WORF (Write Once, Read Forever)
Next Generation Archival Big Data Storage

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***Abstract*. In this paper we discuss a next generation archival architecture for ultra rapid, high-density, parallel writing and retrieval of Big Data. We term this WORF (Write Once, Read Forever)—repurposing a proven long-life optical media technology for digital data, using no power for storage. The data is stored as nano-scale standing waves, optimized for a high SNR, embedding its resultant optical pattern in a monochromatic, silver halide (AgX), super-high-resolution photosensitive emulsion. Applying *M*-ary arithmetic (instead of binary), multiple numerical states are stored in these standing waves, enabling multiple bytes to be stored at one data location. The WORF storage system retrieves data in parallel arrays, providing true random data access, and consequentially transferring data faster than current processors can absorb the stream. Legacy storage devices must continually replicate data during their lifetime in order to mitigate hardware and media failure, and corruption from malware, bit-rot read/write errors, and space-borne radiation. In contrast, WORF applies a proven archival media which can simply be put in a drawer, under normal ambient environmental conditions, and remain stable for centuries. This would be ideal for astronomical observatories, such as the telescope due to go online in Chile in 2023 that will collect 20 Tbytes per day of data—a streaming and long-term sustainability challenge for cloud servers. WORF media is immutable, hack-free, resistant to counterfeiting, anti-microbial, and has been tested by NASA on the International Space Station during 2019 demonstrating that it is impervious to space hazards.**

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1. INTRODUCTION

This paper presents a new system for storing high-density digital data as multiple-wavelength colors captured as standing waves in specially-formulated, archival, *monochromatic*, silver-based (AgX) photosensitive media. Color photographs using a similar technology were first demonstrated over 130 years ago by Gabriel Lippmann who won the 1908 Nobel Prize for this process [1] [2] [3]; extant Lippmann color photographs have stood the test of time, showing no significant degradation to the present day [4] [5].

Creative Technology, LLC, (CTech) patented this technology [6], redesigned and re-purposed for archival *data* storage, with the specific wavelengths of the standing waves representing data. We call our system "Write Once, Read Forever" (WORF). Our novel architecture applies contemporary, low-cost COTS components to simplify implementation for now and for the far future.

These standing waves capture the precise colors or wavelengths of an array projected onto the media, facilitating *parallel data access*. Its planar dimensions are agnostic. Each memory location (we term these locations "worfels") on the WORF media stores multi-state numerical data (beyond simple binary), holding multiple data bytes at each worfel. Due to the archival quality of stabilized silver-halide, data may be stored in perpetuity in a quiescent state requiring no periodic refreshing or power.

The WORF storage system writes and reads many worfels at once as an array. This enables data to be retrieved with true random data access (or direct parallel access), and in consequence provides faster data transfer and processing suitable for big data applications. These new features may require computers based on a new architectural model since WORF data can be read faster than current I/O data rates

WORF media has been tested by NASA on the International Space Station (ISS), and is impervious to space hazards.

2. How Worf Data Storage Works

Standing Waves

A worfel on WORF's media, in essence, acts as non-terminated "radio" waveguide in the optical domain [7] [8] [9],[1] with high standing wave ratios (SWR), storing the resultant standing wave pattern in a monochromatic, silver halide, photosensitive, ultra-fine-grain emulsion. WORF *freezes the standing wave nodes in time* in the AgX emulsion, and locks the optical pattern in the media.

These standing wave patterns are unique for each wavelength. Multiple wavelengths can be superimposed [13] [14] [15] at each worfel; we have demonstrated up to 4 such wavelength superimpositions. As a nano-sized optical waveguide, exposing and detecting the standing waves is done *normal* (90º) to the media, which significantly increases the SNR. Fig. 1 illustrates the high SNR of three wavelengths *superimposed* at one worfel as detected by CTech's specially designed micro-spectrometer.

The WORF Process—Data is stored on the media, and subsequently read into a processor, following these steps:

1. A monochromatic, 2-4µ (micron) thick, high-resolution AgX gelatin emulsion is coated on the *rear* surface of the WORF media substrate, sensitized for a panchromatic spectrum [16]. The media can be rigid or flexible, and is less than 1mm thick.

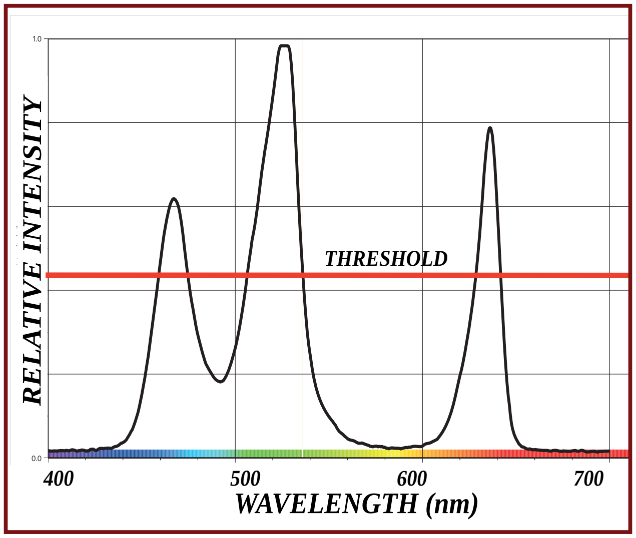

Figure 1. Spectrometer calibrated graph of 3 *superimposed* wavelengths stored at one worfel on WORF media. The human visual system interprets this worfel as 'white,' but the reading spectrometer separates the wavelengths for data processing. WORF media resolves <10nm bandwidths. The red line indicates the detection threshold.

2. The standing waves are generated by a forward wave transmitted through the *front* of the substrate and reflected from the rear due to an index of refraction mismatch between the emulsion surface and air.

3. The emulsion is processed via a special chemical procedure which reveals the standing wave structure by developing and stabilizing (*i.e.*, fully oxidizing) the exposed silver-halide grains, completely removing unexposed residual silver, and hardening the emulsion protecting it from abrasion [17]. After processing the emulsion becomes extremely durable [18].

4. After processing, the standing wave worfel structures are composed of ~8 nanometer (nm) diameter metallic silver grains, which are *literally and figuratively physical delineations* of the wavelengths exposed to the media. The ultimate practical resolution of this special Lippmann emulsion is ~20,000 line pairs per mm, making possible an extremely high worfel density [19] [20] [21] [22] [23].

5. The array of worfels to be read is illuminated in a color-sequential manner thusly:

   a. Selecting from a palette of narrowband (~10nm) wavelengths the array is illuminated in a time-multiplexed mode.

   b. A high resolution *monochromatic* camera,

[1] The extensive literature on Lippmann emulsions mostly describe its interference colors as created by diffraction phenomena (including in our earlier papers) [10]. However, Lippmann color photographs *visually* show white (among other "metameric" hues [11]), indicating that the retina's cones are stimulated by *multiple superimposed* wavelengths [12]; this would be impossible with diffraction, which *separates* the colors as in a prism, rather than *combining* them as required for visual metamerism. Furthermore, WORF media can be read from either side at the normal, further proof that the worfel interference colors are created by standing waves not diffraction gratings. CTech's optical waveguide interpretation, storing *superimposed standing waves* for WORF data, resolves this confusion.

positioned *normal* to the WORF media, captures sequential images of the array. These monochromatic images—separated by wavelength—are stored in a processor's memory as separate layers. For example, "red" wavelengths (and associated data) captured by any worfel of the array are stored in the "red" memory layer according to each worfel's "red" XY coordinates; "green" wavelengths are stored in a separate "green" memory layer, etc.

c. The combined array layers are stored as a stack. The representative worfel intensities are processed according to a detection threshold algorithm (Fig. 1), converting amplitude differences to a binary 1 or 0.

d. The layers are further processed—using CUDA[2] parallel processing engines—applying permutation algorithms which convert the combined layer information at each worfel coordinate to the byte values encoded in the standing wave at that location (see Appendix for an example).

e. The resultant data bytes are then transferred in *parallel* to an output port for use by other data processing devices. In contrast to sequential access, our unique WORF parallel capture technique facilitates *extremely rapid random access to data*.

3. WORF AEROSPACE FEATURES

Space Radiation Impervious

For the ISS mission[3] we developed test media which validated that the technology can provide a permanent, immutable data storage solution that can survive *harsh space environments for long-term, deep space missions* [24] [25]. This includes ionizing radiation, static electricity, electromagnetic (RF) interference, power surges, molecular and particle contamination, microgravity, magnetic fields, solar (plasma) eruptions, and the stresses of 8 G's during the launch and re-entry.

Low-Maintenance Archival Media

WORF media can simply be put in a drawer, under normal ambient environmental conditions [26] [27],[4] and remain stable for centuries. WORF only requires energy during writing and data retrieval. This resolves the long-standing dilemma of how to conserve tenuous digital archives without continual energy inputs, periodic network authentication, and labor-intensive cyclical refreshing.

Unlike modern color film which uses dyes that can fade, no dyes are used for the worfel colors. Compared to accelerated lifetime testing for legacy media, silver-halide media have stood the test of *real* time for almost two centuries without significant degradation [28] [29]. Moreover, silver ions (Ag^+) are anti-microbial, resisting bacterial and fungal attacks, unlike other optical media which degrade under such adverse attacks [30] [31] [32].[5]

In contrast, 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 high-speed moving parts. Legacy storage devices must continually replicate data during their lifetime in order to mitigate hardware and media failure, and corruption from malware or bit rot read/write errors. Total, long-term WORF costs of ownership therefore are lower than that of spinning magnetic disks and solid-state storage devices requiring periodic re-writing.

Visible Text and Images

Since the media is optical, human-readable text (and graphics) is possible on the same media along with the worfel data (Fig. 2). This permits ready identification, metadata, indexing codes and cataloging. Decoding instructions can be included on the media should for any reason the read mechanism be misplaced, or the media retrieved at some point in the future when the access formats are forgotten or lost.

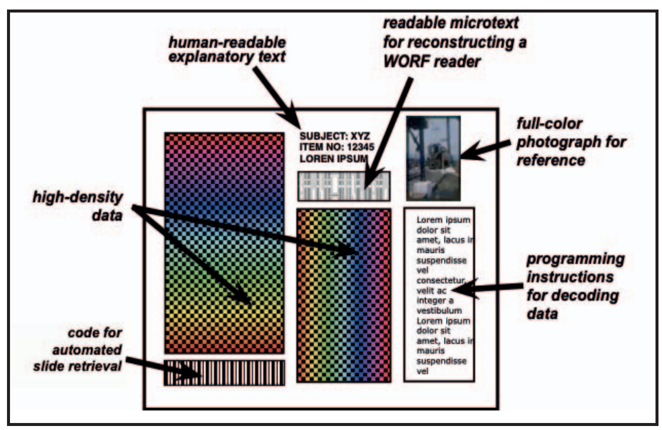

Figure 2. One example of WORF media consisting of multiple readable information.

[2] "Compute Unified Device Architecture." For discussion see Sect. 4, "High Density Data Encoding," *Processing WORF Data.*

[3] See R.J. Solomon, *et. al*, "Next Generation Big Data Storage for Long Space Missions," in Session 2.10 of this conference, on "Space Radiation and its Interaction with Shielding, Electronics and Humans."

[4] Ideally, 50% relative humidity and normal room temperature.

[5] Furthermore, WORF media is covered with a *uniform layer of stabilized silver*, so resistance to fungal growth is substantially increased where silver is deposited, unlike continuous tone silver photographs, where microorganisms tend to grow mostly in *clear* areas with little or no silver deposits.

Immutable Hack-Proof Data Storage.

Data is written only once per data location and cannot be deleted or changed after processing. Error checking is inherent to each worfel so there is no necessity to read any other location to retrieve data, and there is no need to rewrite any worfel during the read process, nor is it possible to do so. Because the standing waves represent a unique set of precise wavelengths, a distributed steganographic pattern can be embedded to make forgery or counterfeiting of a WORF media extremely difficult if not impossible.[6]

4. HIGH DENSITY DATA ENCODING

Multispectral Data Encoding

While legacy binary media formats have a data location bit depth of 1 (*i.e.*, $2^1 = 2$ states), requiring 8 data locations to store a single 8-bit byte = 256_{10} [34], WORF's multispectral encoding technique increases the worfel location bit depth by mapping different data states to different unique wavelengths. Therefore, utilizing *M*-ary arithmetic [35], multiple numerical states may be stored in each worfel. Higher bit depth also facilitates parallel and fast random data access, and allows for increasing data capacity *without altering the planar dimensions of the media*.

Permutations & Multi-state Arithmetic

A straightforward example of *M*-ary multispectral data encoding allows a single data location to store 4 data states (as bits 00, 01, 10, & 11), encoded as a small sample of 4 unique standing waves (*e.g.*, wavelengths in red, orange, green & blue).

However, to greatly increase data density, WORF applies a *selectable set* of ***k*** multiplexed unique wavelengths per worfel—chosen from a larger palette of ***N*** unique wavelengths—that are written to the media and thence decoded by WORF's spectroscopic-based reader.

As writing a wavelength is an *idempotent*—*i.e.*, unchanged or unaltered—matrix operation with our standing wave technology, the number of ***k***-wavelength combinations in the set, ***S***, is given by the formula [36] [37]:

$$\mathbf{S = N! \,/\, ((\, N\text{-}k\,)! \cdot k!)} \qquad (1)$$

[6] This is one of the main reasons that the Lippmann color photographic process was never commercialized because the images could not be copied or duplicated using the same process that created them [33]; Lippmann photos from that period reproduced today, of course, are copied on modern multi-layer color film or via digital processes. These images do not copy the precise, original wavelengths stored on the Lippmann plates, but apply composite colors for human perceptual use, not for spectral decoding.

If, in our previous example, the 4 wavelengths were to be selected from a *palette of 32 different wavelengths*, a single worfel location could store ~36 Kilobits of data [38].

Planar Dimensions and Data Density—Thus, a 1 cm^2 media with $10\mu^2$ data locations ($8\mu^2$ worfels with 2μ spacing on all sides) = 1,000,000 worfels/cm^2. For example, (32!/((32-4)! • 4!)) = *35,960 distinct states*. (An analogous use of formula (1) is drawing a hand of 5 playing cards from a 52-card deck yields *2,598,960 distinct hands*.)

Applying the 35,960-state permutation table for ***k***=4 (*i.e.*, superimposing 4 wavelengths per worfel), and drawing from a palette, ***N***, of *32 different wavelengths*, yields 35,960,000,000 bits (≈35.9 gigabits) per cm^2; or 35.9 x (6.42 cm^2 per square inch) ≈ *230.4 gigabits/in²*. And so for an example of a 4″x5″ media (20 in^2), 20 x 230.4 ≈ *4.6 terabits per 4x5 inch media*.

While presenting a significant increase in data density, this configuration still does not demonstrate the full capabilities of WORF's multispectral, archival data technology. For instance, a 25% increase in the palette, ***N***, from 32 to 40 wavelengths, increases the number of combinations by 254%.

Data density can be dramatically further increased—without altering the planar dimensions of the media—by combining worfels into matrices or "worflets," drawing from even larger palettes of wavelengths and applying advanced permutation formulae (see Appendix for an example).

Data Transfer Speeds

The order of which the data stored in a media can be accessed has a direct effect on the speed of the data being transferred. In the case of the majority of contemporary magnetic and optical archival media, data is accessed in a pre-established sequential order—sequential access memory (SAM). A faster way is to access addressable data locations directly in an arbitrary order; this approach is usually utilized for short-term memory—direct access memory or random access memory (RAM).

In contrast to these legacy access methods, applying WORF's multispectral data encoding process provides for much faster direct data access, important for Big Data analysis and processing.

Bandwidth vs. Throughput—When analyzing data transfer metrics in storage devices two quantitative measurements give relevant information for assessing data transfer performance: 1) *bandwidth* estimates the potential of how fast the data can be transferred in a specific period of time over a *channel*; but, 2) *throughput* determines the amount of *data* being actually transferred between data processing devices over a given period in time.

An analogy to data transfer throughput over time is highway traffic volume: one can increase the speed limit (bandwidth) or increase the number of lanes (channels) to move more cars per hour (throughput). WORF's media format allows for multiple arrays of worfels to be read *simultaneously*, increasing bandwidth *and* shortening retrieval time.

Another key analytic attribute of WORF is its ability to increase the number of wavelengths in its color palette to increase data density while maintaining its planar dimensions. This makes WORF media readers both future-proof and backwards compatible.

WORF's parallel read mechanism uses a single monochromatic sensor to detect an array of worfels. The reader illuminates the array in rapid wavelength sequence, storing each wavelength in a separate layer by its "color" coordinates.[7]

With WORF's approach, moving parts are minimized; no movement is necessary for the camera to read an array of worfels. The data transfer speed is affected primarily by the "frame rate" (fps) of the sensor array, as opposed to the seek time and rotational latency for disks or winding tapes, wherein optical or magnetic data locations not only must be read sequentially but also *in motion.*

Processing WORF Data—WORF employs graphics processing units (GPGPU) as computational engines, using low-cost hardware with CUDA, as an example. (Such low-cost rendering engines have been readily available for more than a decade from NVIDIA [39].)

5. CONCLUSIONS.

The Current Archival Data Storage Dilemma.

Currently there are no satisfactory technical solutions for Big Data which must last in excess of decades or longer. Large commercial, consolidated, cloud data storage systems for Big Data are non-scalable, not secure, and unsustainable for the long term.

Data farms today are located adjacent to power plants and to water sources for cooling. In 2013, energy use for data storage in the U.S. 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 [40]. Moreover, archival storage systems must be constantly maintained and checked for data degradation—an energy-intensive process—and data must be reconstituted periodically to remove accumulated errors due to bit rot.

One critical astronomical application for our novel data storage system would be for the Vera C. Rubin observatory[8] due to go online in Chile in 2023. The telescope will have two hundred 3.2 Gigapixel sensor arrays, with each array collecting multiple spectral channels [41] [42]. The arrays will collect 20 Tbytes per day of data, representing a streaming and long-term sustainability challenge for cloud servers. The camera is expected to generate 1.28 petabytes (uncompressed) per year, far more than can be reviewed by humans. Managing and effectively analyzing the enormous output of this telescope is expected to be the most technically difficult part of the project.

Streaming such huge amounts of data from the Chilean venue to existing cloud servers is not practical. Additionally, installing huge data farms locally would require power plants and cooling facilities adjacent to the telescope. WORF architecture is a better match for archival Big Data processing challenges.

Summary of WORF's Unique Features:

- WORF has been tested by NASA on the International Space Station. The results indicate that the media may provide a permanent, immutable data storage solution which can survive harsh space environments for long-term, deep space missions.
- Silver-based media are recognized mechanisms which can preserve information for decades or centuries without continuous power, based on extant examples not requiring accelerated life tests. Therefore, WORF dramatically reduces maintenance and operational costs for Tier 3 and 4 archiving [43], sustainable beyond that of contemporary data media without excessive energy inputs.
- WORF both increases data density and can perform analysis coincident with the read process by utilizing multi-core data algorithms optimized for parallel data. This unique capability is not possible using contemporary serial-based binary media storage.

APPENDIX: MATRIX PERMUTATIONS TO INCREASE DATA DENSITY

The square matrix in Fig. 3 is a permutation set ($\overline{W}$) containing 16 worfel data locations, wherein data locations **a** contain one unique set (a "worflet"), of up to 5 distinct, superimposed *M*-ary wavelengths, (ω) *i*, *j*, *k*, *l*, *m*; and worflet **b** contains up to 5, *different*, superimposed wave-lengths, (ω) *n*, *o*, *p*, *q*, *r*, dramatically increasing data density for the $\overline{w}$ permutation set

$$\overline{\boldsymbol{W}} = \begin{pmatrix} \mathbf{a} & \mathbf{b} & \mathbf{a} & \mathbf{b} \\ \mathbf{b} & \mathbf{a} & \mathbf{b} & \mathbf{a} \\ \mathbf{a} & \mathbf{b} & \mathbf{a} & \mathbf{b} \\ \mathbf{b} & \mathbf{a} & \mathbf{b} & \mathbf{a} \end{pmatrix}$$

Figure 3. Worfels (data locations) *a* and *b* have different wavelength sets .

The total amount of data computed would have no **a** ω's duplicated in **b**; expressed in set theory:

$$\begin{aligned} a &= \sum \omega i ,\ \omega j ,\ \omega k ,\ \omega l ,\ \omega m \\ b &= \sum \omega n ,\ \omega o,,\ \omega p ,\ \omega q,,\ \omega r \\ &\exists\ \omega \in a \Rightarrow \omega \notin b \end{aligned} \tag{2}$$

[7] See Sect. 2, item 5 for elaboration.
[8] Also known as the "Legacy Survey of Space and Time" (LSST) observatory.

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b. R.J. Solomon, *et. al*., "Write Once, Read Forever (WORF): Proof-Of-Concept Demonstrated For Archival Data Storage…," *Proc. IS&T Archiving 2015 Conference*, Los Angeles, pp. 92-97;

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BIOGRAPHIES

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