up to 10 media were created as a batch. All the test pattern images are identical in form. Each sample contains a colored test pattern at each end (Fig. 1), All media were numbered and identified.

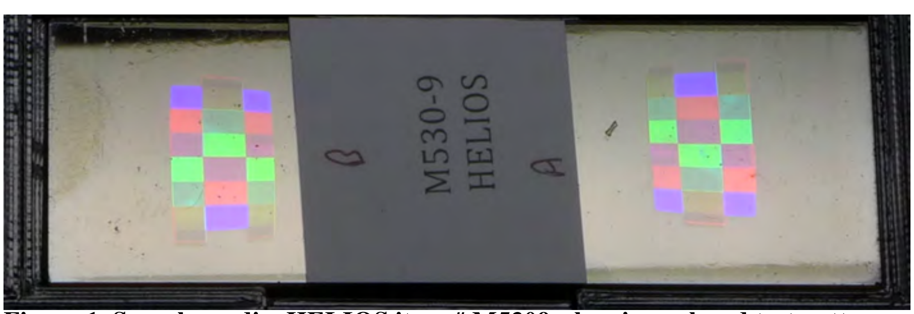

Figure 1. Sample media, HELIOS item # M5309, showing colored test patterns A and B at each end (see Sect. 3.6.2 for explanation of item code).

Two sets of 25 media (5 sets with 5 media from each batch set, as described in Sect. 3.6.1) were placed in two identical sealed cases (Fig. 2): one for the ISS launch; and one for control purposes, placed unopened at CTech's lab in Pennsylvania for comparison after return from space.

Figure 2. Opened ISS case showing two cassettes holding HELIOS test media.

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

The ISS case was delivered to NASA JSC Houston on December 18, 2018, by CTech personnel, via Amtrak avoiding possible radiation contamination from air travel. The case (NASA item # CT-1120), along with a NASA supplied radiation detector (RAM SN 3079), was launched to the ISS on May 3, 2019, on SpaceX CRS-17 from Kennedy Space Center. An identical radiation detector (RAM SN 3078) was stored with the ground control case.

The 25 media in the sealed case were on the station for 246 days, moved June 6, 2019, for space radiation exposure (Fig. 3, & Sect. 3.6.4, Table 2, pp. 13-14).

The HELIOS case splashed down off Long Beach, CA, on January 7, 2020, from SpaceX CRS-19 (Fig. 4, p. 4) and delivered 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, arriving on Feb. 22, 2020.

Figure 3. Sealed HELIOS case mounted in the ISS for maximum space radiation exposure.

3.2. Media case decontamination. Both the ISS and ground control media cases went through a biological test and decontamination 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.

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

As shown in Fig. 5, there was no growth on the petri dish from the ISS. In comparison, the same procedure was used to detect microbial contamination on the CTech ground case which showed the presence of bacterial contamination (Fig. 6). The sterile swab was preserved for later DNA analysis if the ISS HELIOS case bacteria requires identification of the contaminant (Fig. 7).

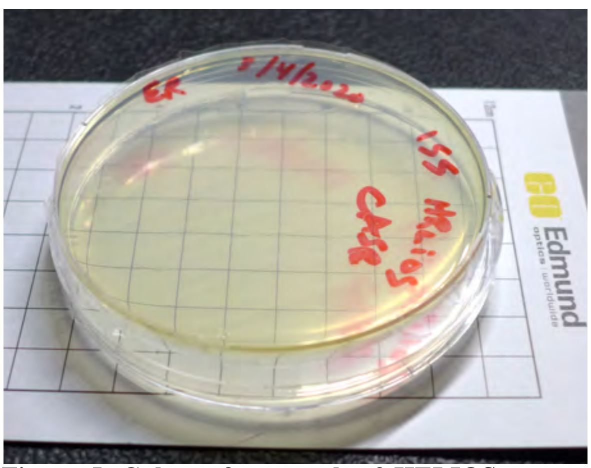

Figure 5. Culture from swab of HELIOS case after return from ISS to CTech's Labs.

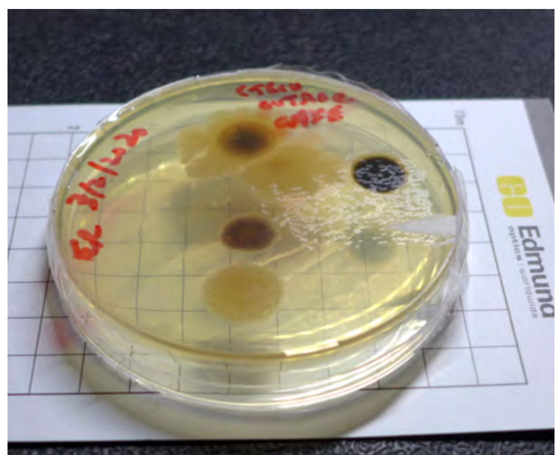

Figure 6. Culture from swab of control case kept at CTech's Labs.

Figure 7. Swab used to store culture taken from HELIOS ISS case kept at CTech Labs for DNA analysis if necessary.

3.3. HELIOS physical media examination. After the case decontamination procedure, CTech inspected the ISS media for physical degradation. A microscope camera attached to the semi-automated reader (discussed next) captured photographs of each of the test patterns on each of the media sent to the ISS as well as the CTech ground media.

No physical degradation of the ISS media was detected — no cracks, scratches, abrasion, etc.

3.4. Spectroscopic Reading Procedure. The ISS and ground control media were read using a CTech designed and fabricated semi-automated spectroscopic reader (Fig. 8) to determine if there were any degradation in the ISS test patterns as 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 (Sect.3.6.1, p.9).

The GCode program to control the CTech automated reader is in Fig. 9 (p. 6).

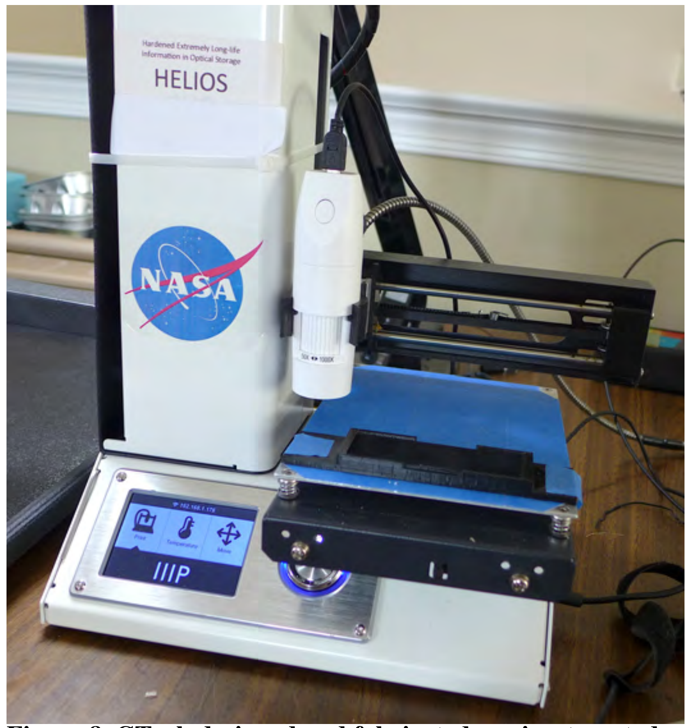

Figure 8. CTech designed and fabricated semi-automated spectroscopic reader for HELIOS media built on a modified 3D printer.

3.5. Scanning process:

3.5.1. Calibration.

1) A front surface mirror was placed in the Media carrier of the reader (Fig. 8).
2) The spectrometer probe was XY positioned to read reflected light from the front surface mirror.
3) The programmable DotStar LED was illuminated (Fig. 11, p. 7).
4) The Z position of the spectrometer probe was tuned to obtain maximum input to the spectrometer.
5) The programmable DotStar LED illuminator was tuned so that RGB values presented equal intensity on the spectrometer display (program in Fig. 12, p.8).

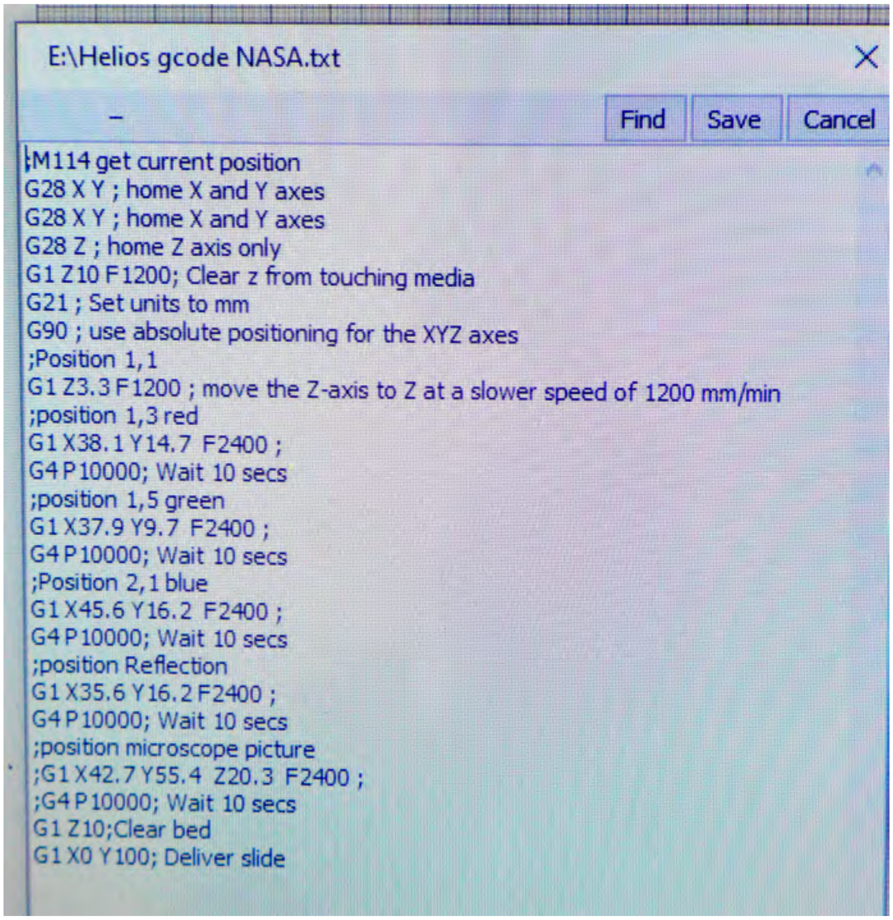

Figure 9. GCode program for controlling CTech's semi-automated spectroscopic HELIOS media reader

3.5.2. Spectroscopic analysis:

1) Spectroscopic measurements were made using a Vernier SpectroVis Plus spectrometer with a custom designed and 3D printer fabricated cuvette, modified for fiber optic excitation (Fig. 13, Functional drawing, p. 8).

2) The SpectroVis Pro was connected to a MacBook Air via USB (Fig. 10, p. 7). Software was Vernier LoggerPro (v. 3.15), running on the MacBook Air with MacOS 10.13.6.

3) Spectrometer sensitivity using Logger Pro 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 each graph (graphs in Sect. 3.6.3).

4) A 3D printer was modified by CTech to act as a robotic mechanism (Fig. 8, p. 5) 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 automated system was programmed with custom Gcode (Fig. 9, p. 6), running on Pronterface Printrun software (v.20140406) on a PC over USB.

5) 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 (Sect. 3.3, p 5).

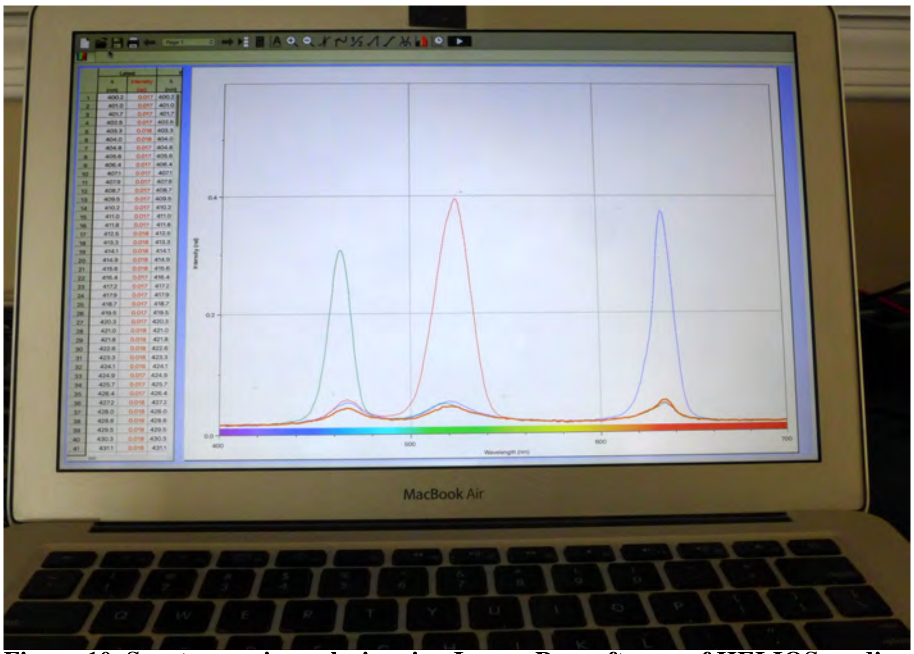

Figure 10. Spectroscopic analysis using LoggerPro software of HELIOS media.

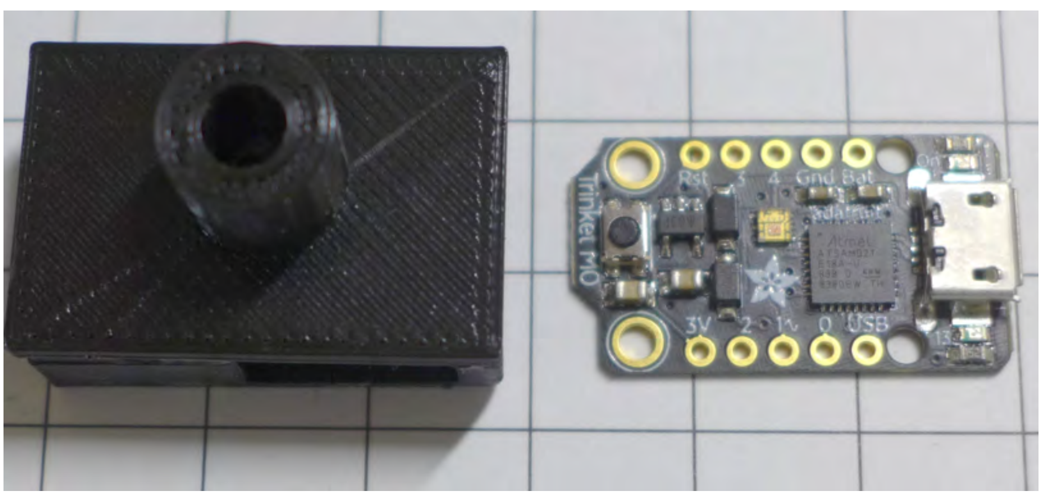

Figure 11. Adafruit Dotstar Trinket programmable light source for spectroscopic measurement of HELIOS media

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//CTech NASA Dotstar Trinket Programmable Light Source for
//Spectroscopic Measurement of HELIOS Media

#include <Adafruit_DotStar.h>
#include <SPI.h>
#define NUMPIXELS 1 // Number of LEDs in strip
#define DATAPIN   7  // for internal dotstar
#define CLOCKPIN  8  // for internal dotstar

Adafruit_DotStar strip = Adafruit_DotStar(
  NUMPIXELS, DATAPIN, CLOCKPIN, DOTSTAR_BGR);

void setup() {

  strip.begin(); // Initialize pins for output
  strip.show();
}
//Set RGB values for Equal levels using front surface mirror on automated reader
void loop() {
  strip.setPixelColor(0, 143, 228, 255); // red, green, blue
  strip.show();
}
```

Figure. 12. Program for Adafruit Dotstar Trinket Programmable light source for spectroscopic measurements using automated reader

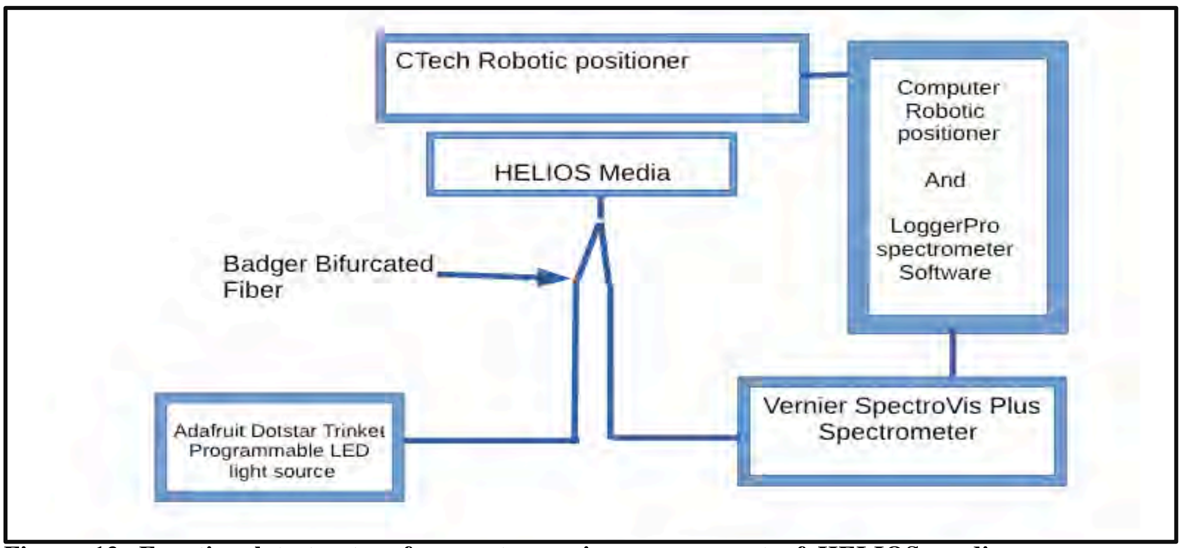

Figure 13. Functional test setup for spectroscopic measurement of HELIOS media. (CTech, April 2020.)

3.6. Research Results:

3.6.1. Media. CTech fabricated media specifically for the purposes of the HELIOS ISS space test. This photosensitive media stores colored test pattern images (Fig. 1, p. 2) in the form of fully stabilized, metallic silver interference standing waves, discussed in detail in Sect 4.0.

Five batches of media were exposed with the same colored test pattern within each batch *sequentially*, and with each batch chemically processed *simultaneously*. Across all batches, each sample contains the identical test pattern at each end, marked A and B; some samples with exposure variables for the A and B ends, others with identical exposures for A and B. All media were numbered and identified.

3.6.2. Media numbering is as follows:

M = processing location; M = Monson, MA.
530 = set batch number
9 = run number within the batch.
A/B = end A vs. end B

Therefore, the 1st 3 digits = batch number; last digit = run number; letter A or B = media end.

3.6.3. Data results.

Each graph, illustrating 6 sets of media, overlays the media test pattern from one ground run with one ISS run from the same processed and exposure batch (Figs. 14,15, 16, 17, 18, 19, following pages)

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 process discussed in Sect. 3.5, p.5. The RED curve is the ground control media and the BLUE curve the ISS in all the graphs. The media batches and items graphed are identified in the headings and captions.

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

Therefore, the data shows *no indication of space environmental effects on the media* from the ISS as compared to the ground control media.

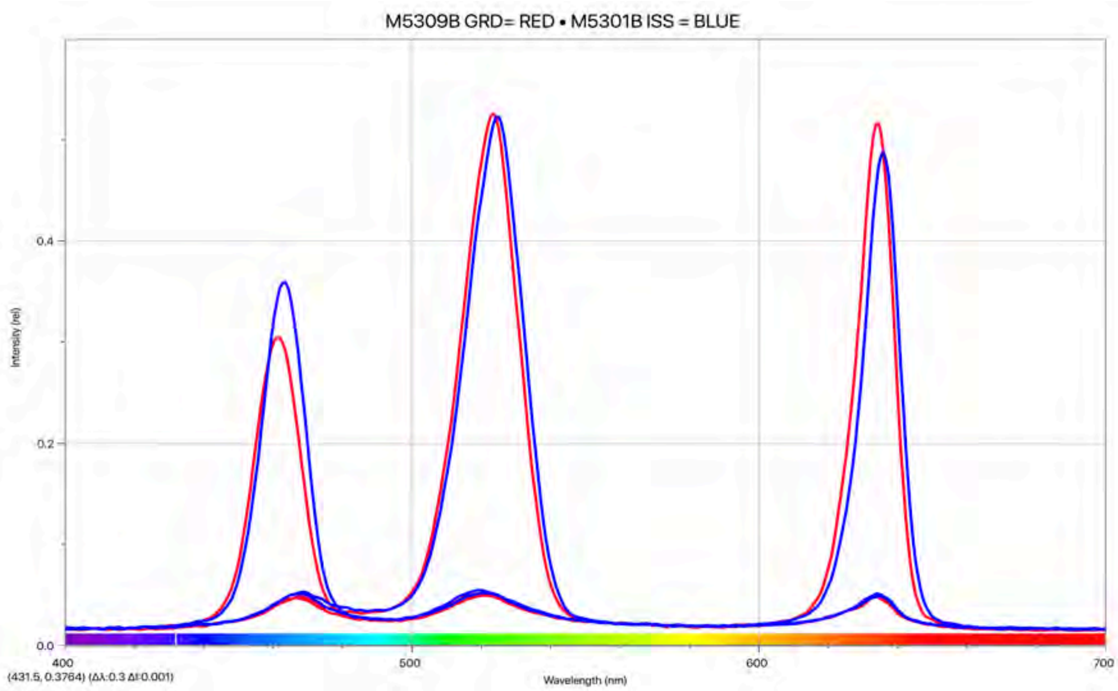

Figure 14. Batch 530, ground #9B vs ISS #1B

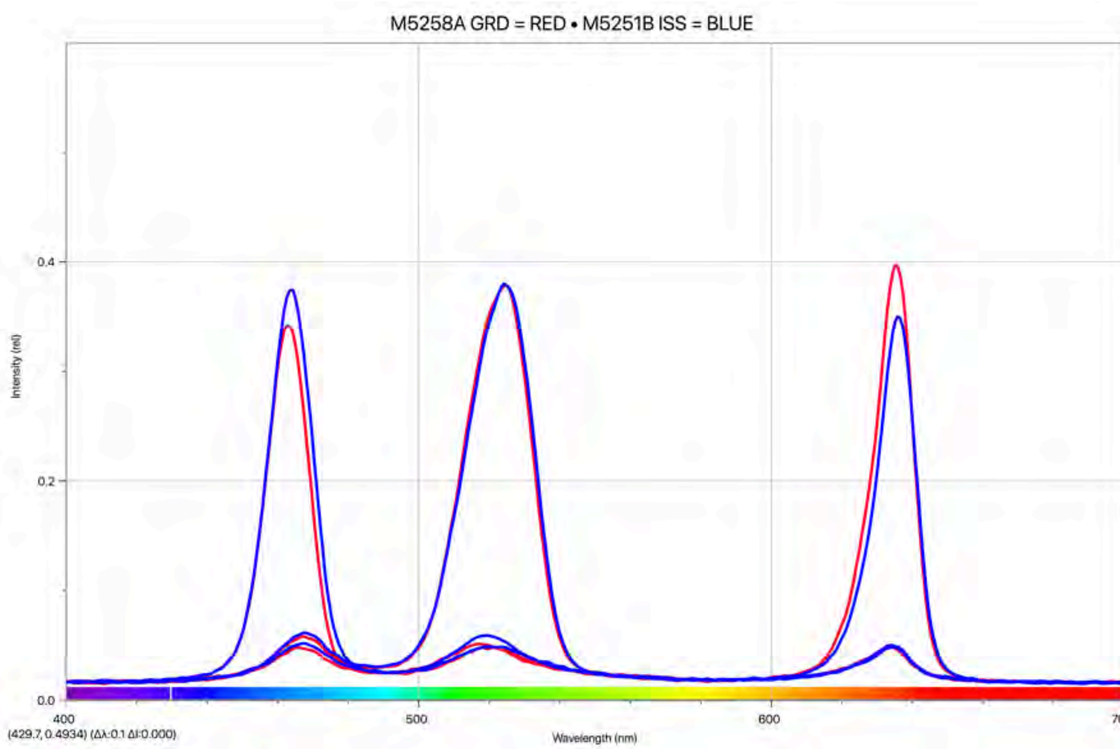

Figure 15. Batch 525, ground #8A vs ISS #1B

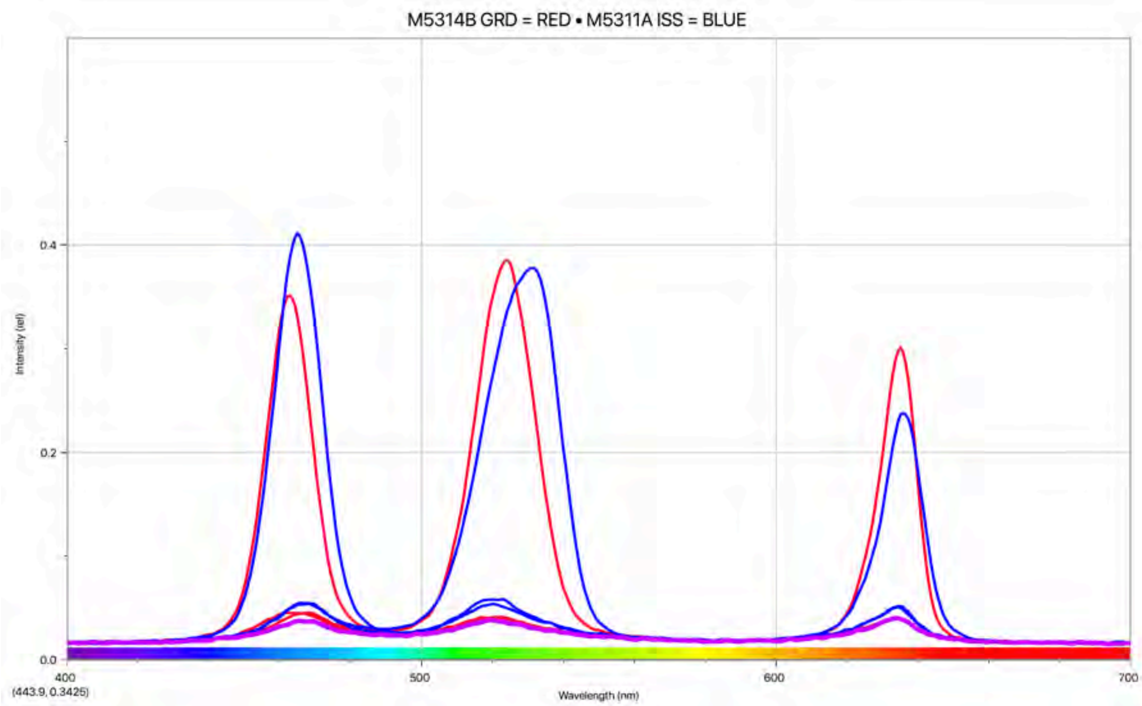

Figure 16. Batch 531, ground #4B vs ISS #1A

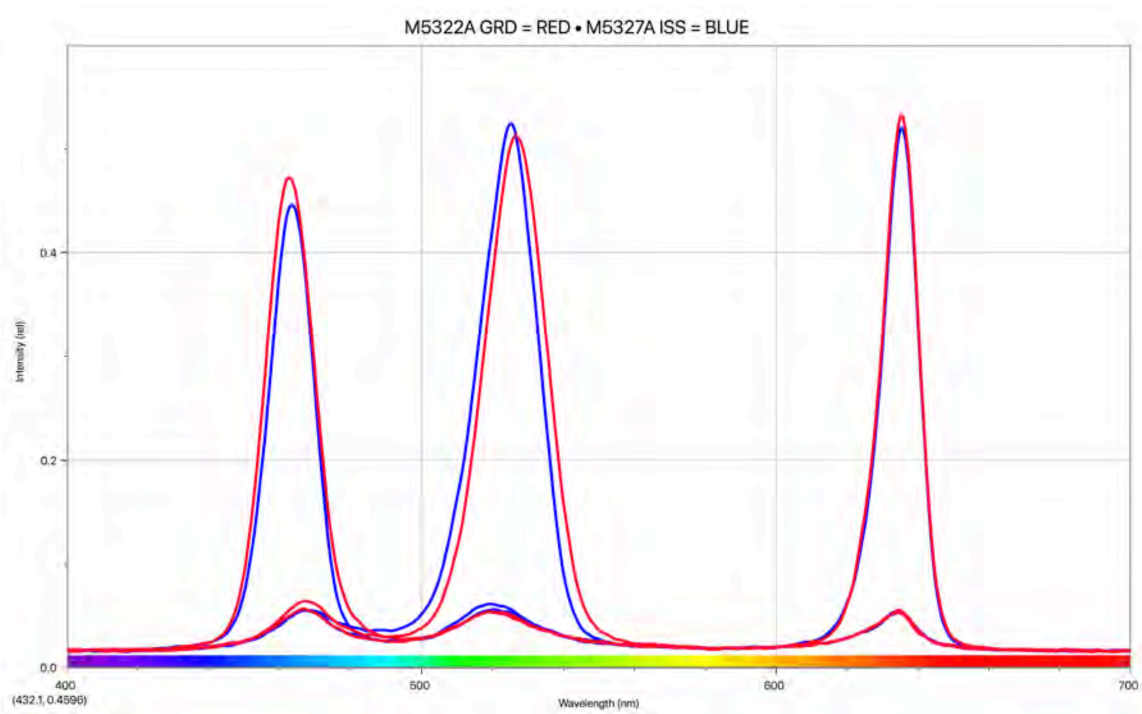

Figure 17. Batch 532, ground #2A vs ISS #7A

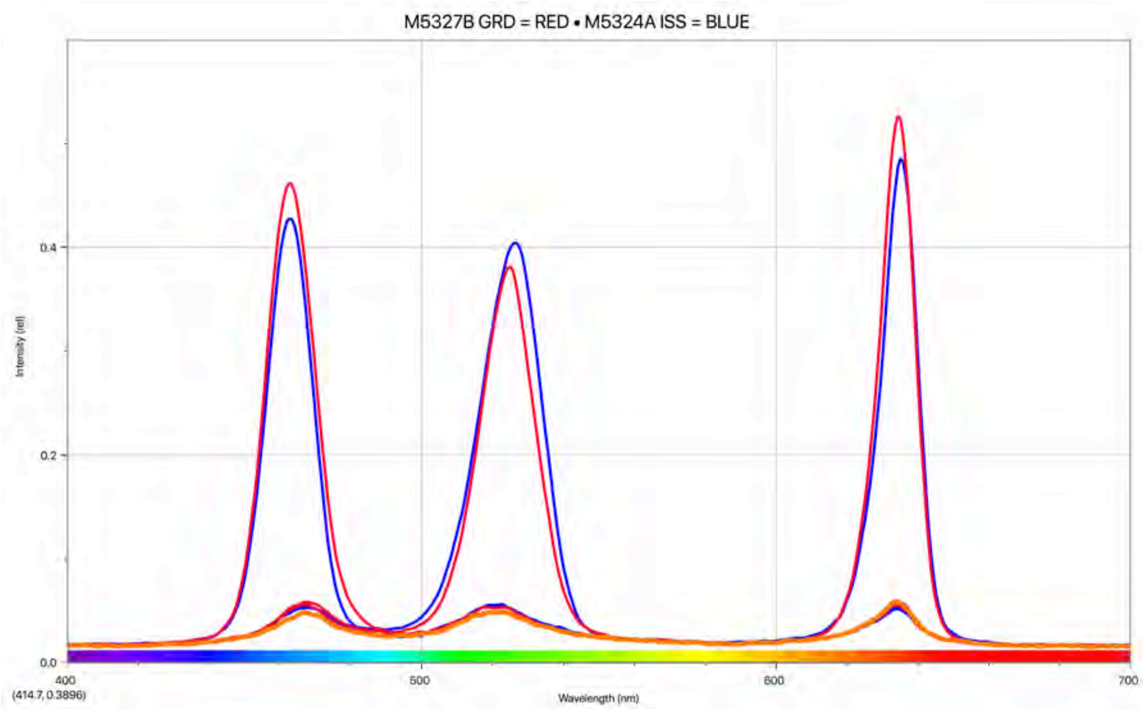

Figure 18. Batch 532, ground #7B vs ISS #4A

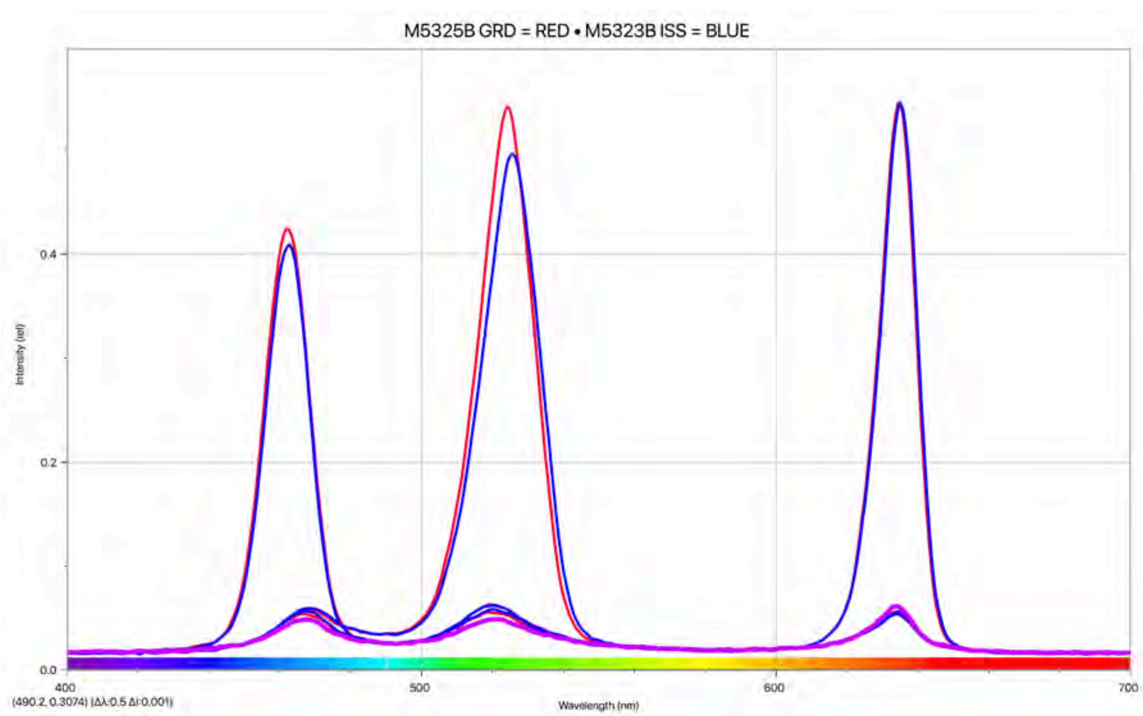

Figure 19. Batch 532, ground #5B vs ISS #3B

3.6.4. RAM results. 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. 20). 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. Details on different types of thermoluminescence dosimeters and their characteristics are provided by Gaza *et. al*., 2017.[3]

Figure 20. Image of the HELIOS Radiation Area Monitor units as delivered for SpX-17

The HELIOS RAM was launched to ISS aboard the SpX-17 flight on 4 May 2019, 06:48UTC and returned to the ground aboard SpX-19 on 7 January 2020. The mission total duration was 248 days. On ISS, the HELIOS Payload and associated RAM were removed from the Dragon vehicle on 7 May 2019 and stowed in the Node 2 module until deployed on the ISS on 6 June 2019. The HELIOS RAM was removed from the ISS per nominal packing activities for the SpX-19 return on 7 January 2020 (Timeline, Table 1).

Table 1. HELIOS RAM Exposure Timeline.

RAM Label	RAM S/N	Delivered to JSC B421	Launch Date SpX-17	Land Date SpX-19	Received at SRDL	Measured at SRDL
Helios RAM kept on ground Nov 27,2018 –May 1 2020	3078	11/27/2018	*N/A	*N/A	4/23/2020	5/1/2020
Helios RAM flown to ISS May 4, 2019 – Jan 7, 2020	3079	11/27/2018	5/4/2019	1/7/2020	4/23/2020	5/1/2020

3. R. Gaza, M. Kroupa, R, Rios, N. Stoffle, E. R. Benton, E. Semones (2017). "Comparison of novel active semiconductor pixel detector with passive radiation detectors during the NASA Orion Exploration Flight Test 1 (EFT-1)." *Radiat. Meas.* 106, p 290-297, Nov 2017. https://doi.org/10.1016/j.radmeas.2017.03.041.

3.6.5. Measurements And Data. The RAM thermoluminescence measurements were performed in the Space Radiation Dosimetry Laboratory (SRDL) at NASA/JSC on May 1, 2020. (More details of the experimental setup is provided by Gaza, *et. al*., *op .cit*.)

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 RAM were either not exposed to X-ray or exposed inside lead-lined bag and thus protected). The flight RAM (S/N 3079) was exposed to 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. A summary of the dose measurement results are in Table 2.

Table 2. Summary of HELIOS RAM Dosimetry 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

*** RAM Mission Dosimetry values have been already corrected to subtract the ground handling and shipping exposure as measured by S/N 3078, no additional correction needed.**

3.7. CTech Deliverables to NASA.

Three sets of media (15 items), consisted of media from distinct batches will be delivered to NASA. Two sets (10 items) will remain at CTech.

4.0. Technical Details of the HELIOS media:[4]

The HELIOS optical media stores interference standing waves on a substrate that captures the precise colors or wavelengths of a color image projected onto the media. 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.

4.1. Data storage. CTech redesigned and re-purposed this technology for data storage with the standing waves representing numerical data. For the HELIOS project a colored image set of specific wavelengths are embedded in an extremely thin, photosensitive, *monochromatic,* highly durable emulsion. These interference colors cannot fade or degrade over time since the standing waves are in physically stabilized (fully oxidized) metallic silver; no dyes are embedded for this storage system.

4.2. Media structure. The ultimate practical resolution of this special emulsion is ~20,000 line pairs per mm, making possible an extremely high data density. For HELIOS, the test photosensitive media was formulated with 8nm silver halide grains embedded in a 2 to 4 micron thick hardened emulsion applied to a dimensionally stable glass substrate, 75mm x 26mm (3 x1″), 1 mm thick.

This emulsion was processed in a special chemical process which stabilizes the exposed standing waves, removes the residual silver, and hardens the emulsion protecting it from abrasion. Stabilized silver has a known, exceedingly long life — silver halide photographs >170 years old have shown little degradation — moreover silver is an anti-microbial resisting bacterial and fungal attacks, unlike other optical media which degrade under adverse such attacks.

Unlike most conventional storage media, no power or supervision was required for HELIOS storage on the ISS, reducing the astronaut work load.

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4. 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, Society for Imaging Science and Technology.

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 in the waveform analysis Sect. 3.0.

4.3. Features of the WORF technology:

4.3.1. Rapid parallel processing for true random data access. 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, where an enumeration of the set of available colors (*e.g.,* red, orange, green, blue) encodes 1,2,3,4 (or as bits, 00, 01, 10, 11) at each data location.

4.3.2. High data density. Unlike legacy *bin*-ary storage media, where a byte (or 8 bits) would take 4 data locations, multiple data states permit one data location to store multiple bytes depending on the number of wavelengths that the media can embed. We have demonstrated so far up to 4 colors per data location; if the colors at each data location were selected from a larger palette of 32 colors, for example, (*i.e.,* varying the color combinations at data locations according to a standard combinatory formula) this would yield ~ 36 Kilobits *per data location!*

Data density can be further dramatically increased by combining data locations into matrices, drawing from even larger wavelength palettes, and applying advanced permutation formulae.[5]

4.3.3. Data transfer speeds. Since the data is stored as an optical image, 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. This technique meshes well with novel parallel processing computer architectures being advanced.

A highspeed, parallel read device would contain an array of *n* optical sensors reading *n* data points *simultaneously*, essentially taking a high-resolution electronic photograph of *n* multi-state, standing wave, data locations on the media for downstream processing. *No movement is required* for these sensors to detect the waveforms in parallel, as opposed to disks or tape where optical or magnetic data must be read sequentially and in motion.

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5. See mathematics appendix in footnote 4, ref. a, preceding page.

Transfer speeds depend on the capture or frame rate for the read sensor array. For example, assuming a media size = 10 x 10 cm (10 cm^2), storing 8 TeraBytes, a sensor capturing 72 fps would be able to *transfer 1.44 TeraBytes in one second* of *uncompressed raw data*, assuming processing equipment and software is devised to store information at that rate.

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

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 physio-chemistry of microscopic metallic silver particles is well understood to last for centuries. As noted, CTech has re-purposed and patented this silver interference technology, applying contemporary COTS components, for archival storage *under normal ambient temperatures and relative humidity*.

4.3.5. Human-visible text and images are possible on the same media since it is optical. 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 (Fig. 21). Metadata, indexing codes, human-visible images and instructional text can be incorporated on the media along with data if necessary.

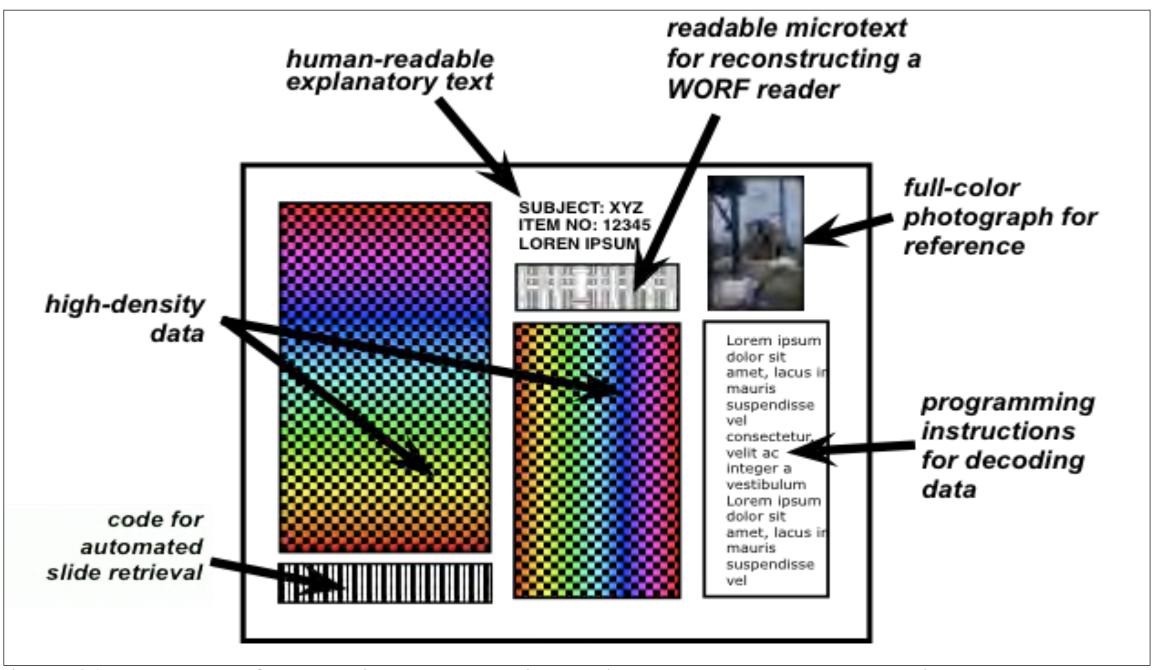

Figure 21. Example WORF media layout showing various elements that can co-exist. Note that the size and shape of the media is agnostic — most any shape or size is feasible.

4.3.6. Immutable and hack proof data storage. Data is written only once per data location. Error checking is inherent to each point so there is no necessity to read any other point to retrieve data, and there is no need — nor is it possible — to rewrite any data point during the read process.

5.0 Potential NASA applications of HELIOS/WORF media include:

- Long-term storage of data for use on long space missions
- Long-term archival storage of data and media without continual reprocessing
- Long-term storage of data for astronomical extended-term analysis:
    - Data captured by high powered radio and optical telescopes
    - Solar data
    - Space weather
    - Long term archiving of existing data and media
    - Lunar/Space Gateway

6.0 Next Steps for HELIOS

The next steps for NASA to test HELIOS technology would be to send media containing actual ISS program experiment data, along with a space-certified CTech HELIOS media reader to the ISS. This list includes:

- Summer 2020: Needs assessment for 4th quarter 2020
- Lunar/Space Gateway
- Media to be stored on ISS
- Design and spec for space-certified reader
- A ground-based writer-system with reader at the station, or a writer/reader system, with media processing on the ISS
- Software for writing NASA ISS program data

7.0 Personnel and Facilities:

Rodney Grubbs, NASA Imagery Experts Program Manager NASA/MSFC

Lee Pitts Chief Engineer, Science and Engineering Services, Civil Division, NASA/MSFC

Principal Investigator

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