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Test Data Reader for Write Once, Read Forever (WORF) Interference Spectra Archival Media

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Abstract

We report on the test results of a recently fabricated data reader for our Write Once, Read Forever (WORF) high-density, very long-term archival data storage system. At the 2014 and 2015 IS&T Archiving conferences we described our technology and our progress establishing that multi-state data can be stored on monochromatic, dye-free, silver halide (AgX) media using our patented processes. WORF "freezes the wavelength" configuration of light within the media, which is restructured as a data constellation. Hitherto unreported chemical and optical phenomena are documented. WORF presents novel opportunities for security, encryption, data compression, and simple information recovery for the far future. It is known that AgX will last many centuries in ambient room temperature without continuous energy inputs or continual replication and authentication. This is an "existence proof" for the long-term archivability of data storage based on AgX chemistry.

Background

The greatest vulnerability of any contemporary digital archival system is the transient nature of permanent storage. Sometimes referred to as "dark" or tertiary storage—whether off- or on-line backup—this is the part of the process that promises the long-term preservation as opposed to the access preservation.

In our two previous papers [1, 2] for the IS&T Archiving Conferences in 2014 and 2015 describing our WORF technology we indicated that long-term preservation of digital content—*measured in centuries*—requires a true, immutable, archival solution not requiring laborious and expensive refreshing and migration efforts with continuous energy inputs.

Also essential is that WORF provides means for decoding the digital information without having to maintain legacy hardware and software.

Unfortunately, the standard metrics assessing storage tend to be the initial cost per bit and related data density. While appealing for near-term accounting purposes, without considering long-term viability such metrics are misleading for assessing sustainable archival systems.

We suggest that the eleven criteria listed below are essential for a storage system which will *archive data in perpetuity.* Unlike any other data storage system, WORF has been specifically engineered from its outset to be truly archival by following these criteria:

1. dramatic reduction of data storage energy (in 2013 U.S. data storage required the capacity of 34 coal-fired power plants! [3]);
2. eliminates any requirements for continual replication and authentication;
3. verifiable actual media life without speculative accelerated lab life testing;
4. un-forgeable media;
5. non-proprietary, low-cost mechanisms for writing and reading, using parts that can be readily manufactured in the future if need be;
6. compact, volumetric storage;
7. rapid, parallel write and read;
8. agnostic media sizes;
9. built-in ability to be readily deciphered in the far future;
10. relatively short, low-risk development cycle to move the technology quickly into the commercial field for mass data storage; and,
11. cannot be destroyed by gamma rays, or an electromagnetic pulse from lightning, an earthquake, or nuclear explosion.

WORF Developments

In our last two papers we described in detail how WORF works [4], and in the 2015 paper demonstrated our proof-of-principle proving the chemical and physical feasibility of the WORF process for storing data as non-fading interference colors or wavelengths [5] in an archival silver halide (AgX) suspension or emulsion. In particular, we proved that *multiple, separable wavelengths (at multiple intensity levels) can be stored at the same location* on the AgX media, making it possible to store multi-state data within small "storage locations," or WORF dots.

Our initial goal has been to demonstrate writing and reading these interference wavelengths in dots approaching 2 microns (μ) in diameter, whereby one or more numerical values may be stored in each dot. By structuring a *constellation* of these separable wavelengths, WORF can use the mathematical algorithms developed for multiplexed telecommunication infrastructure for encoding and decoding *M*-ary modulation alphabets [6, 7, 8, 9]; *i.e.,* directly facilitating multi-state numerical systems *beyond binary*.

Besides WORF's true archival qualities, this data storage solution can support robust error correction [10], and provides practical mechanisms for decoding in the far future. And, because the data is stored as colored wavelengths, the data can be *visible* to the eye, unlike other optical media or magnetic storage. This makes it practical to store metadata both as WORF wavelengths, and as we explain below, also as human readable text and images, using the same archival WORF technology.

How WORF Works

To recap, the WORF process creating the interference colors essentially *freezes lightwaves in time,* known as "standing waves," structured as microscopic diffraction gratings. The gratings are physically composed of *nano-scale,* ~5-15 nanometer (nm) diame-

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ter, stabilized silver grains embedded in a special type of extremely high resolution, *monochromatic*, photosensitive, AgX suspension, known as a Lippmann emulsion. So, the diffraction gratings are literally and figuratively *physical delineations* of the wavelengths captured [11].

Unlike dyes or pigments, being stabilized silver, WORF media cannot fade. In an "existence proof," AgX photographs have been demonstrated to last almost two centuries without deterioration [12], therefore *no accelerated lab testing is necessary* to verify silver halide as archival.

In addition, since WORF media are fundamentally an *image* of data, both writing and reading can be performed in *parallel*, making it possible to write and read large amounts of spectrally-stored data rapidly and simultaneously.

Results of Current WORF Research

Herein, we report on our key developments for the past year:

1) fabrication of a test fixture for precisely reading and locating colors on WORF plates;

2) discovery of previously unreported and potentially useful Lippmann interference phenomena;

3) mathematical and physical analyses showing the potential for storing 2μ dot sizes on a Lippmann emulsion; and,

4) a design for an advanced WORF write/read test fixture currently underway.

1. Fabrication of Read Test Fixture

We fabricated an early stage, but functional, test fixture of a WORF media reader to explore parameter optimization for the light source, optical path, color detection and data reporting. The design uses the following five main components:

1. CMU PixyCam5 [13];
2. Arduino microprocessor [14];
3. Beam splitter;
4. WORF media on a glass plate; and,
5. RGB Collimated light source with diffuser.

The illuminator uses an integrating light source which generates wavelengths matching the colors used to expose the WORF media, *e.g.,* 3-watt LEDs outputting 620-630nm (red), 520-530nm (green), and 445nm (blue). Color detection is via the CMU PixyCam5—a camera that learns up to 7 different colors and then detects them 50 times per second, reporting their wavelengths and location as objects. The output of the PixyCam is an ASCII text string which we input into the Arduino microprocessor. With the PixyCam software, we are able to detect 5 to 7 colors simultaneously from the WORF media.

Fig. 1 shows four colors as detected by the PixyCam, and identifies their location on a video image from the camera. (Note that the yellow is the superimposed red and green wavelengths.) The image is updated 30 times per second displayed on a MacbookPro laptop computer screen connected to the Arduino.

Fig. 2 is a functional diagram of the WORF test fixture. Fig. 3 is a photograph of the test fixture indicating its 5 main components.

This read test fixture proved that we could detect the specific wavelengths stored on a WORF plate using non-coherent, co-axial irradiance, *i.e.,* collimated light with a beam splitter. Saturation was sufficient for the PixyCam to reliably identify individual colors.

Figure 1. *Macbook displaying 4 colors detected by PixyCam.*

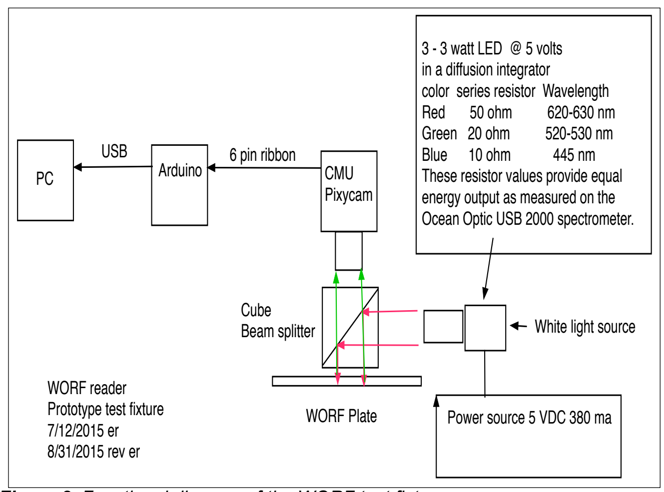

Figure 2. *Functional diagram of the WORF test fixture.*

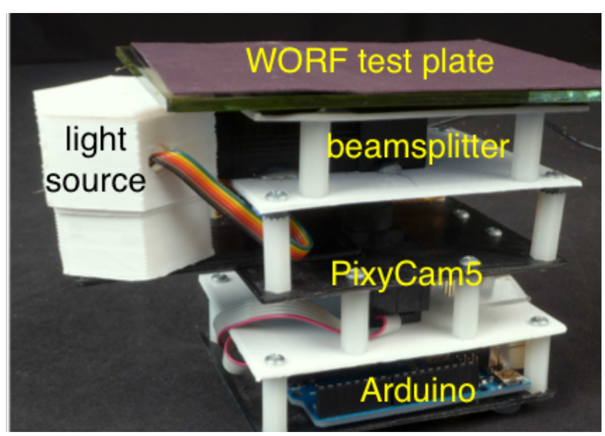

Figure 3. *Annotated photograph of WORF read test fixture.*

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2. WORF Phenomena

We have discovered that a Lippmann emulsion exhibits at least *two different layers* of silver halide responding to WORF's irradiance exposure. The diffraction gratings for storing data as interference colors are embedded just *below the surface* of the emulsion. The other principal layer is on the *surface* of the emulsion, consisting (after development, but before bleaching [15]) of both unexposed and exposed AgX grains, much like normal photographic emulsions.

We have observed that the density of the surface silver image is determined by at least three variables: 1) initial exposure time creating the image; 2) the bleach chemistry; and, 3) time of exposure to ambient light after immersion in the bleach. Further research on the surface process is underway; we anticipate that there are more variables to examine.

These layered phenomenon (previously unreported in the Lippmann literature) may be useful in differential masking for archival applications, for various data verification procedures such as partial wavelength masking, and for combining surface visual text, pictures, and metadata with the embedded interference data [16]. Human-readable surface information would aid in decoding WORF plates in the far future, as we discuss later in this paper in the section on implementing a true archival preservation stack.

3. WORF Physics & Chemistry

The theoretical resolution limit for Lippmann emulsions has been calculated to have a *line-pair* spacing of ~0.26μ. However the practical limit created by focusing an image via a lens is ~1.0μ [17]. This corresponds to our nominal objective for a 2μ diameter, high-density WORF dot.

The emulsion must be thin enough (not much more than 2 or 3 times the longest wavelengths captured) so that the "freezing in time" converts a non-coherent irradiance waveform into a coherent standing wave for reading. This limit for emulsion thickness is critical for storing *embedded* Lippmann interference gratings for WORF spectral data as opposed to storing a traditional photographic image on the emulsion *surface*. In addition, the optimum AgX grain size has to be small enough to capture the shortest half wavelength of interest, but large enough to be practical for exposure.

Such emulsions have been fabricated over the past six decades for applications ranging from etched micro-circuits for electronics to various holographic processes, so we have confidence that the chemistry required for fabricating and processing WORF plates is readily available [18].

In our earlier experiments we reported exposure times ranging from minutes to 9 seconds [19]; with different techniques we now expose WORF plates under ½ second (for 4nm and 8nm nominal grain sizes), with the signal-to-noise ratio (SNR) kept at a very high level. We are gradually increasing grain size which should increase sensitivity by an order of magnitude, reducing exposure times further, and improve emulsion fabrication processes. Shorter exposure times combined with parallel exposure of a multitude of WORF dots will facilitate extremely rapid effective data rates for writing.

Analysis of Optical Path

We have performed a mathematical analysis of the optical path for our test fixtures to determine if a 2μ dot size is within the limits of diffraction, applying current off-the-shelf microscopy optics for reading and writing. Our conclusion that there is no physical reason that this cannot be achieved, *to wit:*

WORF interference dots exposed by light through an aperture will have an optical diffraction pattern approximating an Airy disc [20], assuming a linear response for the emulsion. In practice, however, the input light to an aperture is rarely uniform unless the aperture is grossly overfilled. A diode laser, for example, emits a Gaussian-like intensity pattern. The functional form of this intensity scan is the square of the ratio of a first-order Bessel function to the angle (or, equivalently, the distance across the dot pattern).

This works out to a radius for the first dark Airy ring being equal to,

$$0.61\lambda / NA \tag{1}$$

where λ is the wavelength of light and *NA* is the numerical aperture of the focusing objective [21].

A Gaussian-like intensity profile leads to a trade-off on how to fill the aperture of the objective lens. Overfilling gives a slightly narrower "full-width at half-maximum" (*FWHM*) of the central lobe of the diffraction pattern, but also reduces the fraction of light that gets through that objective.

Ultimately, data rate depends on how much power can be delivered to the media. Typically, the optimum is achieved when the e^{-2} width of a Gaussian-like beam profile fills the aperture. In addition, the dots will need to be spaced sufficiently apart on the media to avoid significant crosstalk. (We do not anticipate any Rayleigh diffusion issues to further degrade SNR since the interference gratings are embedded in an extremely thin emulsion, unlike thicker photolithographic and holographic emulsions [22].)

The *FWHM* of the intensity profile is about 3.2. Since $NA = \sin\theta$ in vacuum, so approximately,

$$FWHM = \lambda / NA \tag{2}$$

However, this is just to the half-intensity point. The central dot that forms in the developed emulsion will extend to the first Airy dark ring ***W***, which has a diameter,

$$\boldsymbol{W}_{\text{dark}} = 1.22\ \lambda / NA \tag{3}$$

So, for example, using a 650nm laser and an *NA* of 0.45, the first dark ring diameter would be 1.76μ, *well within our target dot size for WORF of 2*µ.

4. Advanced write/read test fixture design

As noted, the scope of our current work is to develop hardware and software to approach a dot size of 2μ for writing and reading. Since WORF requires that *both illumination and wavelength detection* (or viewing) be on the same optical axis (coaxial illumination), we are using a metaloscope for our testing and development process.

This device—normally used to examine the surface of metals—incorporates a beam splitter in its optical path so that the illuminator beam reflected from the sample is on the same axis as the objective lens.

We modified a metaloscope by fabricating an adaptor with a 3D printer to attach a fiber from an Ocean Optics USB2000 spectrometer (Fig. 4, next page).

Spectral testing was performed with a MacBook Pro running Ocean View software using a WORF slide coated with 8nm grain sized emulsion (Fig. 5, next page).

We will be using this metaloscope arrangement as a writer and reader in the next steps of our development process. We have

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also fabricated much smaller and lower cost writer hardware, and have modified a fiber optic microscope for use as a WORF reader.

Figure 4. *Custom eyepiece with fiber inserted in metaloscope.*

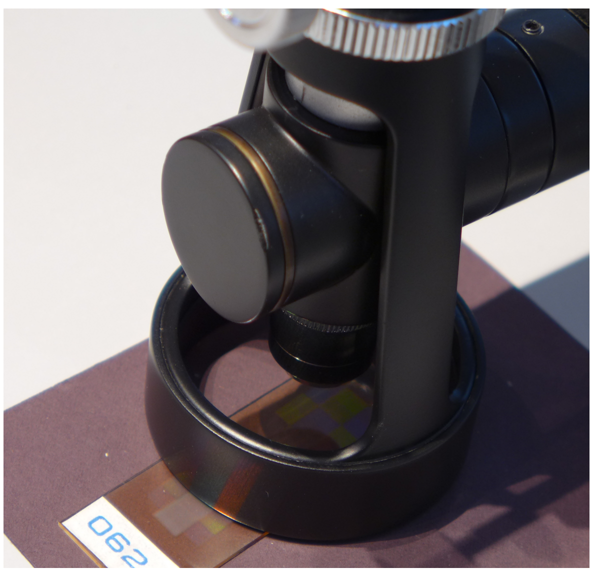

Figure 5. *Metaloscope inspecting WORF slide.*

An end-to-end archival system

Preserving *physical* items for posterity is a practice with a long history, including: permanence testing, environmental controls, proper organization of material, and the work of generations of archivists and librarians. *Digital preservation* presents entirely different sets of problems. With digital preservation the *object* saved is binary data information generally delivered to the preservationist as magnetic information on a disk.

To reconstruct the original object from this representation the binary data must be readable, then interpreted as numbers, text, colors, or music code, etc. This information then has to be reconstructed as a meaningful object, such as a document, image, or video. Next, this information then has to be delivered either in a human readable form, such as a screen image, printout, sound or instructions, or more abstractly as input to some process, not necessarily for direct human comprehension. Fig. 6 illustrates a typical *preservation stack* [23].

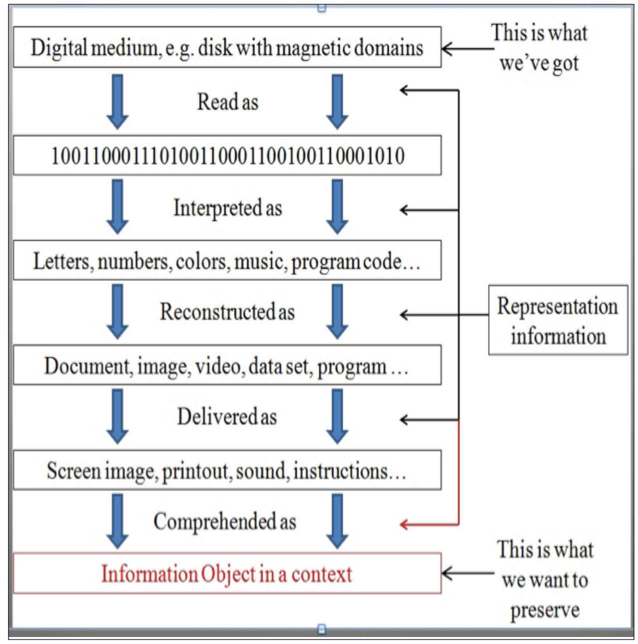

Figure 6. *Preservation stack (courtesy Robert L. DeCandido)*

To understand the item as an information object in context the computer's environment (*e.g.* the OS), and metadata—and often even more information—is required. Preserving unknowable and unintelligible information *is not preservation*; so without this entire stack of activities—which includes reading, interpreting, reconstructing, delivering as well as comprehending—*nothing meaningful is saved for the future*.

True archival media

Currently most digital archives are stored on magnetic media; by their very nature these are not long term nor archival since they are subject to thermal decay and magnetic field data erasure (further exacerbated by environmental conditions). In addition, LTO ("Linear Tape-Open") tapes are vulnerable to binder stiction, hydrolysis, and demagnetization; moreover, they can be read on *only two generations* of reader equipment; *e.g.,* once LTO7 readers become available they will not be able to read LTO4 tapes! [24].

IT successor technologies are already on the horizon, however any backup system without *humanly visible* metadata for far future deciphering on the media itself—or media that requires warehousing obsolete read mechanisms—cannot be considered truly archival. We propose that only technologies which address the eleven criteria listed at the beginning of this paper, and that fit completely within the illustrated stack, can be truly qualified as archival media.

WORF, by ameliorating or avoiding the pitfalls of current systems not intended or engineered for true long-term storage, fits those eleven criteria.

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[3] 2013 energy use for data storage was 91 billion Kw hours, the total continuous capacity of 34 coal-fired power plants; 2020 data storage energy is estimated to require 140 billion Kw hours. <http://www.nrdc.org/energy/data-center-efficiency-assessment.asp> (Web: 15 Jan. 2016)

[4] Solomon, *et. al.* (2014), *op. cit.*, pp. 119-120, esp. Figs. 2 and 3.

[5] Solomon, *et. al.* (2015), *op. cit.*, Figs. 1-5.

[6] For an example, see the “phase plane representation” of the possible signals for a 64 QAM in *AT&T Bell Laboratories Record,* Jan. 1986, p. 31. WORF would swap *temporal* QAM for *spatial* gratings.

[7] *Cf.* Haykin S & Moher M, *An Introduction to Analog and Digital Communications,* (2nd Ed.), Wiley, 2006. Ch. 7.7 “*M*-ary Digital Modulation Schemes,” *esp*. signal-space diagram in Fig. 7-20.

[8] Hanson WH, “Ternary threshold logic,” *IEEE Trans. Electronic Computers*, vol. EC-12, no. 3, p 191-197. 1963.

[9] Frieder G & Luk C, “Algorithms for binary coded balanced and ordinary ternary operations,” *IEEE Trans. Computers*, vol. C-24, no. 2, pp. 212-215. 1975.

[10] U.S. Patent No. 8,891,344 B1, col. 5; and U.S. Patent No. 8,891,344 B2, Fig. 3.

[11] *Cf.* Solomon (2015), *op. cit*., p. 92, col. 2, on how standing waves representing WORF data are embedded in the emulsion.

[12] Solomon, et. al. (2014) *op. cit,*. p. 119, col. 1, and *fn*. 19-20; Solomon (2015), *op. cit,*. p.95, col. 2.

[13] <http://www.cmucam.org>; <http://charmedlabs.com/default/products/> (Web: 15 Jan. 2016).

[14] The Arduino is a low-cost solution for the detection of small data sets. <http://www.arduino.cc> (Web: 15 Jan. 2016)

[15] See Solomon, *et. al* (2015), *op. cit*., p. 93 for processing chemistry.

[16] U.S. Patent No. 8,891,344 B2.

[17] *Cf.* Wolfe , “The Spatial Photographic Recording of Fine Interference Phenomena,” *JOSA*, vol. 40, pp. 143-146, 1950.

[18] Bjelkhagen H, *Silver-Halide Recording Materials for Holography and Their Processing*, Springer, 1995. Ch. 5.1.2.

[19] Solomon, *et. al,* (2015), *op. cit.,* p. 93, col. 2.

[20] An Airy Disk is the diffraction pattern (“rings”) created by light of uniform intensity passing through a circular aperture. Ditchburn RW, *Light,* Dover, 1991. Ch. 6 “Diffraction,” *esp*. sect. 6.16.

[21] Some energy around the central intensity pattern will fall on adjacent dots, reducing readout SNR, however this linear crosstalk is unlikely to be a major impediment for WORF.

[22] Compare discussion in the 1955 ed. of James, TH (Kodak Labs, *et. al.*), *The Theory of the Photographic Process*, pp. 1000-1004, with James’ 1977 ed., pp. 580-583; Bjelkhagen, *op cit.,* p. 82-83, notes that thick emulsions (~6μ) are on the border of acceptability for hologram scattering, but WORF thickness is significantly below that threshold.

[23] Graphic courtesy of Robert L. DeCandido, private communication.

[24] www.quantum.com/technologies/lto/index.aspx Web: 23 Jan. 2016.

Author 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 for US Dept. of Defense and NASA. 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 technologies. Prior, he was a Research Fellow in Harvard’s School of Engineering and Applied Science.

Melitte Buchman is the Digital Content Manager at NYU’s Division of Libraries, responsible for digital imaging and preservation of video. Prior to NYU she worked at The New York Public Library both in their Digital Library Program, as Head of the Digital Imaging Unit, and in the Exhibition Department. Serving on the boards of Independent Media Art Preservation, Association of Moving Image Archivist’s Magnetic Tape Crisis Committee, and the Penumbra Foundation.

Eric Rosenthal, CEO/CTO of Creative Technology, LLC, is 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.

Clark E. Johnson has more than 60 years experience as a magnetics expert and physicist. At 3M he directed R&D on photoelectrically active materials for data recording and reading; optical analysis of retroreflective media (e.g. “Scotchlite”); and advanced magnetic recording technologies. As an IEEE Fellow he has been an advisor to the US House of Representatives’ Science Committee, and a consultant to US Dept. of Defense on digital HDTV implementation. University of Minnesota, BS (Physics) and MSEE.

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Dr. Donald Carlin is an expert in developing and commercializing semiconductor lasers, optical data storage, optical communications, display technologies, and medical devices. He held technical leadership and senior executive positions at LuxPhotonics, Conversus Group, Cardiovascular Solutions, Optex Communications, and Sarnoff Corporation. Massachusetts Institute of Technology, SB, SM (Physics); Yale University, PhD (Laser Physics); post-doctoral research at Harvard University.

William Butterfield has had 48 years of Signals Intelligence Engineering Support for US Dept. of Defense. Led major software development acquisition for a new, real-time, mass storage data flow management system. Program management for in-house software development of a large-core cryptanalytic processing system. Solved a major space science problem, and coordinated international approval, development & building for new ground station site. Research on emerging ISO & ITU multimedia standards, on video compression and human vision. University of Vermont, BSEE; and Johns Hopkins University, MS (Space Technology).