Write Once, Read Forever (WORF)—Proof-Of-Concept Demonstrated For Archival Data Storage Using Interference Spectra

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Abstract

Based on a proven, century-old archival technique, we have successfully demonstrated the feasibility of storing high density, multi-state data in the form of interference gratings embedded in archival silver halide media. Data stored as interference gratings cannot be erased remotely, or altered after writing and processing, yielding a verifiable backup storage tier for archives and data security applications. WORF is engineered to be a permanent and low energy data storage medium not requiring periodic refreshing or authentication. Should the original reading devices be lost in the far future, human visible instructions for creating a reading device and decoding the formats—a digital "Rosetta Stone"—are included on the data media. The unalterable WORF medium has ancillary uses for other critical data storage applications such as securing an operating system against hacking, and verifying data transactions.

Introduction

Recently there has been awareness in the mainstream press that there is no methodology for the long-term preservation of digital content. There has been a public call for some sort of permanent carrier—a "vellum"—to preserve digital materials [i]. The difficulties of preserving digital material are well known to the library and archives communities. As early as 1999, many information professionals were expressing concerns about the long-term sustainability of digital materials, especially digital scholarship, due to rapid obsolescence of digital formats and software, restrictive copyright laws [ii], issues of leasing and saving e-journals [iii], lack of playback equipment, and the locking of digital information in proprietary formats.

Add to these issues the difficulties associated with the need to archivally store digital data over long periods of time. Long-term storage requires storage media capable of persisting for durations measured in decades, if not centuries. In addition, elaborate plans for migrating archived digital files is required in order to read and display them in the future as software and hardware able to read them continually become obsolete. Either that or maintain access to all the hardware and software needed to read the old file formats in a given collection.

The main objective with Write Once, Read Forever (WORF) technology is to replace tertiary storage practices with a true, immutable, archival solution not requiring laborious refreshing and migrating efforts, continuous energy inputs, or the need to maintain legacy hardware and software. Built into WORF technology is the means for decoding the digital information stored on the same media along with the digital data itself. WORF therefore is positioned to be a trusted, sustainable, archival technology.

Since we first proposed WORF media at the IS&T Archiving 2014 Berlin conference [iv] we have successfully produced a proof-of-concept (POC) demonstrating how multi-state digital data (numerical notation beyond conventional binary data) can be stored in an archival emulsion. WORF does this via multiple, superimposed interference "colors"—with several irradiance levels for each color—all written to the same data location on its media.

WORF is intended for true permanence, not necessarily for lowest initial cost per bit or highest data density, as is the current metric. However, over the long-term, WORF will prove to be the least expensive archival system, since its *energy inputs are nil* and periodic regeneration and authentication are not necessary.

The physics and optics of our system are described in more detail in our 2014 paper and in our patent issued last November [v, vi]. This current paper is an update, discussing our successful experiments to produce these interference gratings including the imaging and chemical processes we implemented, and our next objectives.

Research Results & Procedures

WORF's color frequencies representing data are embedded in a specially formulated, ultra fine grain, photosensitive, *monochromatic*, silver halide (AgX) "Lippmann"-type emulsion [vii, viii, ix] currently on glass. Unlike conventional color films no dyes or pigments are used—the stored "colors" cannot fade if processed correctly since they are physical, microscopic, metallic diffraction gratings made of stable silver salts and not filters. (Experiments for storing these interference gratings on flexible media are underway.)

We initially wanted to confirm our hypothesis that interference gratings for data storage could be created with *non-coherent* light even though conventional wisdom thought that was impossible. Our theory is that while the lightwave that impinges upon the AgX grains may be non-coherent (in that the wave peaks are not aligned over time), the physical process of creating the standing waves embedded in the emulsion essentially *freezes the lightwave* in a moment of time. In other words, the WORF gratings are a physical representation of the frequency stored in the identical dimensions of the lightwave, and therefore the process of storing these waves as silver particles converts a non-coherent wave into a coherent one, albeit with just the minimum of wave peaks as necessary for storage and reading. This would be important in building writing and reading devices since the light sources would not necessarily have to be lasers, but could be frequency-agile light synthesizers [x].

Our past year's experiments have successfully produced encouraging results for multi-state interference data archiving on

AgX emulsions, including the feasibility of using non-coherent light, and extremely accurate, narrowband capture of colors written. For these POC experiments, we obtained specially coated 4x5″ glass plates, 3mm thick, formulated by Ultimate Holography of Bordeaux, France [xi]. While these are their model U04 plates intended for RGB color holography, we specified that the U04 emulsion be modified with optical sensitizers for the full visible light spectrum, specifically for Lippmann interference photography. The chromatic sensitization process is critical for WORF's implementation of a wide range of frequencies necessary to store multi-state interference data [xii, xiii]. (After experimentation, we did detect a reduction in sensitivity from the norm for the shorter wavelengths; nevertheless our results described below contained sufficient capture of blue and green interference colors as well as red [xiv].) The U04 plates' nominal resolution is specified at 20,000 lines/mm with a grain size estimated at ~4nm [xv, xvi].

The U04 plates were processed using Ultimate Holography's catalog No. 08 Developer, diluted 1:10 with distilled water, and Ultimate's Bleach to clear the surface silver (see specific parameters below for each experiment). Rinsing and washing was in filtered water (purity ~50 ppm). Drying was done with a hair dryer on low, hand held at ~30cm distant from the plate. All solutions were kept at approximately 20ºC, ±2ºC, with the darkroom at ~50% relative humidity.

Development for each plate was by hand (gloved), in a tray with continuous agitation. Each plate was then drained for 10 seconds, immersed directly in a clean water rinse for 30 seconds, and then into the bleach solution. After ~1 minute, a 100 watt incandescent bulb ~1m above the tray was turned on and the surface silver was observed until it appeared clear in the bleach tray. The plate was then washed for 1-2 minutes, drained, and dried as above. No wetting agent was used (we didn't want to insert an additional variable in case the wetting agent might affect the structure of the interference gratings).

The interference colors only reveal themselves when the plate is completely dry, so after drying each plate was irradiated via the overhead incandescent bulb (now about 2m distant) to determine if any interference colors could be seen. If the initial results looked promising, further examination and spectral tests, with full and selected narrow spectrum radiances, were performed afterward, as detailed next.

Experiment No. 1 — incoherent light with mercury reflector

Ultimate Holography's website [xvii] lists general specifications for holographic exposure in terms of microjoules per cm^2; that is useful for lasers but not for calculating exposure with the broader band non-coherent light which we wanted to estimate for our initial experiment. Furthermore, the WORF media captures only *spectral* information which can be done with either coherent or non-coherent light, instead of holography where the goal is to capture *3D spatial* information and so only coherent light can be used. Therefore, in order to first produce a successful POC, exhibiting sufficient spectra to demonstrate the feasibility of multi-state data capture via non-coherent light, we needed to calibrate the ISO sensitivity of the U04 plates for initial exposure time and radiance levels.

Initial test exposures were made with a Beseler Model 45MX enlarger using non-coherent light from a GE Model FLE23HT compact fluorescent (CF) lamp rated at 1600 lumens. Correlated color temperature [xviii, xix] measured with a Minolta Color Meter II was 2840ºK direct, and 3700ºK after passing through the condensers located in the Beseler Universal Colorhead lamphouse. We measured the incident illuminance in lux at the plate's plane using a Minolta electronic Auto Meter IV-F, both with its flat diffuser and its Mini Receptor fiber optic probe with 12mm spherical diffuser. (A Sekonic Studio Deluxe II L-398M silicon-based meter with flat diffuser was used to corroborate the results.) [xx] Through an iterative process we calculated that the plates have an ISO = ~0.3, at an illuminance level of approximately 40 lux at the plate plane [xxi].

With the enlarger setup, we projected a 4x5″ color transparency of an IT8 chart [xxii], with a Schneider Componon 150mm lens at full aperture, f/5.6, to expose a plate. The plate was ~49cm from the lens, plano-parallel with the transparency, with the emulsion side *face down* in a small pan of mercury to create the interference standing waves by reflection, as per the Lippmann process [xxiii]. The image was pre-focused on a white card located close to where the emulsion plane will be when touching the mercury mirror bath.

We maintained identical irradiance levels for this test chart for each iterative test, holding other variables constant while we experimented independently with exposure, development and bleach times. The goal was to find a first approximation for a range of parameters that would give us some indication that interference-derived colors were achievable on these monochromatic plates. (We plan to fine-tune the process for optimum results later.)

After several iterations using mercury for reflection and the above enlarger irradiance setup, our working parameters for an acceptable plate were: 3.5 minutes exposure, 6 minutes development, and 4-8 minutes bleach to clear the plates. (If the surface silver grains were not bleached away they would act as neutral density filters unnecessarily absorbing light energy for reading the diffraction gratings.)

A conventional photographic fixing bath using sodium thiosulfate is not necessary for archival purposes, since if the surface and unexposed embedded silver are completely cleared with the bleach process what remains on the plate are only the diffraction gratings, embedded in the emulsion as *stable metallic silver crystals*. In this respect, chemical processing for Lippmann plates is akin to that found with conventioinal reversal photographic development, such as was used for the multiple layers in Kodachrome film and positive black & white slide and motion picture films [xxiv, xxv, xxvi]. Further research will determine the optimum bleach process to achieve archival permanence.

Fig. 1 is a photograph of plate #12 irradiated with skylight—our initial result from exposing the IT8 chart via non-coherent light (no post-processing of the photograph was performed). This plate indicates that not only were interference frequencies successfully captured across the visible spectrum using the non-coherent CF lamp and the mercury bath reflector, but more important, at least 5 irradiance levels for each interference color were captured as well. However, with this initial test we did not remove all of the surface silver, nor optimize for other variables, so, as can be seen in the illustration, saturation is low indicating a low signal-to-noise ratio. We used this plate as a baseline to improve the SNR in later tests.

Figure 1. *Plate #12 showing multiple irradiance levels for each color of an IT8 transparency exposed with CF non-coherent light and constructed with a mercury bath for a reflector. Photographed as irradiated by skylight*

Experiment No. 2 — narrowband RGB lasing diode lights with an airgap reflective surface

In our second set of experiments our goals were:

A) to eliminate the necessity for mercury as a reflecting surface;

B) to explore the plate's diffraction gratings' response to narrowband frequencies (~1 nm in chromatic width) instead of the broader frequencies transmitted from a CF lamp; and,

C) to increase saturation—an indicator of its signal-to-noise ratio.

A. *Reflective surface*

Working with mercury can be hazardous and inconvenient. Instead, we created the necessary standing wave reflective surface via an air gap: a mis-matched index of refraction on the emulsion (bottom) side of the glass plate by elevating the plate ~1mm above an 18% reflectance gray test card [xxvii] (Fig. 2).

B. Frequency response

To test frequency shift or spread, instead of the broadband CF enlarger lamp and IT8 transparency in the enlarger, we exposed the plate using a Picop "i-connect" laser projector, maximum output 1mW, with narrowband red (642nm), green (532nm), and blue (442nm) lasing diodes radiating a 1024x768 VGA color bar image generated by a test signal generator connected to the projector (see Fig. 2 for setup).

We compared the frequencies radiated by the projector and the irradiance frequencies stored on the plate using the same RGB projector which exposed the plate. Fig. 5 (next page) illustrates the frequencies written by the projecter on Plate #31 and the frequencies reflected from the interference gratings created on the plate after processing (Figs. 3 and 4), as measured by an Ocean Optics USB2000 spectrometer [xxviii]. The narrowband RGB *frequencies written and read are identical.*

This experiment also shortened the exposure time since the laser projector radiated higher levels of energy. Illuminance at the plate surface using the projector was now averaged across the plate at ~4500 lux. The best exposure time was now 15 seconds—a significant reduction in exposure time. Development at 19ºC was 6 minutes, water rinse 30 seconds, bleach at 4-8 minutes for clearing; washing and drying as above.

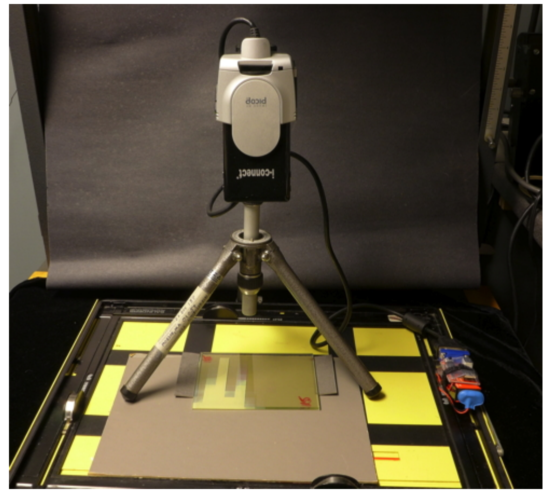

Figure 2. *Picop laser projector setup (with color bar signal generator on right) showing test plate resting on side tabs elevating plate ~1mm above an 18% reflectance gray test card. Easel aided plate alignment in the dark.*

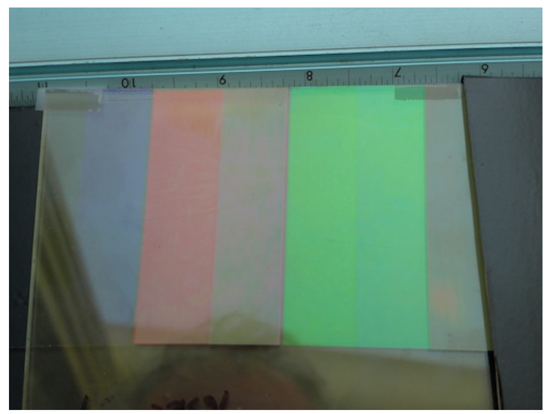

Figure 3. *Plate #31 with color bars as irradiated by diffuse skylight.*

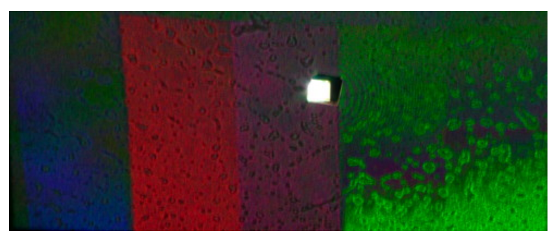

Figure 4. *Saturated color bars (and a high SNR) demonstrated by irradiating Plate #31 with the RGB laser projector reflecting its interference colors onto a white card. Photographed in darkroom with no ambient light. The white square in the center is the aperture for projector beam. Color reproduction is only approximate to what the human eye would see. Bubbles are watermarks due to lack of a wetting agent. Color images are available at <http://www.creative-technology.net/CTECH/WORF.html>*

C. Saturation and SNR

The higher energy from the projector also significantly increased saturation of the color bars. Fig. 3 is a digital photograph of Plate #31 produced by the RGB laser projector method, the plate irradiated by essentially a full-spectrum, diffused skylight; Fig. 4 is a photograph of Plate #31, irradiated by the same RGB laser projector that exposed the plate, as reflected onto a white card—a more saturated reflection than in Fig. 3, and illustrating its *very high SNR*. (No post-processing was performed on these photographs; however color reproduction in the photographs is not quite the same as perceived by the eye *in situ* [xxix].) Fig. 5 indicates that the spread of the captured RGB frequencies is negligible.

Moreover, what appears to the human eye as metameric colors due to the combination of the narrowband RGB irradiances proves that *multiple frequencies are stored at the same spot*. This is particularly significant for the yellowish-green (2d bar from right in Figs. 3 and 4, and the central columns in Fig. 1), since yellow is the color which human vision registers when red and green are superimposed [xxx].

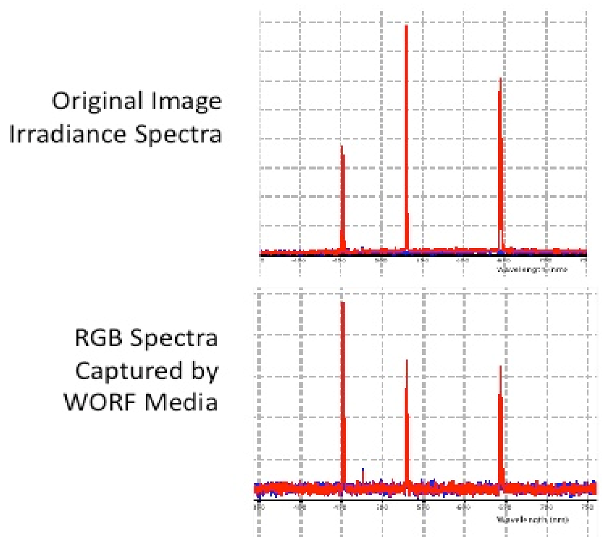

Figure 5. *Irradiance frequencies of Plate #31 compared to frequencies captured are virtually identical, with a high SNR.*

Summary of POC results

Our proof-of-concept experiments have confirmed that:

- multiple, extremely narrow-band frequencies (*e.g.,* ~1nm in width) can be written and retrieved, *superimposed at the same, precise location* on the media;
- *five or more irradiance levels of the identical frequencies* can be written and retrieved;
- frequencies (*i.e.,* “colors”) stored as interference gratings in the emulsion are highly saturated and intense, demonstrating a *high signal-to-noise-ratio* for retrieval;
- *non-coherent light* may be used for writing and reading the frequencies;
- the *reflective layer can consist of a very small air gap* creating a mismatched index of refraction at the photosensitive layer;
- the use of *mercury or other dangerous chemicals is not necessary*;
- the *media does not have to be completely flat* for data to be written or retrieved (we are currently exploring flexible substrates); and,
- the writing and processing times can be *shortened by several orders of magnitude*.

Discussion

A huge gap in information from the late 20th and early 21st Century is likely to be created unless something is done quickly to alleviate this problem [xxxi]. Recently the idea of trusted, digital repositories with sufficient safeguards to sustain themselves for long historical periods of time have been receiving more attention [xxxii]. Some organizations are attempting multi-institutional federated approaches such as a Digital Preservation Network [xxxiii]. Certifying the long-term safety of repositories and group efforts are to be commended, but the basic issue that many preservationists see looming is the tremendous increase in the volume of the materials deposited.

How will it be possible, technologically, to sustain the exabytes of information on magnetic drives that must be constantly spinning and cooled to maintain data, or on tapes (currently, linear tape-open type magnetic tapes—LTO) that have to be rewound and often regenerated every few years to prevent magnetic and substrate deterioration? Will there be random or organized de-accessioning to lower environmental impact and cost of feeding energy to such huge digital libraries?

A decade ago, New York University’s digital preservation efforts were pleased to create a terabyte of information every four months [xxxiv]. Cameras were slow, and it was well before mass digitization of analog audio-visual signals was possible. Today we have reached “pulse weeks” of 10.6 TB of new digital material in a five-day work week. As born digital deposit grows, even this amount will be dwarfed by the exabytes and zettabytes of information soon to come. Storing, authenticating and regenerating vulnerable materials for the vast libraries that we are creating will not be sustainable. Not all organizations can continue to regenerate robust copies indefinitely due to the vicissitudes of business cycles, and personnel and institutional turnover. For some industries—such as motion pictures—long-term archiving is approaching a crisis [xxxv, xxxvi].

Silver Halide’s Inherent Archival Attributes

WORF should prove to be a ground-breaking solution for numerous archival data storage markets, replacing current magnetic and other volatile media. AgX life expectancy is evident from photographs over 150 years old that show no deterioration. Furthermore, the silver ion (Ag^+) is hostile to most bacteria and other micro-organisms that attack conventional media [xxxvii].

The specific Lippmann AgX interference emulsion and techniques, which we re-engineered for data, dates to the 1890s; Lippmann’s full-color images on that emulsion are still extant and show no deterioration [xxxviii, xxxix, xl]. This is a true test of time, unlike accelerated testing which depends upon statistical extrapolation of chemical processes in the lab.

Next Steps

There is more than two centuries of R&D experience, and a vast library of literature and data, on silver halides as a photosensitive medium. Nevertheless, we plan to investigate other archival media for their potential of storing interference colors for multi-state data. However, to be viable for archival purposes such media must have, at a minimum, the critical properties which AgX emulsions have:

- proven ability to last centuries or more;
- multi-chromatic sensitivity, preferably for the full light spectrum;
- immutable data storage;

- the reading and writing process must be simple enough to be implemented without complex equipment;
- the media must allow a wide variety of sizes and formats to be created in order to accommodate multiple applications;
- ability to use non-coherent light for writing and white light for reading to avoid the necessity for lasers; and,
- no requirement to warehouse specialized or proprietary reading mechanisms for reading and decoding in the far future (*i.e.,* have ability to store human-visible instructions on the same media as the data).

Our continuing research program to optimize the WORF process includes:

- testing different emulsions and chemistry to improve exposure time, development, wash and bleaching times, spectral sensitivity, and SNR (saturation), including more accurate and stable temperature controls;
- experimenting with flexible media;
- experimenting with different modes of non-coherent radiation for writing and reading;
- measuring irradiance at the plate with a power meter, instead of a photographic exposure meter, for greater consistency and accuracy;
- research on methods to insure long-term media archivability, including coatings, silver removal, environmental storage conditions, etc.; and,
- fabricating POCs to demonstrate different potential applications, and to improve data density.

Research is continuing on critical ancillary applications, including testing data algorithms and optical techniques for error control and correction.

WORF can also be applied to verifying the integrity and authenticity of data such as logs, code or imagery stored on mutable media. WORF's immutability allows it to be used in roles requiring tamper-resistance, such as a hardware "root of trust," a basis for cryptographic hashes such as those used in message authentication codes, secure bootstrap [xli, xlii], and trusted execution, etc. This feature of WORF can also be very important in insuring the authentication of archived media for future generations of researchers.

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[xiv] The plates also have a sharp, narrow wavelength drop in sensitivity in the ~500-560nm range allowing their prolonged use under a Kodak No. 3 Safelight Filter (dark green), transmittance >0.1% at 520nm (Kodak Photographic Filters Handbook, Eastman Kodak Co., Pub. No. B-3, p. 76. 1990.), and for brief exposure under a green (555 nm) LED which facilitated handling in otherwise completely dark environments.

[xv] Typical film grain sizes are compared in Zelikman, *op cit*, Table 1, p.13.

[xvi] <http://shop.usa.ultimate-holography.com/product.php?id_product=83> (Web, 18 Mar. 2015).

[xvii] *ibid.*

[xviii] Fluorescent lamps do not have a continuous spectral distribution, hence the measured ("correlated") color temperature is only an approximation of a blackbody radiator. Woodlief T, ed., SPSE Handbook of Photographic Science and Engineering (Wiley, 1973), Sect. 16.6.1.

[xix] Visual examination via a diffraction grating optical viewer showed some diminution of light in the short wavelengths. Nevertheless, the CF lamp provided sufficient spectral radiance for our plates to exhibit interference colors in the shorter wavelengths.

[xx] These are photographic meters calibrated for illuminance, measuring lux (lumens/cm^2) not irradiance, based on the spectral chromaticity of the human eye and monochromatic film, and not the actual irradiance spectra impinging the plate's surface. The Focal Encyclopedia of Photography (Desk Ed., Focal Press, 1969), p.556a, "Spectral Sensitivity." In future experiments we will use a

power meter to determine energy levels in terms of microjoules/cm^2.
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[xxix] Digital photographs made with a Panasonic Lumix LX-7, Leica DC Vario-Summilux Lens, speed set at ISO 80, aperture priority @ f/8, white balance pre-set with a white card for each scene. Stored as a JPEG with no compensation made for reciprocity failure or any other color correction.
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