Avoiding Temporal Error in the Measurement of Modulated Displays

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Introduction

High Dynamic Range (HDR) imaging is widely used in both photography and light measurement applications. Traditional Multi-Exposure Fusion (MEF) HDR involves capturing multiple images at different exposure levels and combining them to create a single HDR image. Advanced algorithms in video applications have been developed to align and merge these images, minimizing artifacts such as ghosting caused by moving objects.

When measuring modulated light with a camera or spectrometer, if the light modulation period is not significantly shorter (ideally 100x to 1000x shorter) than the measurement integration time, the resulting images or spectra may lack reproducibility. The irreproducibility caused by this effect is known as Temporal Aliasing.

The objective of the new method is to use a modified HDR measurement sequence to eliminate the measurement errors related to light modulation.

The TAA HDR method addresses image exposure stitching mismatches by automatically anchoring the values from the longest exposure to the successively shorter exposures in the HDR sequence. Pixel data values that are valid in two successive exposures are compared, and all image data from the shorter exposure data is uniquely scaled to match the values from the longer exposure. The two exposures are then fused. The process repeats until all exposures are complete.

Experimental Setup

An LED light source is connected to an arbitrary waveform generator. A diffuser is placed between the LED light source and the WP525 imaging colorimeter / spot spectroradiometer.

The worst-case scenario for aliasing is a Pulse Width Modulated (PWM) square wave with 100% modulation depth and low duty cycle. Measurements for such a light source with the spectroradiometer and imaging colorimeter with no correction and with TAA HDR imaging are compared for measurement precision.

Since the LED used in this experiment was not stabilized, drift of the LED during the tests could be a significant source of error. To gauge this drift, 10 measurements were taken of the setup with the LED lit, but unmodulated.

Figure 1. Westboro Photonics' WP525 Imaging Spectral Colorimeter

Spectrometer

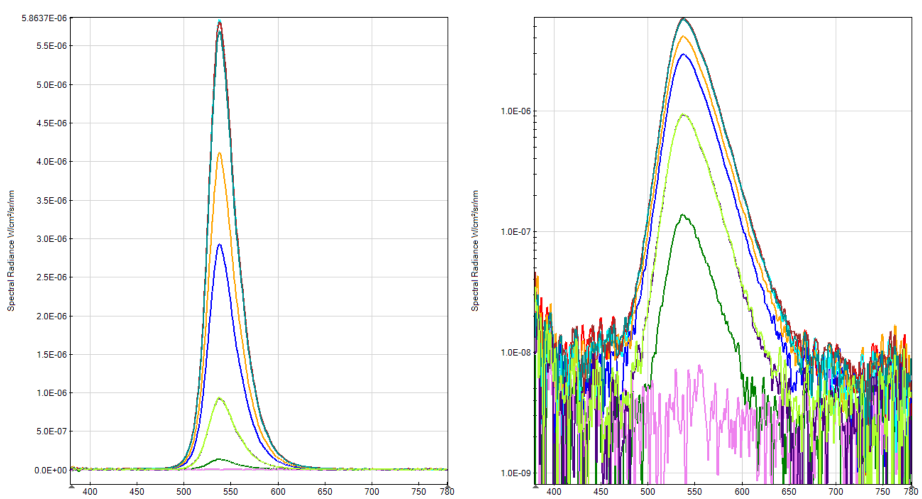

Figure 2. Ten, 8 ms exposure spectra of a light source PWM modulated at 45 Hz and 20% duty cycle. Left is linear scale and right is log scale.

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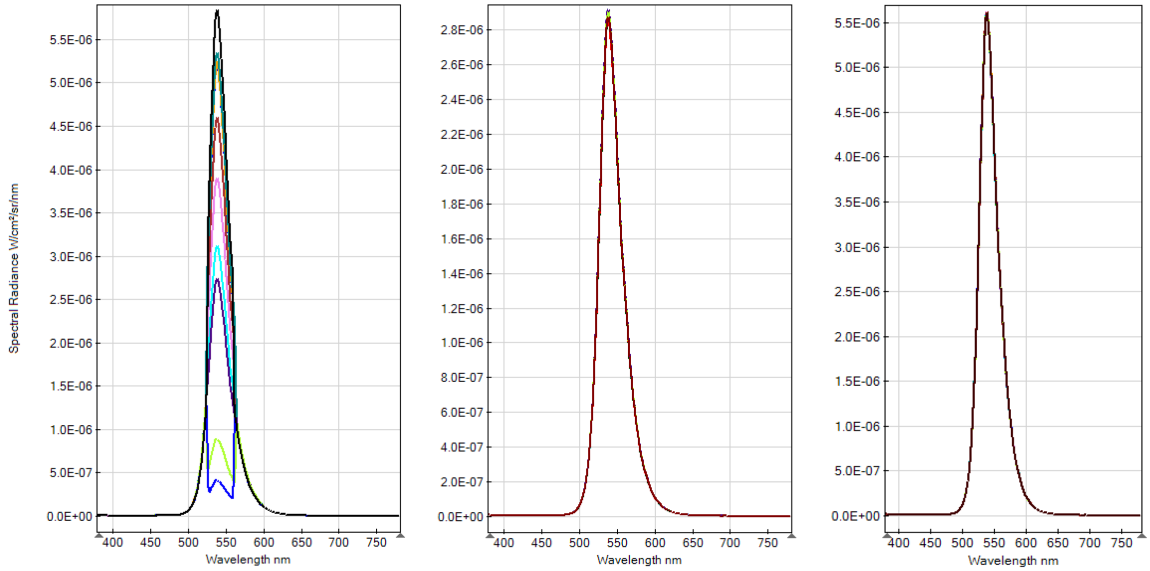


Figure 3. Left and center spectra are ten HDR measurements of a 45 Hz modulated source at 20% duty cycle and 100% depth of modulation. Center has TAA-HDR, while those on the left do not. Right hand measurement has no light source modulation (as a reference).

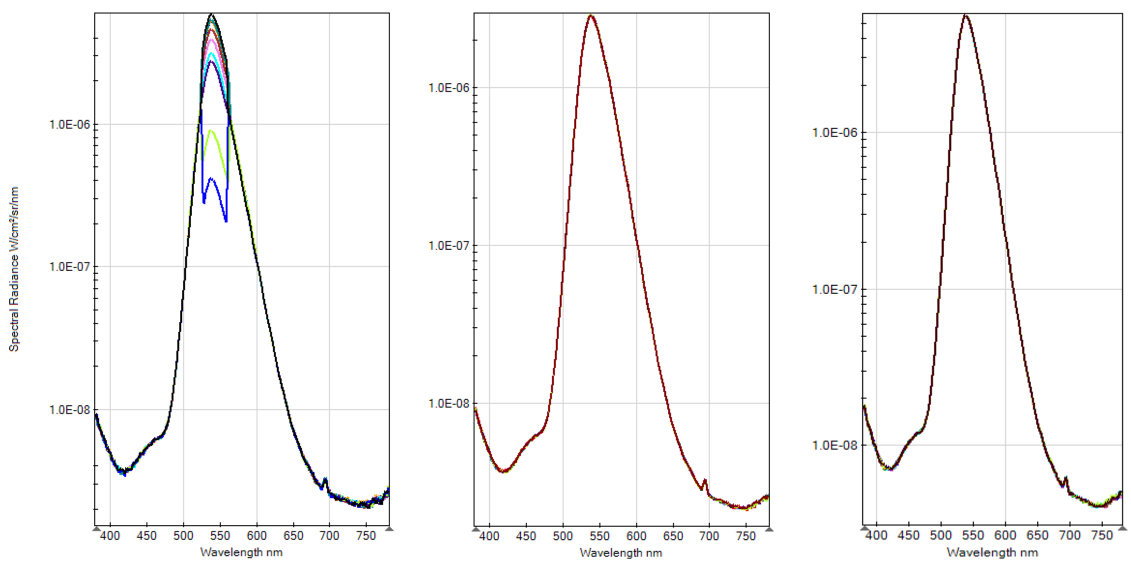


Figure 4. As Fig. 2, above, except log-scaled.

Table 1. Summary of standard deviation for key results from the spectrometer measurements.

Modulation?	45Hz, 20% duty, 100% mod, PWM		None
TAA?	TAA off	TAA on	TAA off
Luminance	85%	0.65%	0.07%
u'	0.09000	0.00007	0.00005
v'	0.02260	0.00009	0.00005
x	0.03570	0.00005	0.00000
y	0.04699	0.00005	0.00000
Dom. Wl, nm	5.90	0.05	0.00
Purity	0.0369	0.0000	0.0000

Imaging Colorimeter

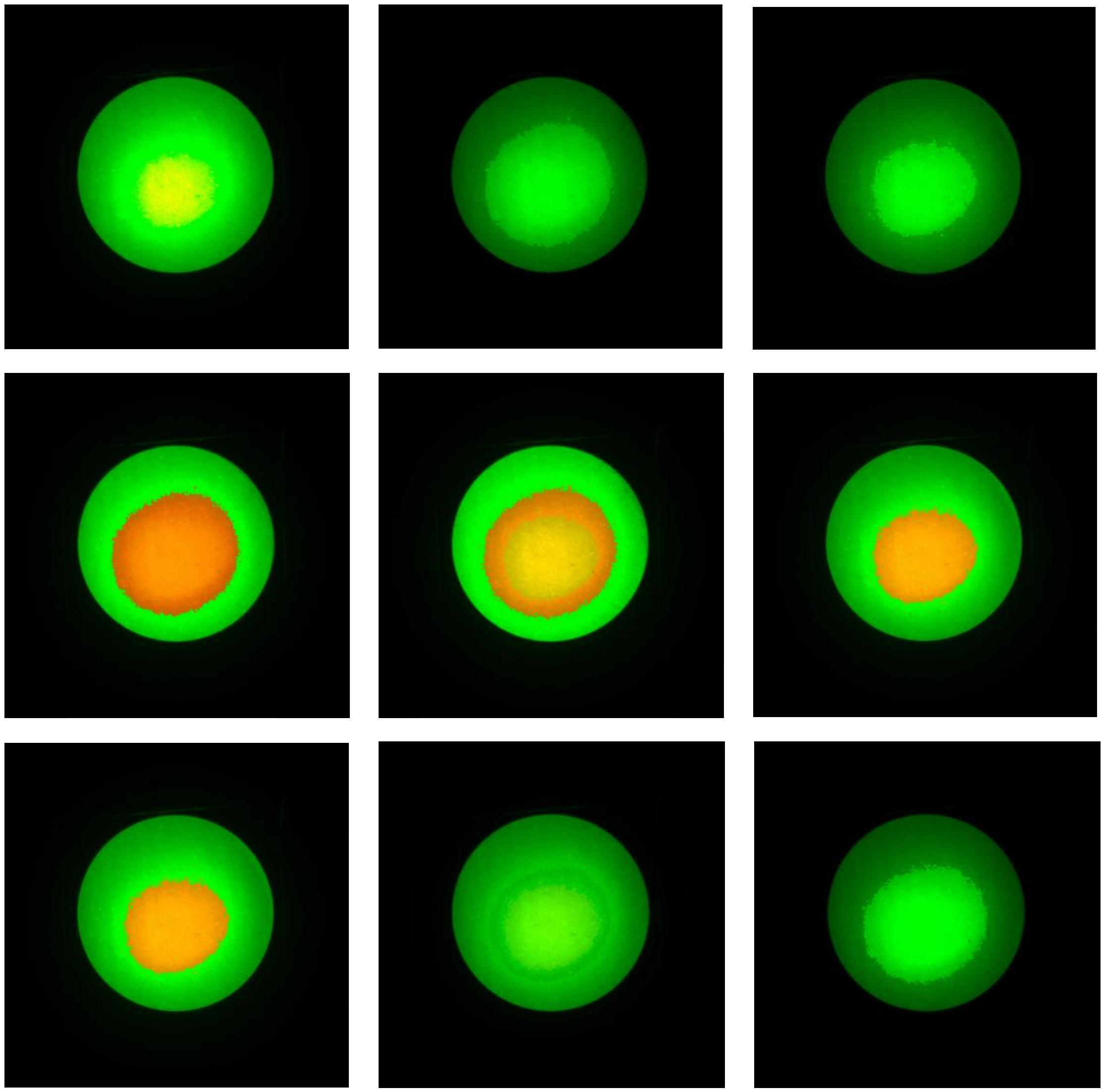
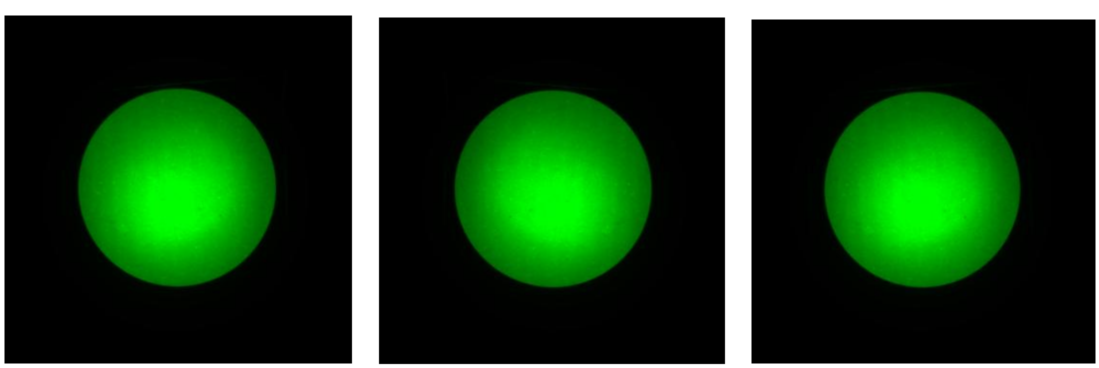


Figure 5. Nine successive HDR Imaging colorimeter measurements at 45 Hz modulated source at 20% duty cycle and 100% depth of modulation.



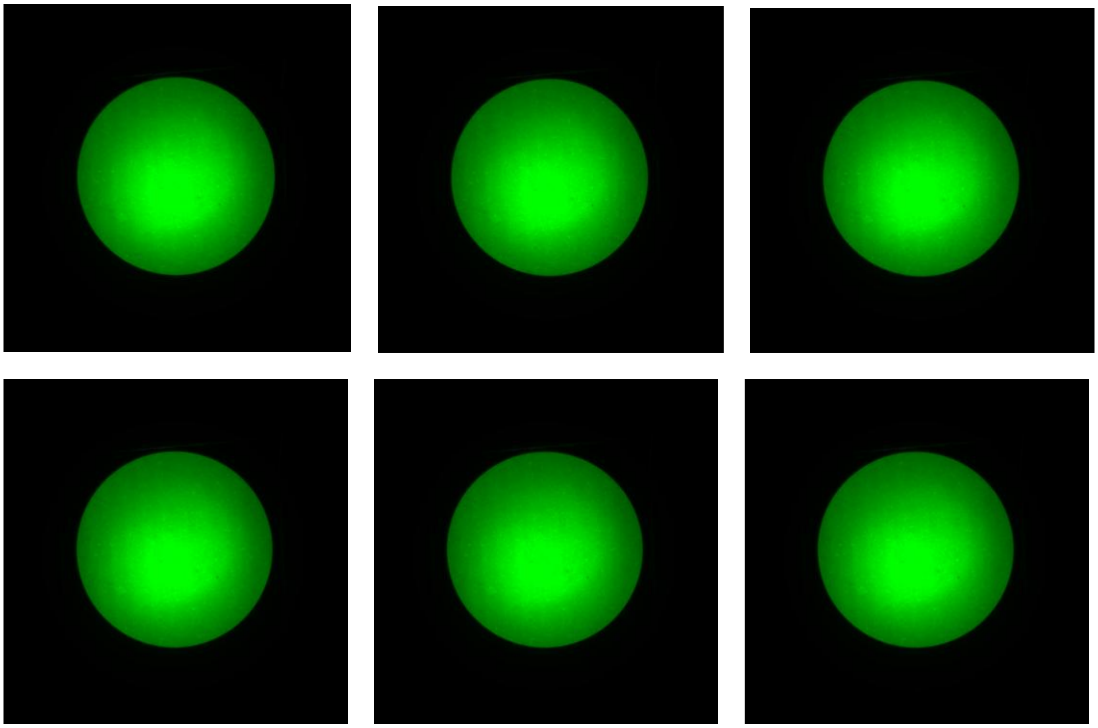


Figure 6. Same conditions as Fig 5, except TAA-HDR is enabled.

Table 2. Standard deviation for WP525 Imaging Colorimeter data when measuring PWM light source at 45 Hz, 20% duty cycle and 100% modulation depth.

Modulation?	45Hz, 20% duty, 100% mod, PWM		None
TAA?	TAA off	TAA on	TAA off
Luminance	49%	0.41%	0.04%
u'	0.10997	0.00187	0.00018
v'	0.01748	0.00026	0.00003
x	0.09401	0.00384	0.00038
y	0.09195	0.00352	0.00037
Dom. Wl, nm	13.41	0.52	0.05
Purity	0.02	0.00	0.00

Summary of Findings

The spectrum and images are demonstrably improved with the application of the TAA HDR methods. Similarly, the key metrics for luminance and chromaticity are improved by at least 100x for the spectrometer, and over 20x for the imaging colorimeter.

TAA-HDR imaging has been shown to make dramatic improvements in the precision and accuracy in the measurement of modulated light sources.

Implications

Although only one light source is shown here, lab testing has been shown that with a 45 Hz modulated light source, exposures as short as 0.5 ms can be acquired to add data in the HDR fusion process described herein. If one were to not use HDR and constrain measurements to be long enough to avoid aliasing altogether, one might settle on a 2 second measurement as the shortest measurement. Such as scenario could require neutral density filters. Furthermore, these attenuation strategies would take a very long time to acquire HDR measurements – which may not be feasible. Other features of the TAA-HDR imaging method are:

1. Works on any modulated light source (with the proviso that the longest exposure is much longer than the modulation period)
2. Does not require knowledge of the light source modulation frequency
3. Does not require signal averaging

There are some limitations of the method:

1. There must be no motion of the camera or objects being imaged – otherwise spatial aliasing errors are likely.
2. The longest exposure needs to have a quantity of pixels that are not saturated, otherwise it cannot act as an anchor for shorter exposures. Therefore, there needs to be dark areas in the field of view.

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