Spatially Varying Persistence for High Dynamic Range VR Displays

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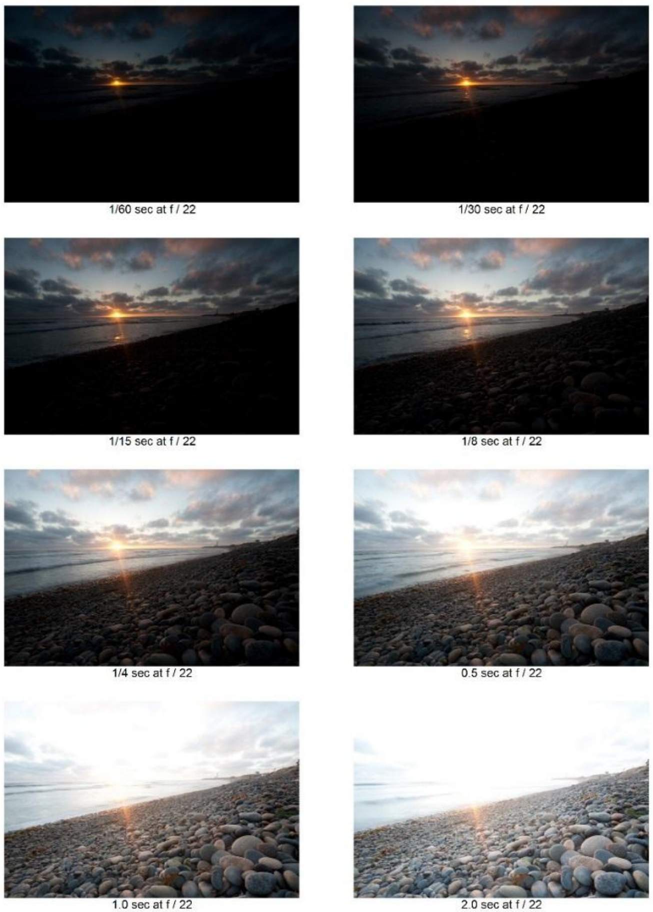
Motivation: Photorealistic VR

Real world is high dynamic range

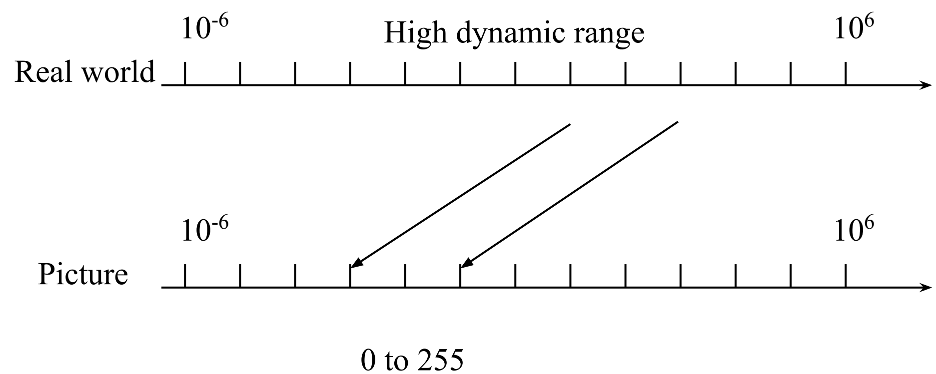


Today's VR headsets use an LDR display

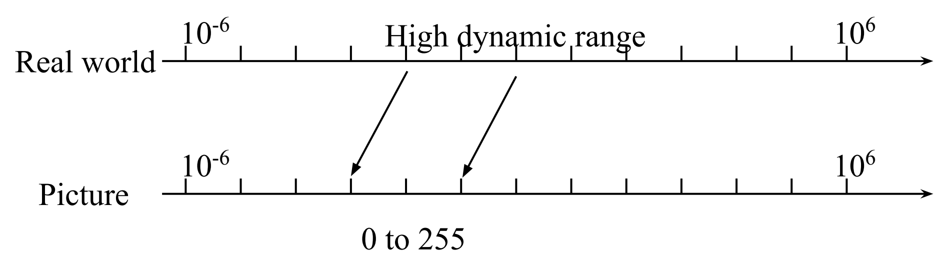
Dynamic Range of Human Vision

- Human vision contrast ratio
  - Instantaneous - 10^4: 1
  - With Adaptation - 10^{20}: 1
- Commonly available displays - 255: 1

1/60 sec at f / 22



2.0 sec at f / 22



Images courtesy of Alexei Efros

Existing methods to display HDR image

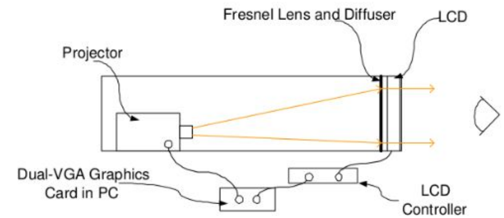
- Using LDR displays:
  - Tonemapping
  - After-images
- HDR displays - perceptual study shows this is preferred

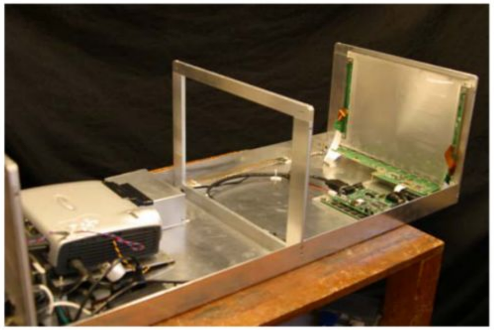
Akyuz, Ahmet Oguz, et al. "Do HDR displays support LDR content?: A psychophysical evaluation." ACM Transactions on Graphics (TOG) 2007

Ledda, Patrick, Alan Chalmers, and Helge Seetzen. "HDR displays: a validation against reality." Systems, Man and Cybernetics, IEEE, 2004.

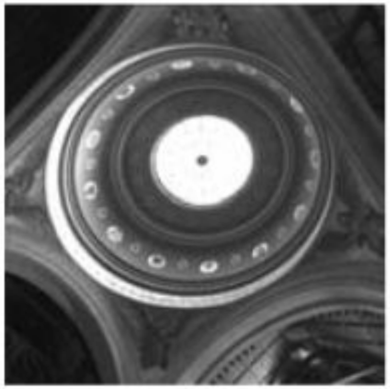
2004 HDR Display: Projector prototype

- Limitations:
  - Power consumption
  - Form factor

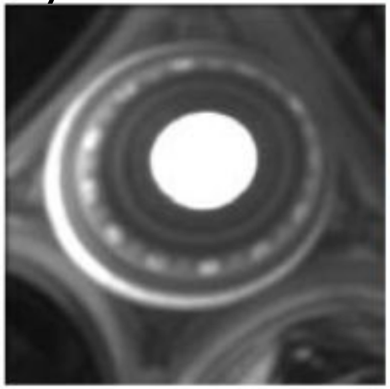




Projected image



After diffusion layer

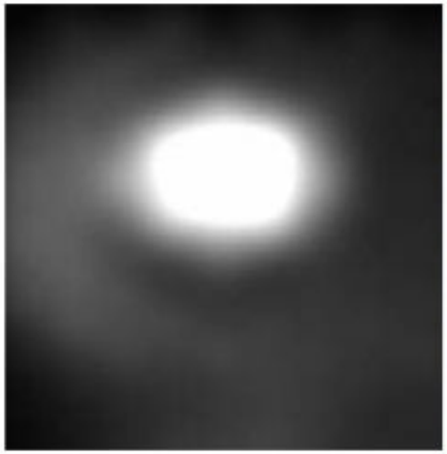


After LCD

Seetzen, Helge, et al. "High dynamic range display systems." *ACM Transactions on Graphics (TOG)* 2004

2004 HDR Display: LED array prototype

Backlight image after diffusion

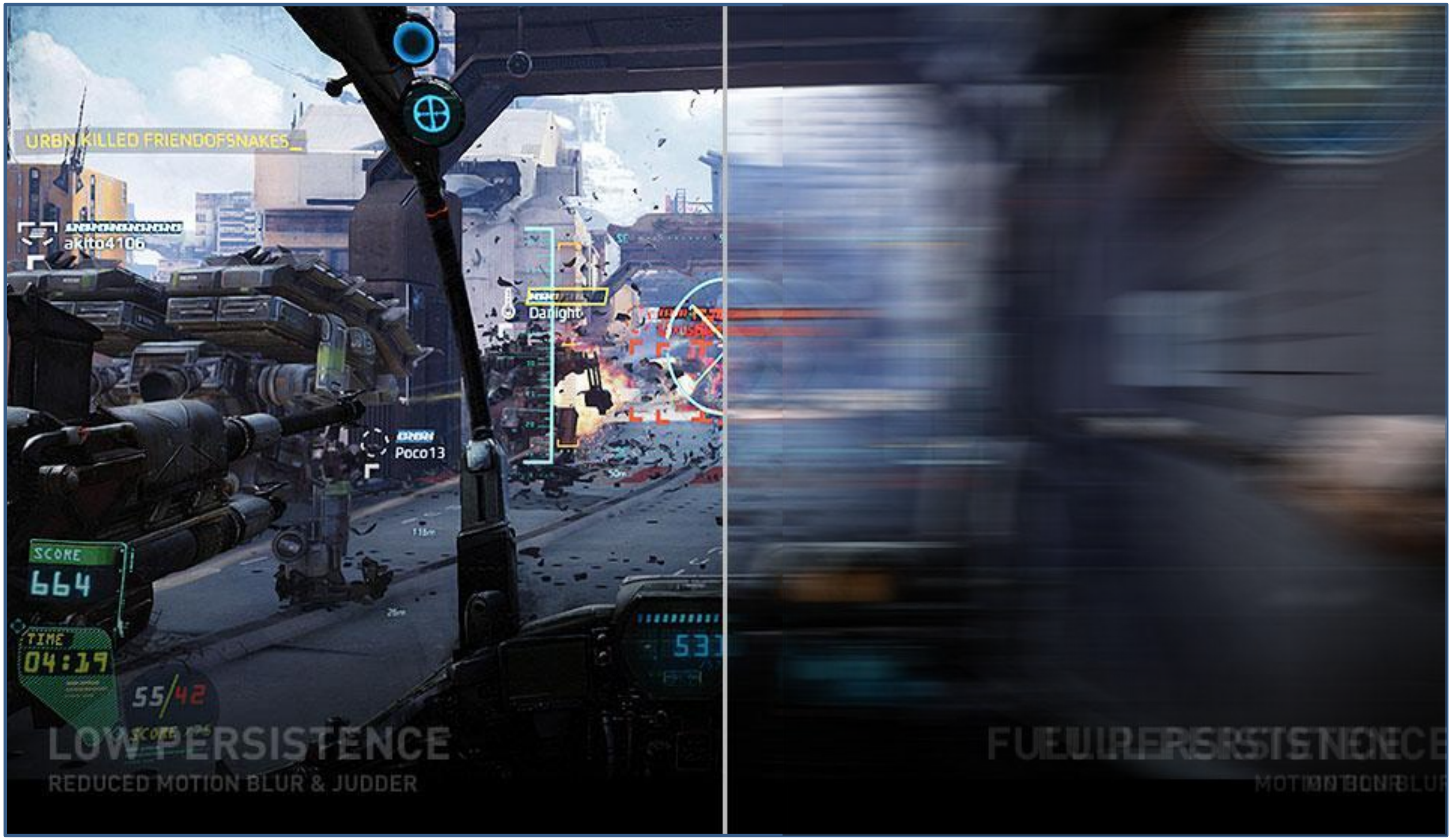


After LCD

	HDR 2004	Our LED array
Quantization	1024	16
Max luminance		
Controller scheme	Individual control	Row wise control

Seetzen, Helge, et al. "High dynamic range display systems." *ACM Transactions on Graphics (TOG)* 2004

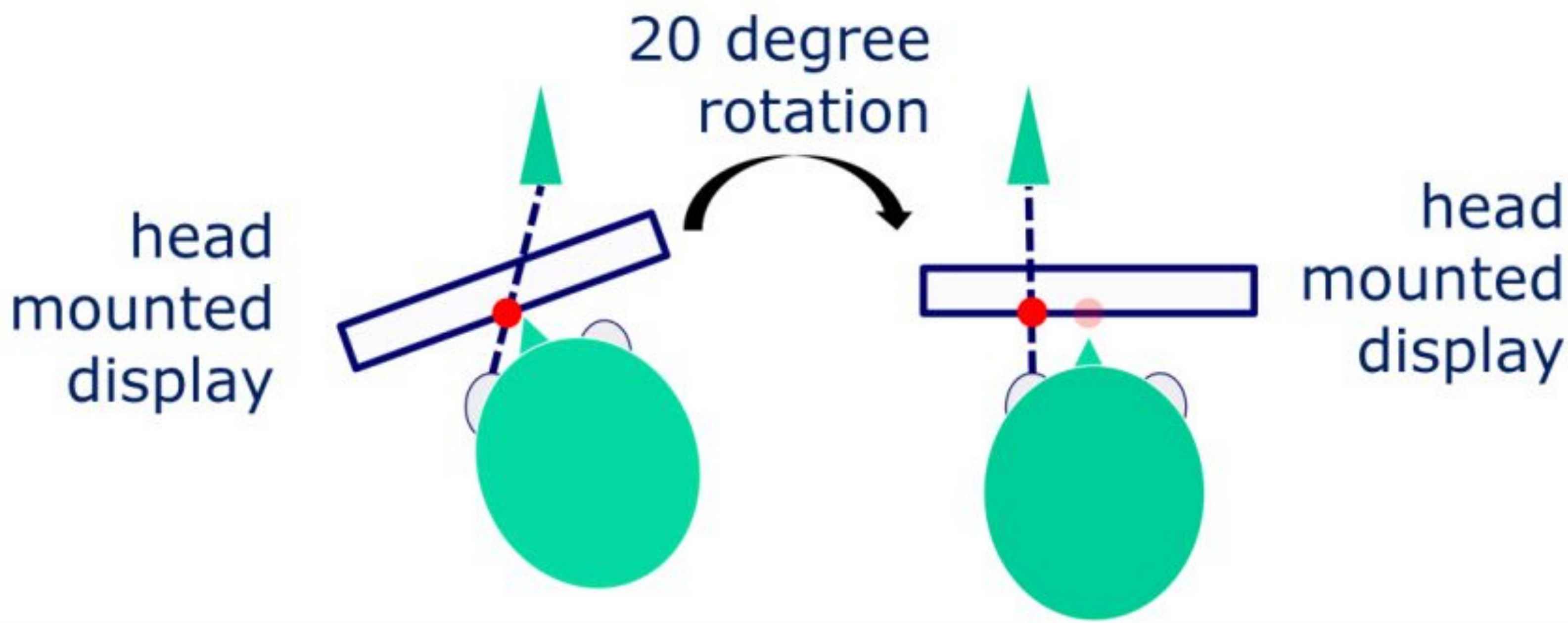
Judder in VR



http://www.theriftarcade.com

Judder in VR

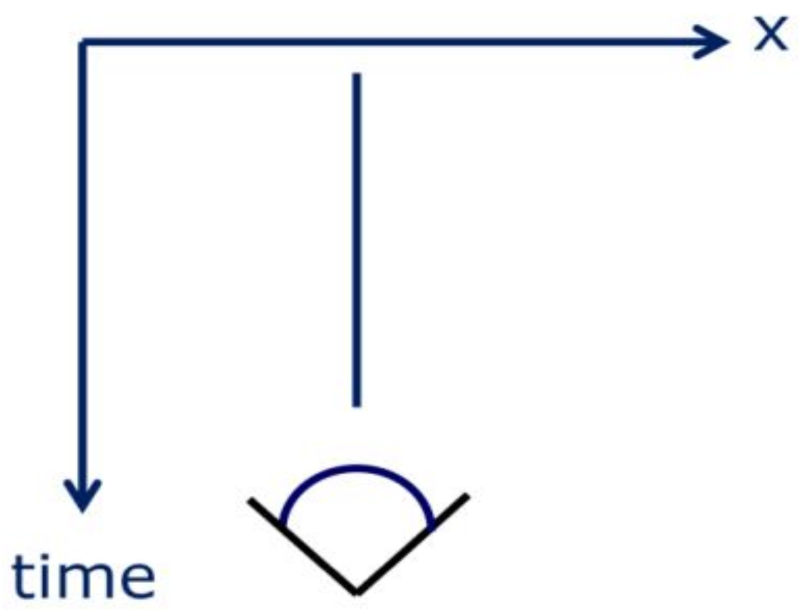
- Cause: rapid relative motion between display and eyes
  - Smooth pursuit
  - Vestibular Ocular Reflex (VOR)



Images courtesy of Michael Abrash

S-T diagrams

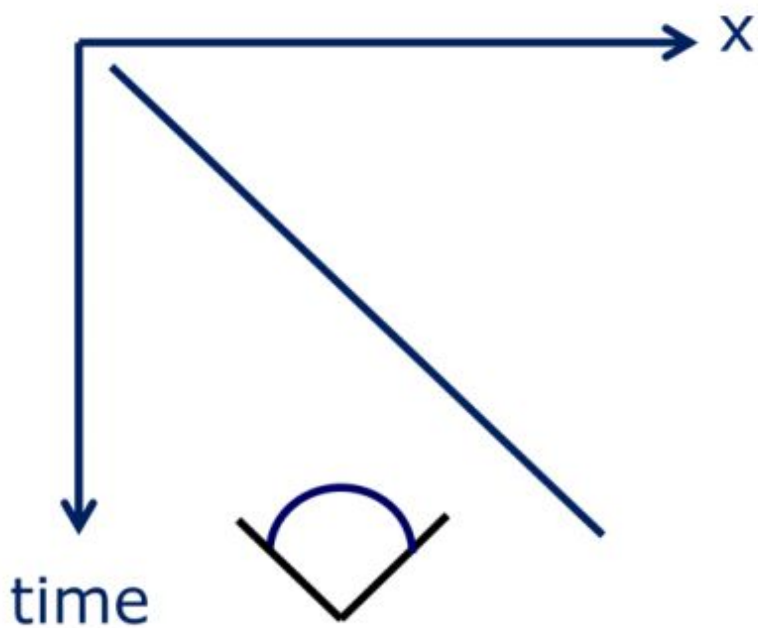
- Stationary object in real world



Images courtesy of Michael Abrash

S-T diagrams

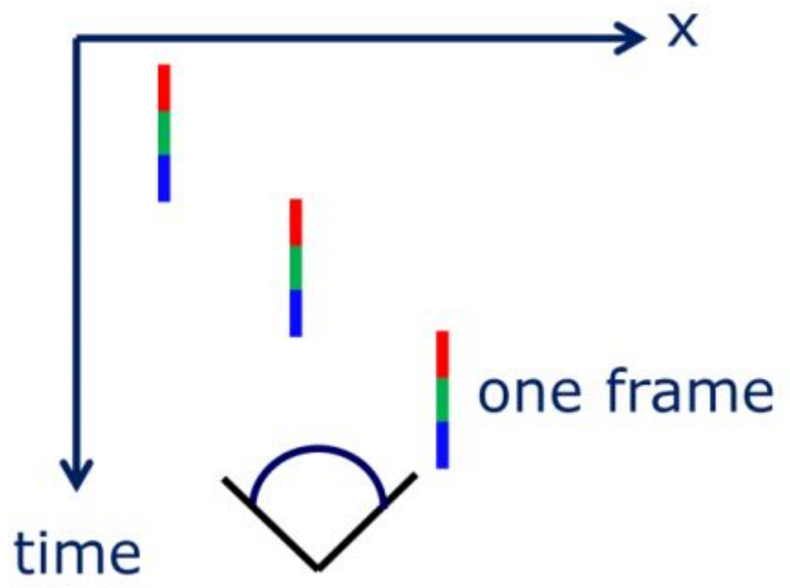
- Moving object, fixed gaze in real world



Images courtesy of Michael Abrash

S-T diagrams

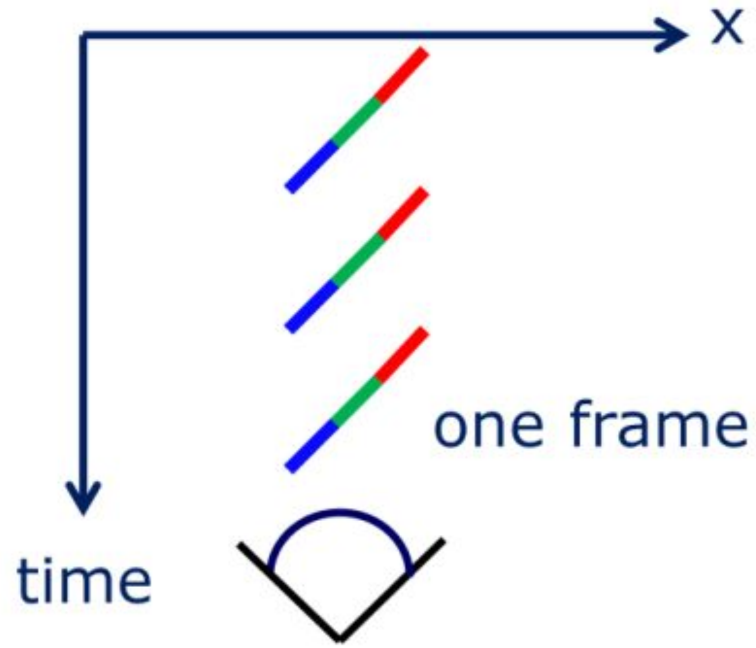
- Moving object, fixed gaze in HMD
- Artifact: Strobing (depends on fps)



Images courtesy of Michael Abrash

S-T diagrams

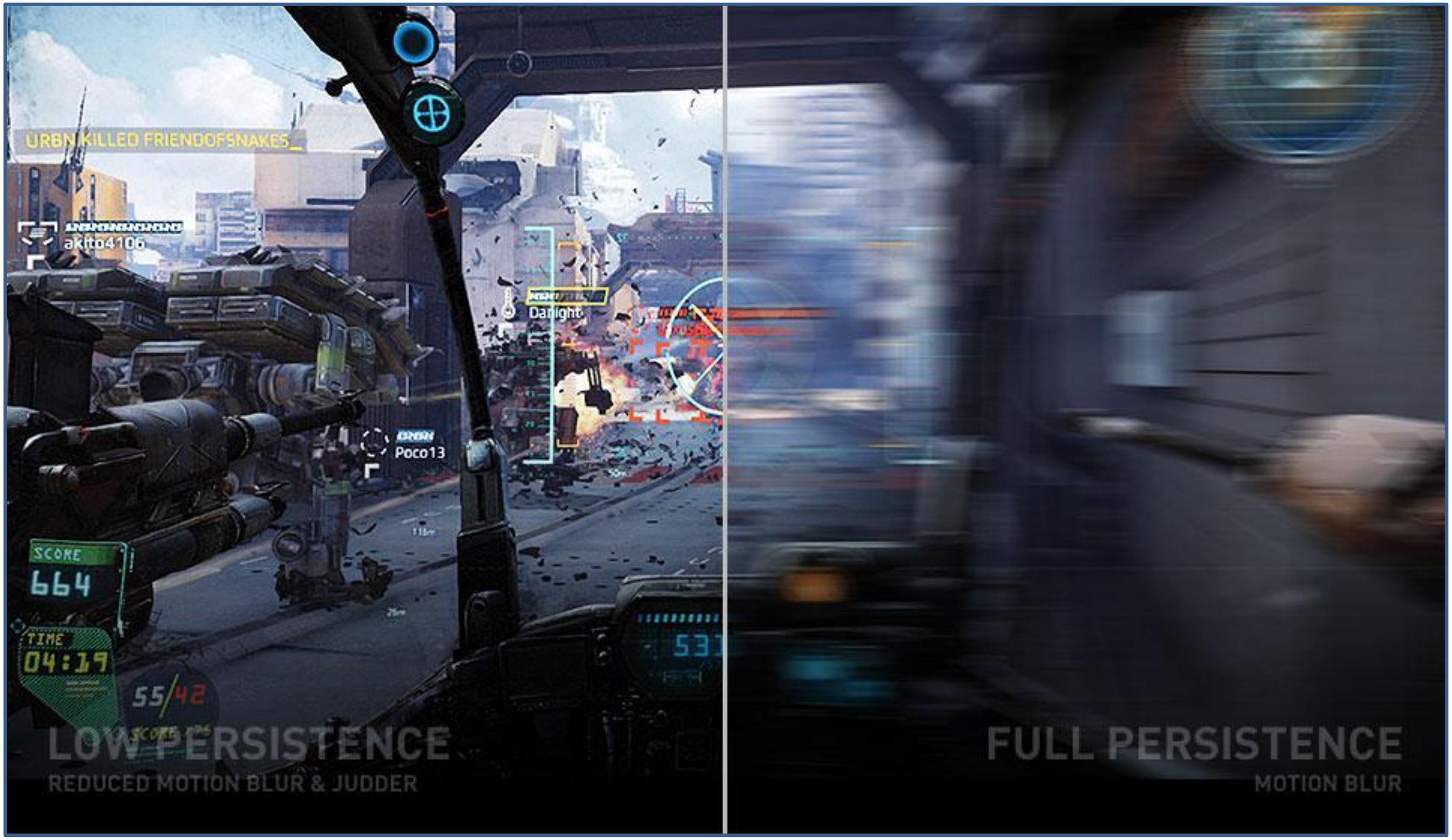
- Eyes following moving object in HMD
- Artifacts: Motion blur, chromatic aberration



Images courtesy of Michael Abrash

Judder in VR

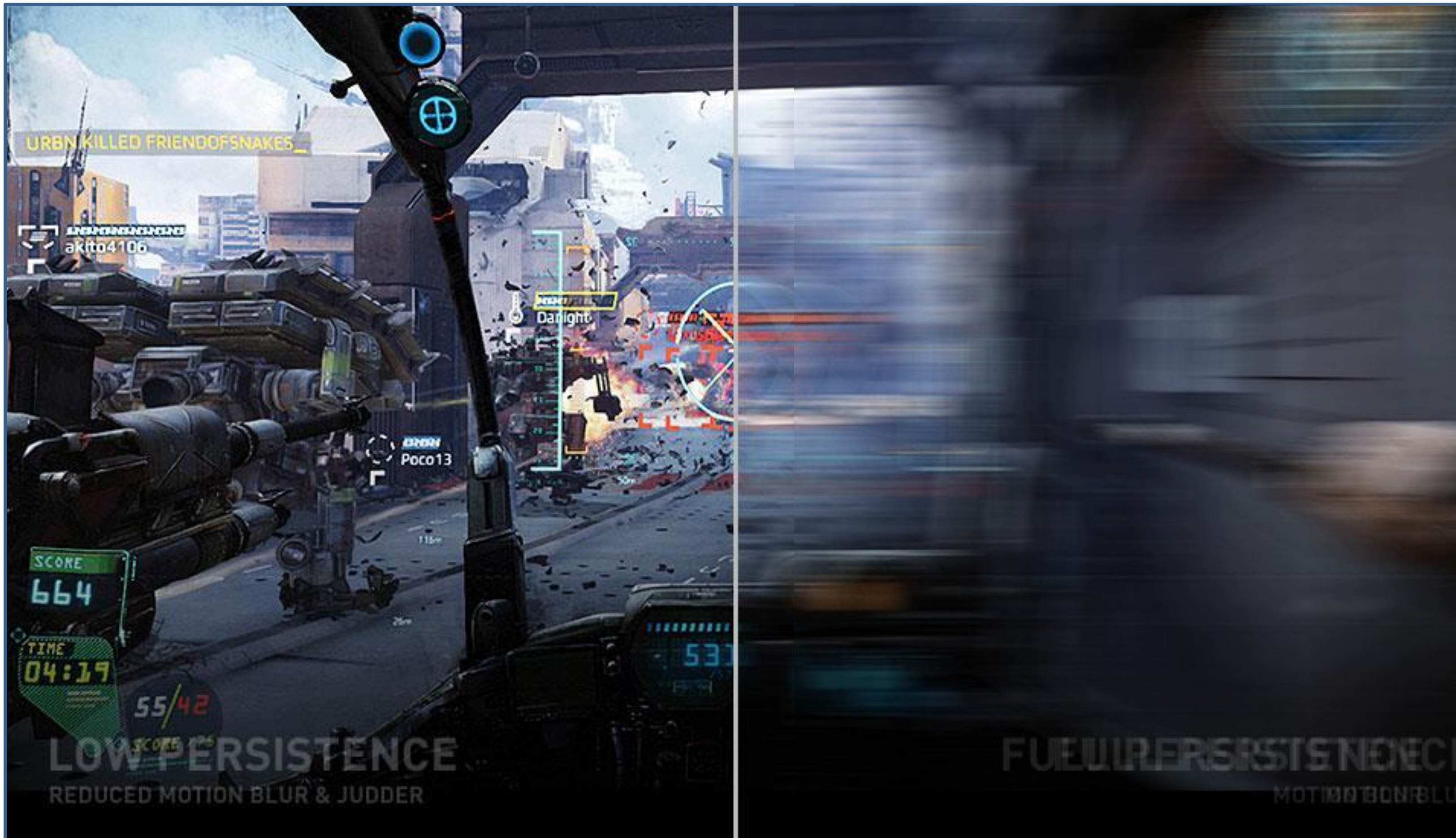
- Motion blur



http://www.theriftarcade.com

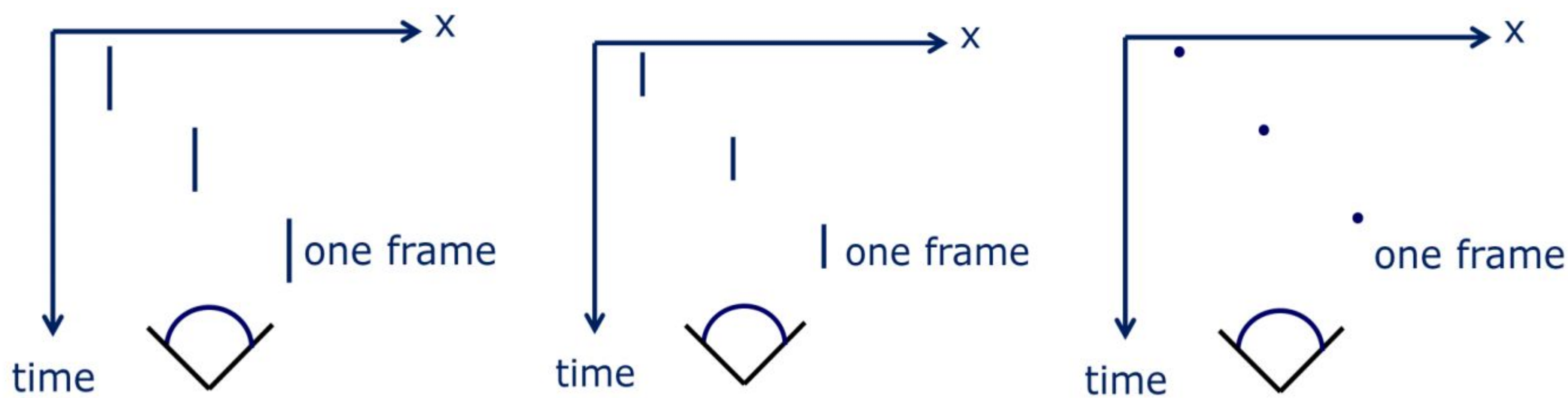
Judder in VR

- Strobing* + Motion Blur



Solutions for Judder in VR

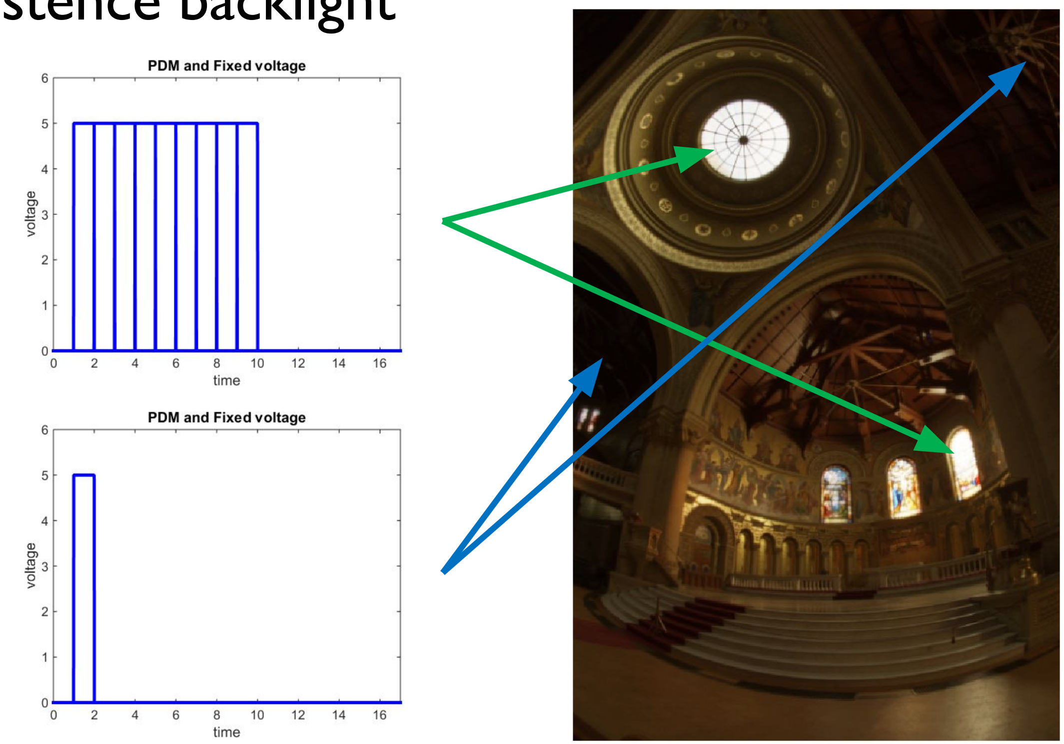
- ~1000 fps low latency display
- Low persistence



http://blogs.valvesoftware.com/abrash/down-the-vr-rabbit-hole-fixing-judder/

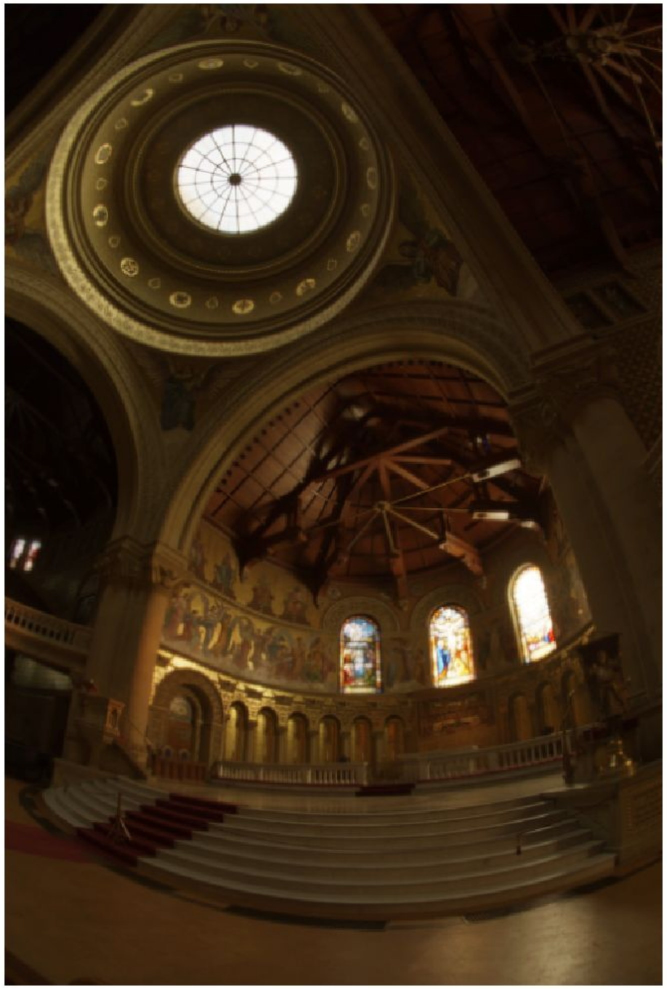
Main challenge for HDR VR display

- Trade off between brightness and persistence
- Proposed approach:
  - Allow for high persistence for bright pixels
  - Spatially varying persistence backlight
- Basis for approach
  - Glare phenomena

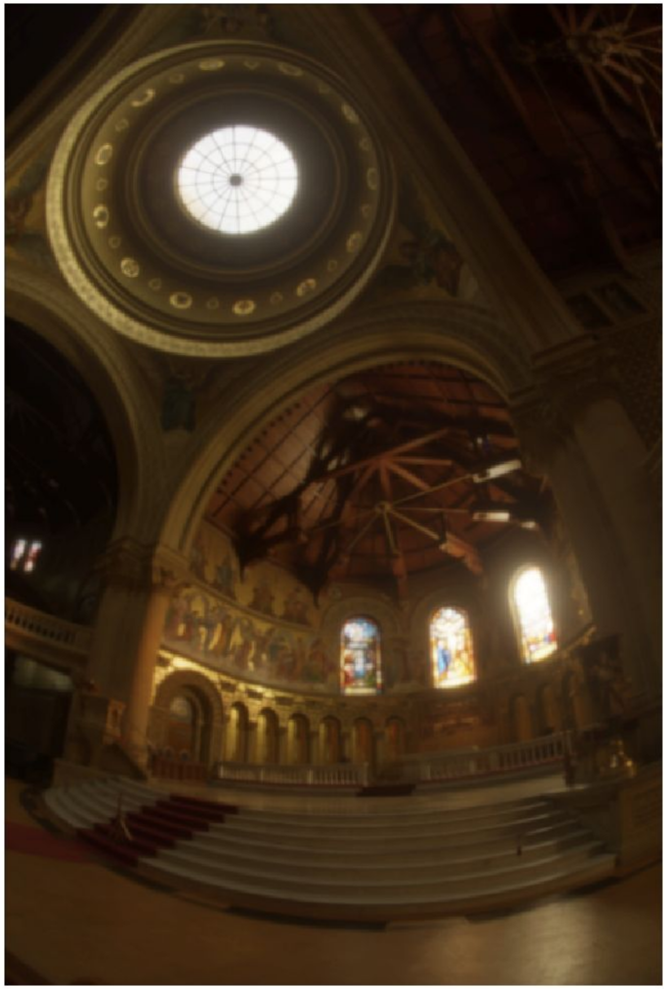


Simulating perceived HDR image

Original HDR image



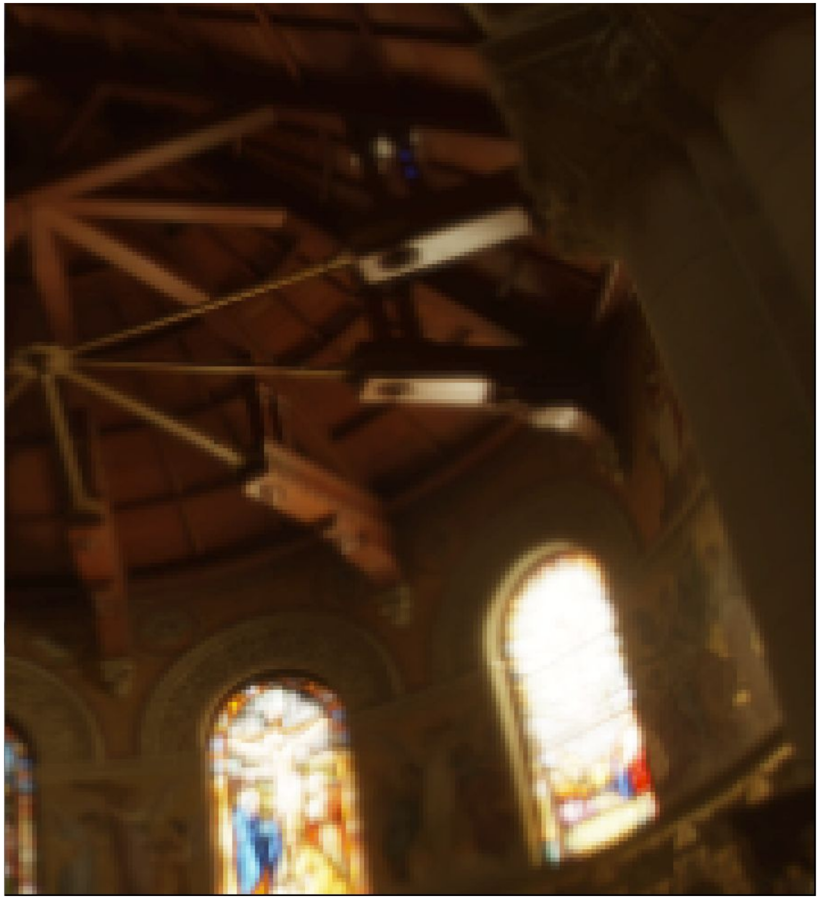
Perceived HDR image



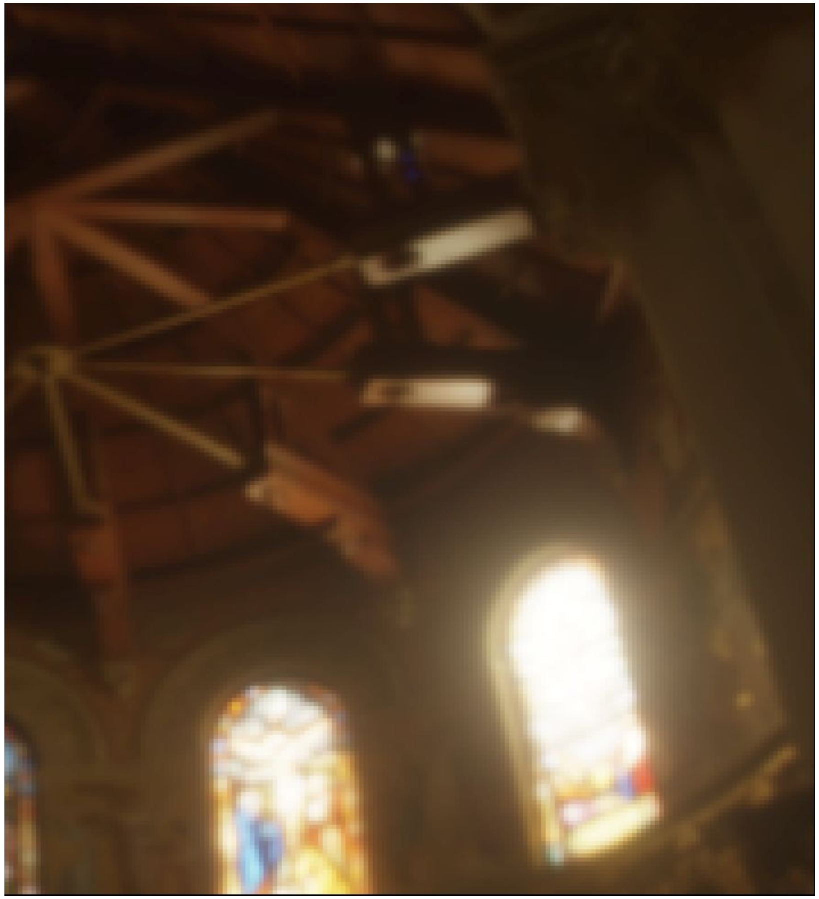
Spencer, Greg, et al. "Physically-based glare effects for digital images." SIGGRAPH 1995.

A closer look…

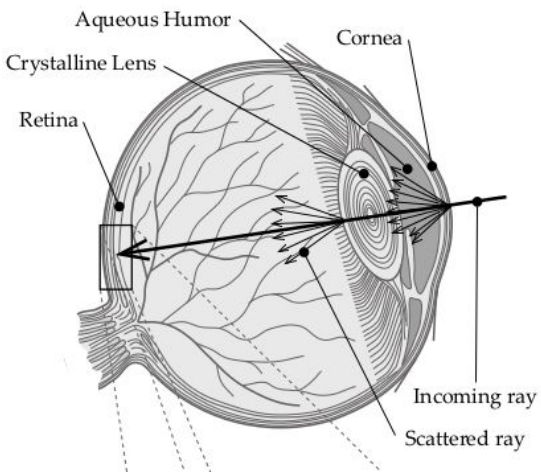
Original HDR image

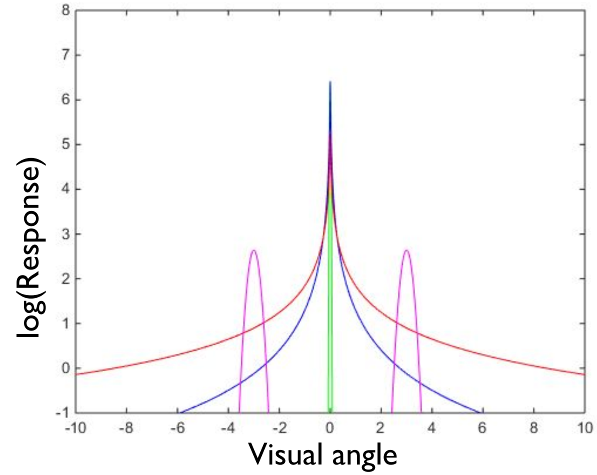


Perceived HDR image

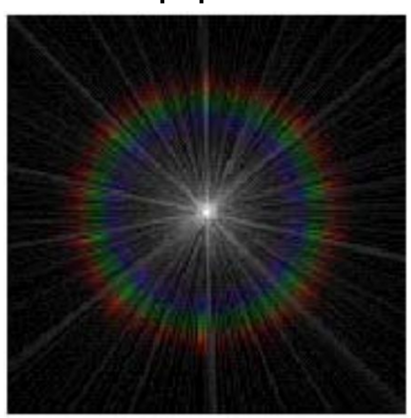


Modelling glare function

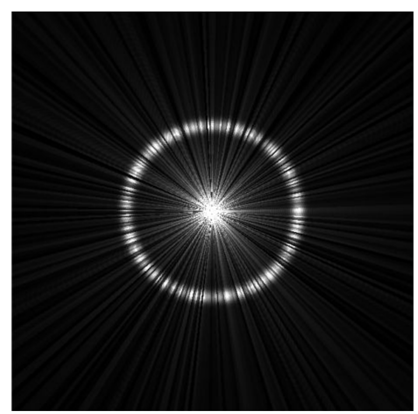




Glare filter from paper



Glare filter from our implementation



Spencer, Greg, et al. "Physically-based glare effects for digital images." SIGGRAPH 1995.

Our approach

- Minimize difference between
  - Perceived HDR image
    - $image * PSF_{glare}$
  - Perceived Display image
    - $image * PSF_{glare} * (eye\ motion\ vector)$

$$E = ||I - MP||^2$$

$$R = I - MP$$

$$M_{k+1}^T = M_k^T + \frac{RP^T}{PP^T}$$

$$P_{k+1} = P_k + \frac{R^T M}{M^T M}$$

$$E = ||G * I - \sum_{t=1}^{N} G * M \cdot (K * tv * B_t)||^2,$$

where,

G is the glare filter

I is the HDR image

M is the LCD modulation image

K is the diffusion kernel

v is the eye gaze-change velocity

B_t is the brightness of LED at time t

Design choices

- Perceived Display image:

$$image * PSF_{glare} * (eye\ motion\ vector)$$

LED array

Various modulation schemes are possible

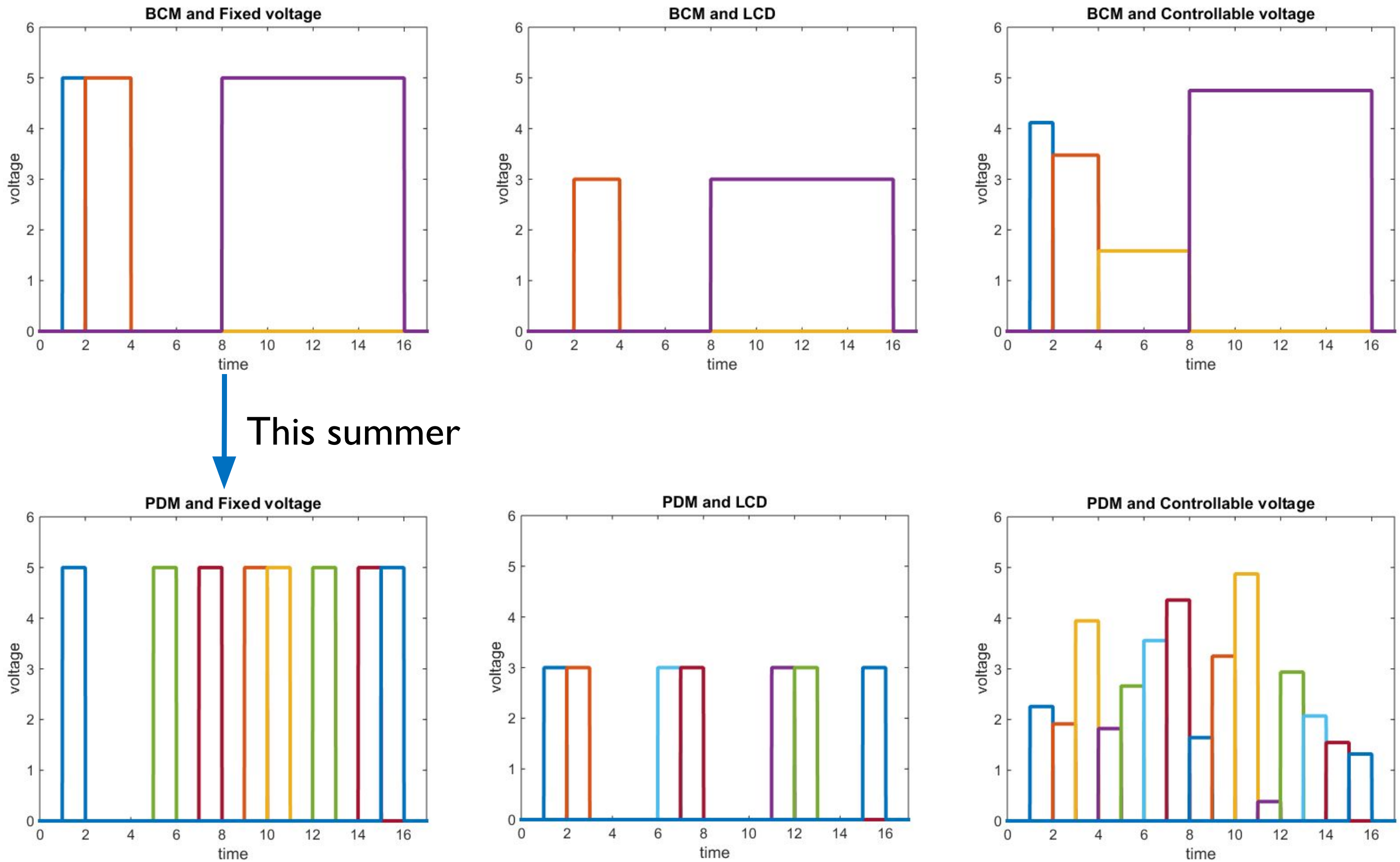
LCD panel

Not much can be done here. One update per frame time

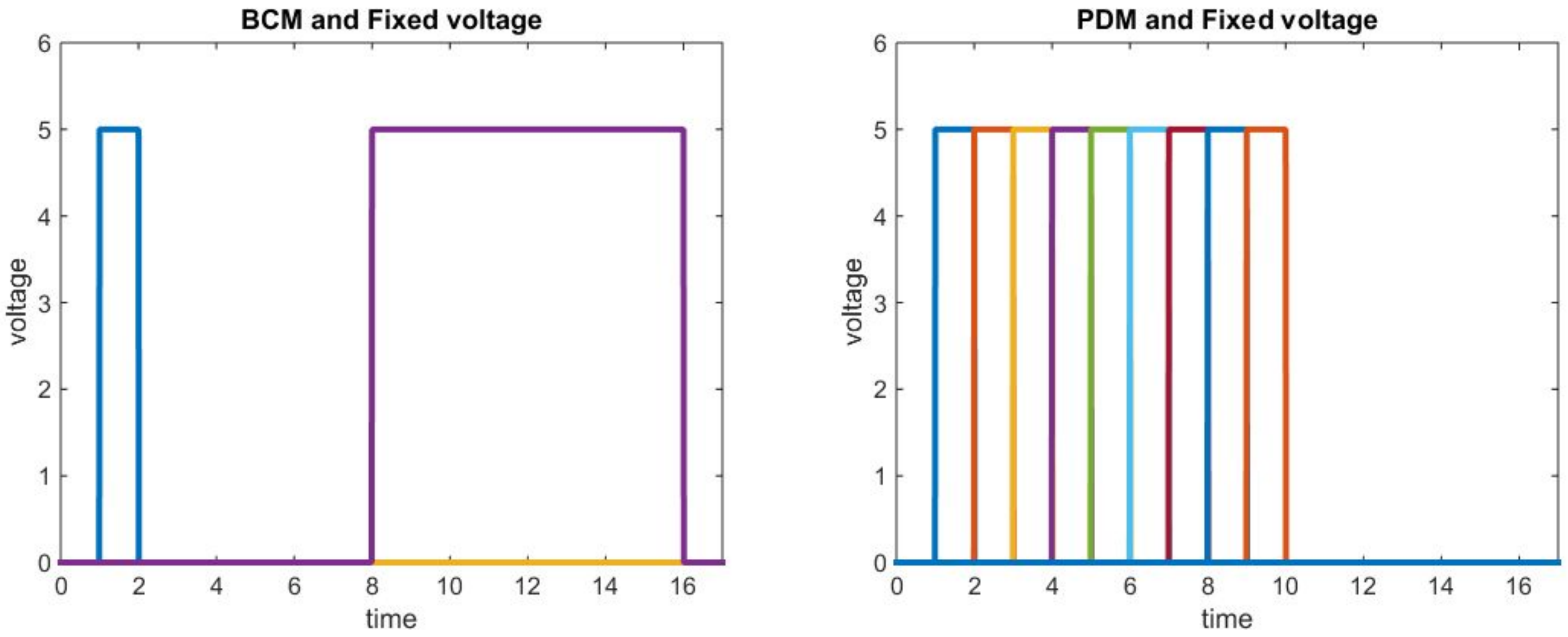
Variations in LED array

- Temporal control of LED:
  - PWM vs PDM
- Voltage control of LEDs:
  - Fixed voltage for all LEDs (binary images)
  - Controllable voltage for full frame-time (LCD placed over binary LED array)
  - Controllable voltage for quantized frame-time

Variations in LED illumination

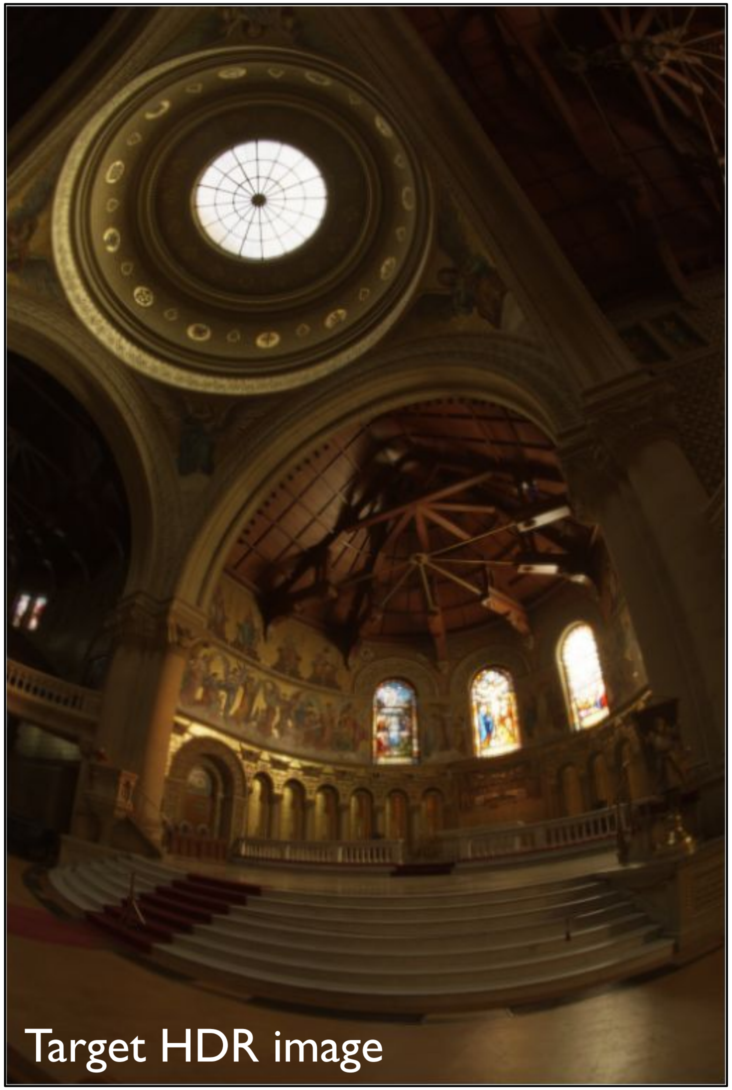


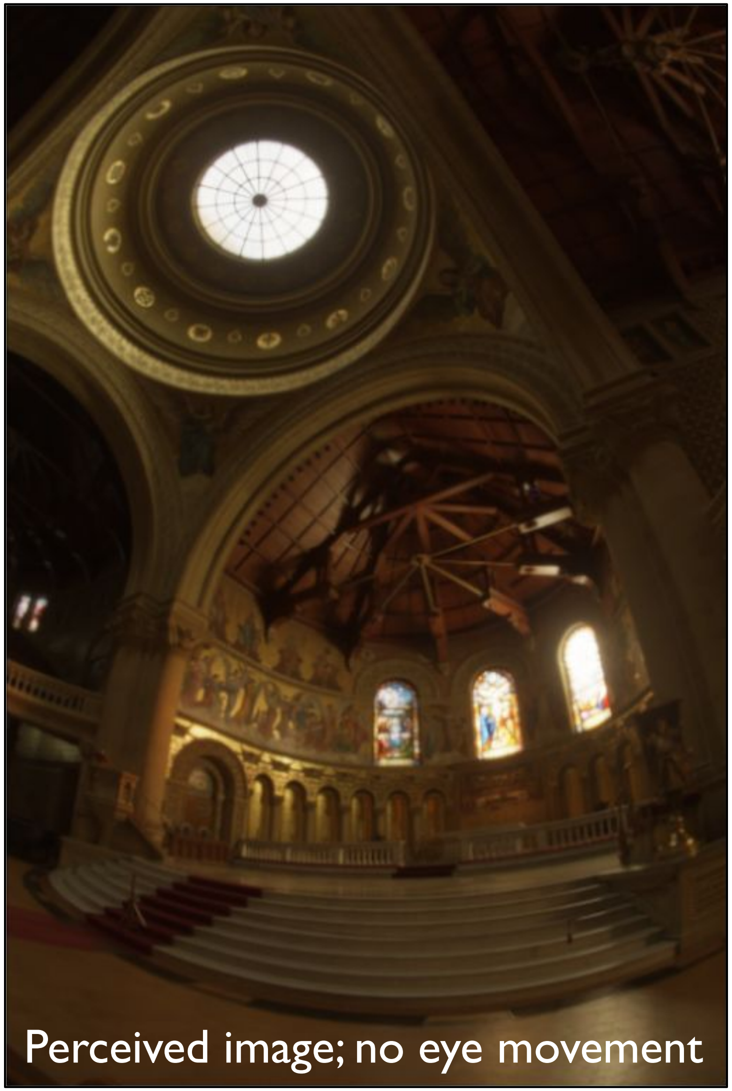
BCM vs PDM



BCM and Fixed voltage
PDM and Fixed voltage
voltage
time
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16

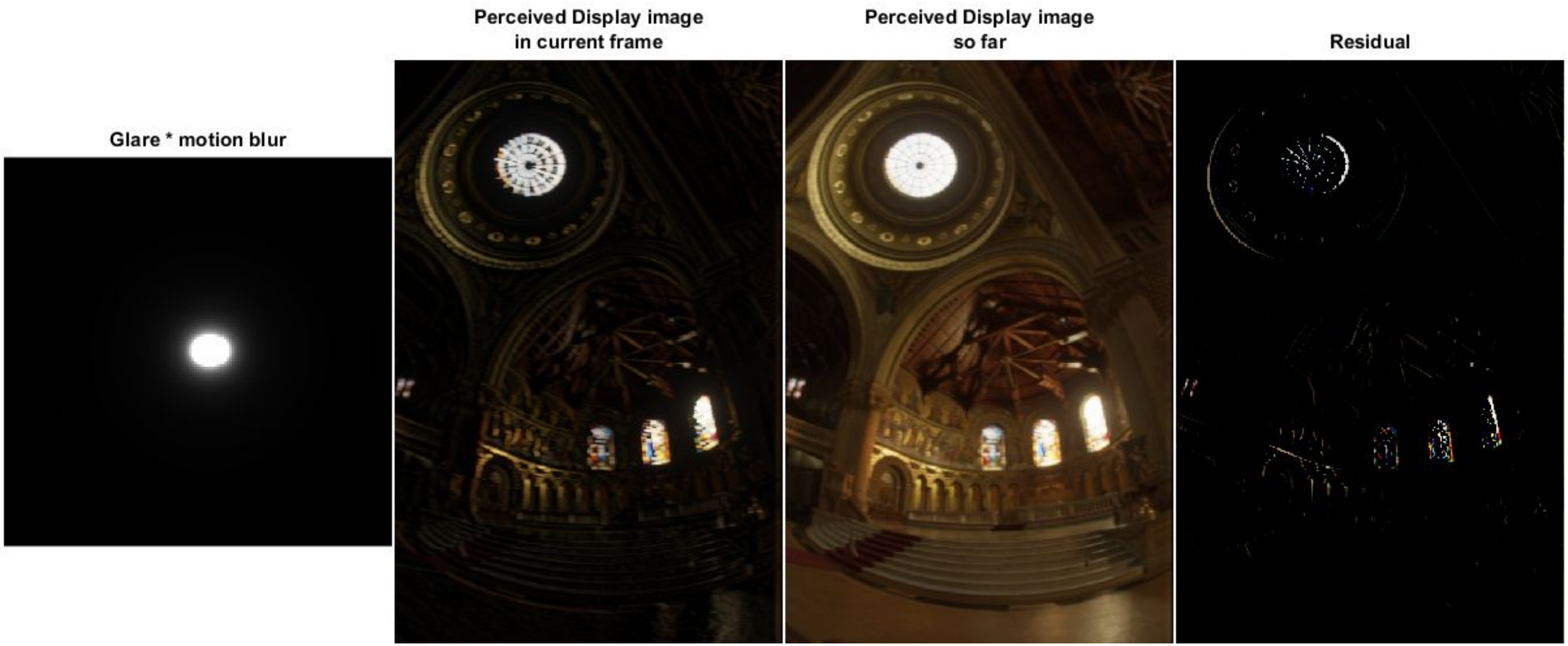
Simulations for PDM and Fixed Voltage



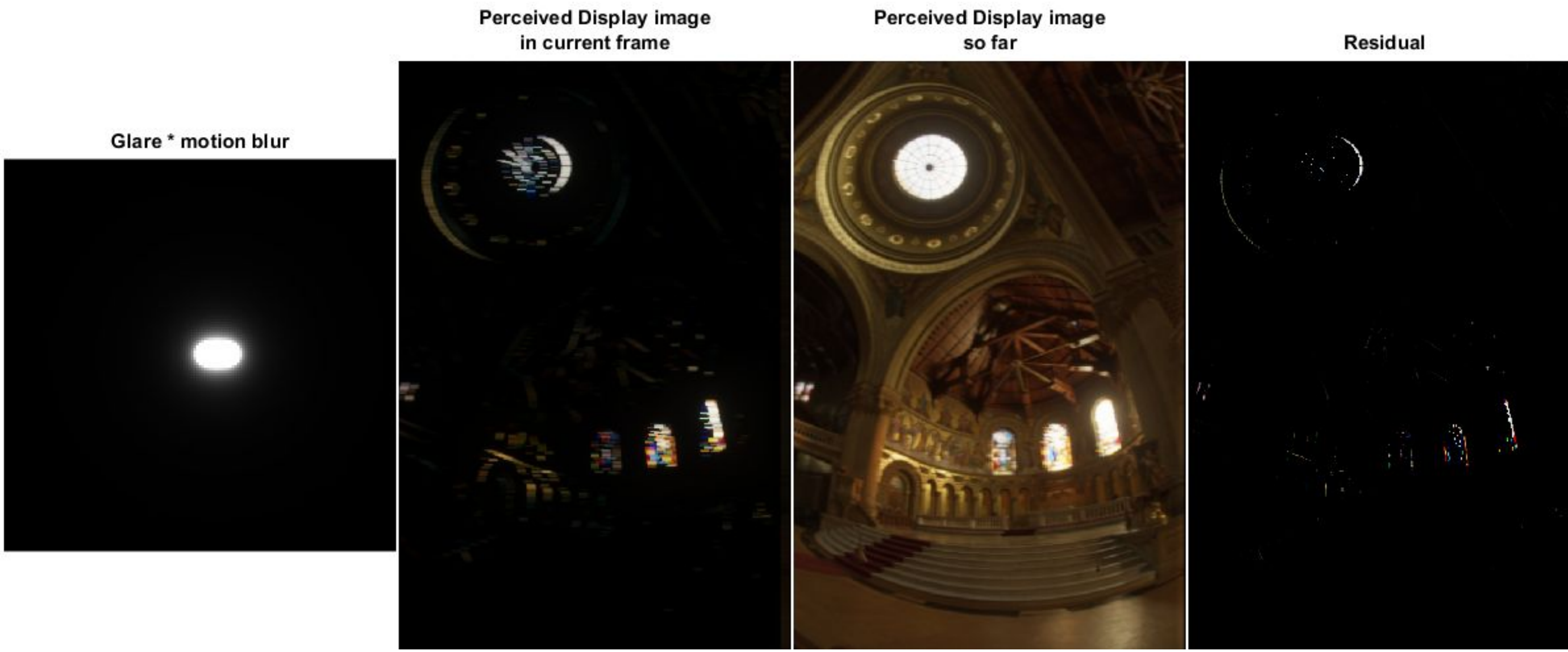


Simulations for PDM and Fixed Voltage; t = 1ms

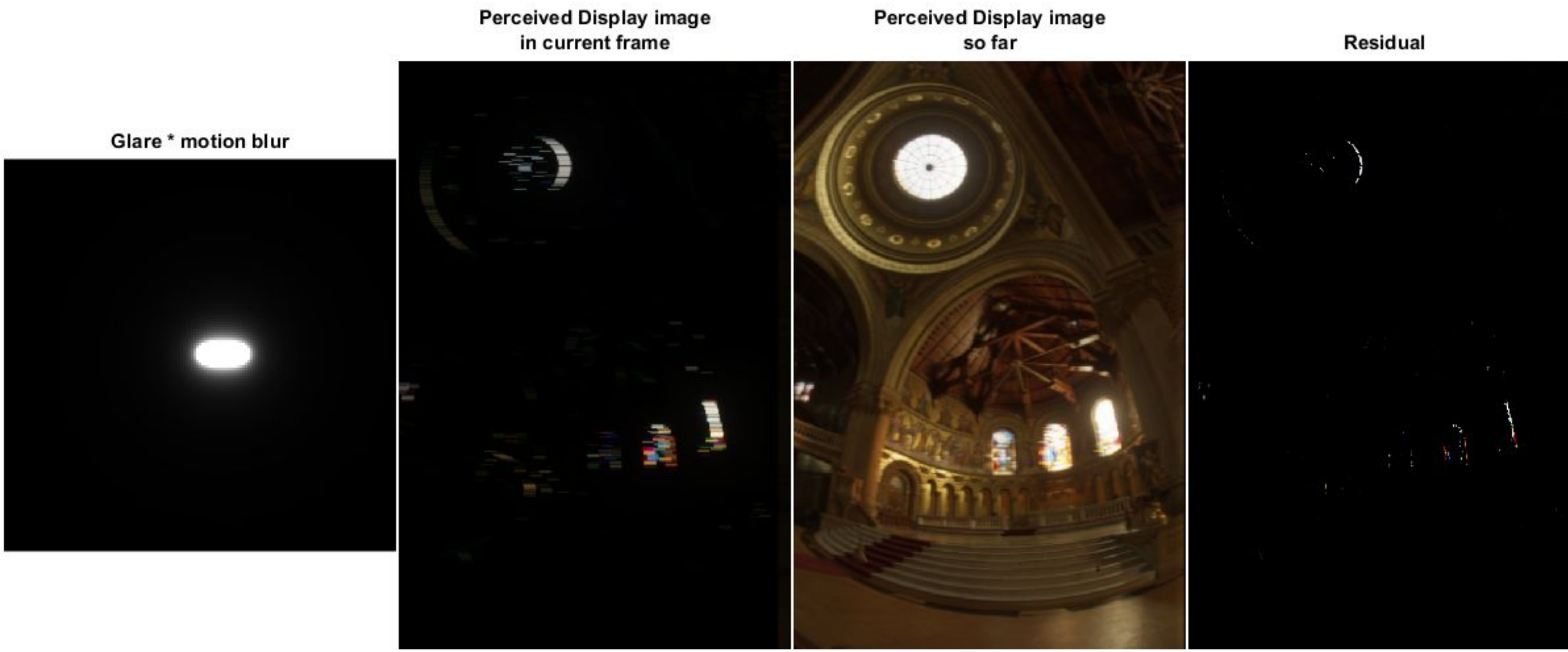
Simulations for PDM and Fixed Voltage; t = 2ms



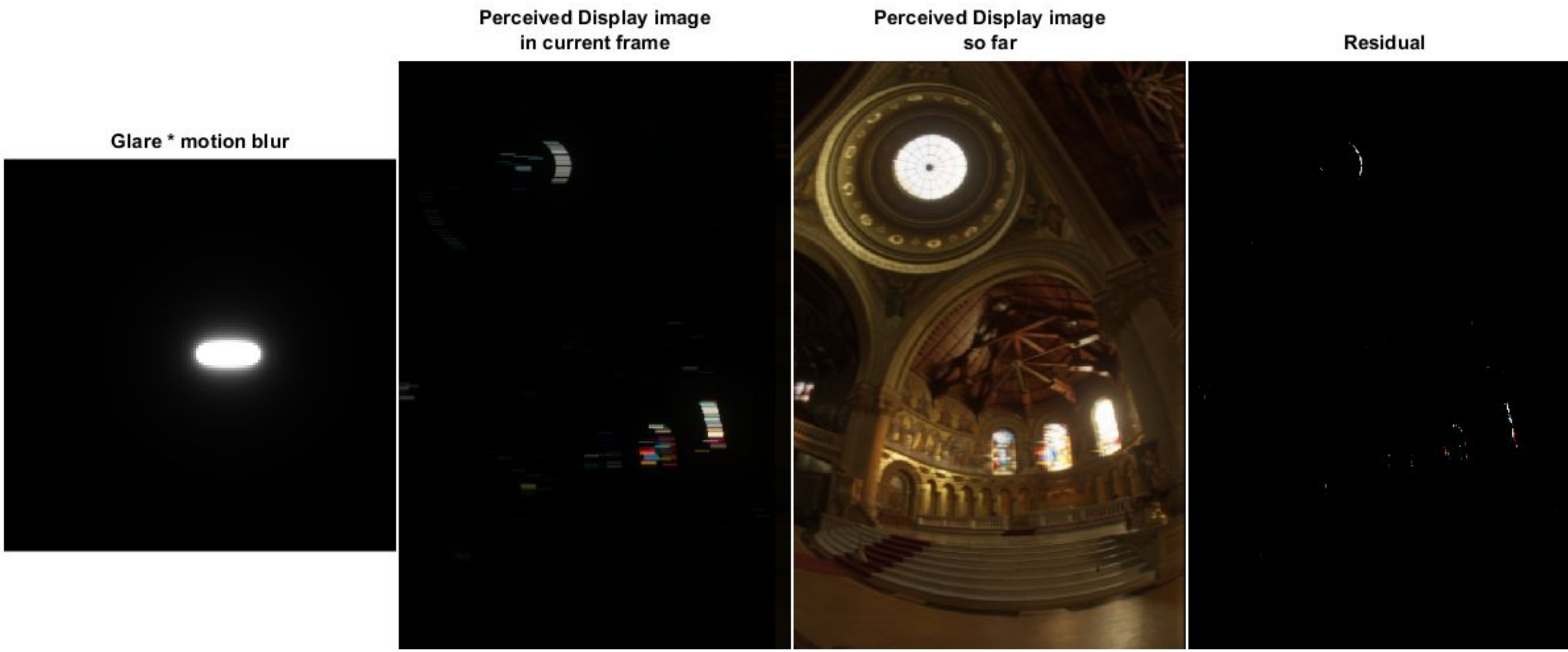
Simulations for PDM and Fixed Voltage; t = 3ms



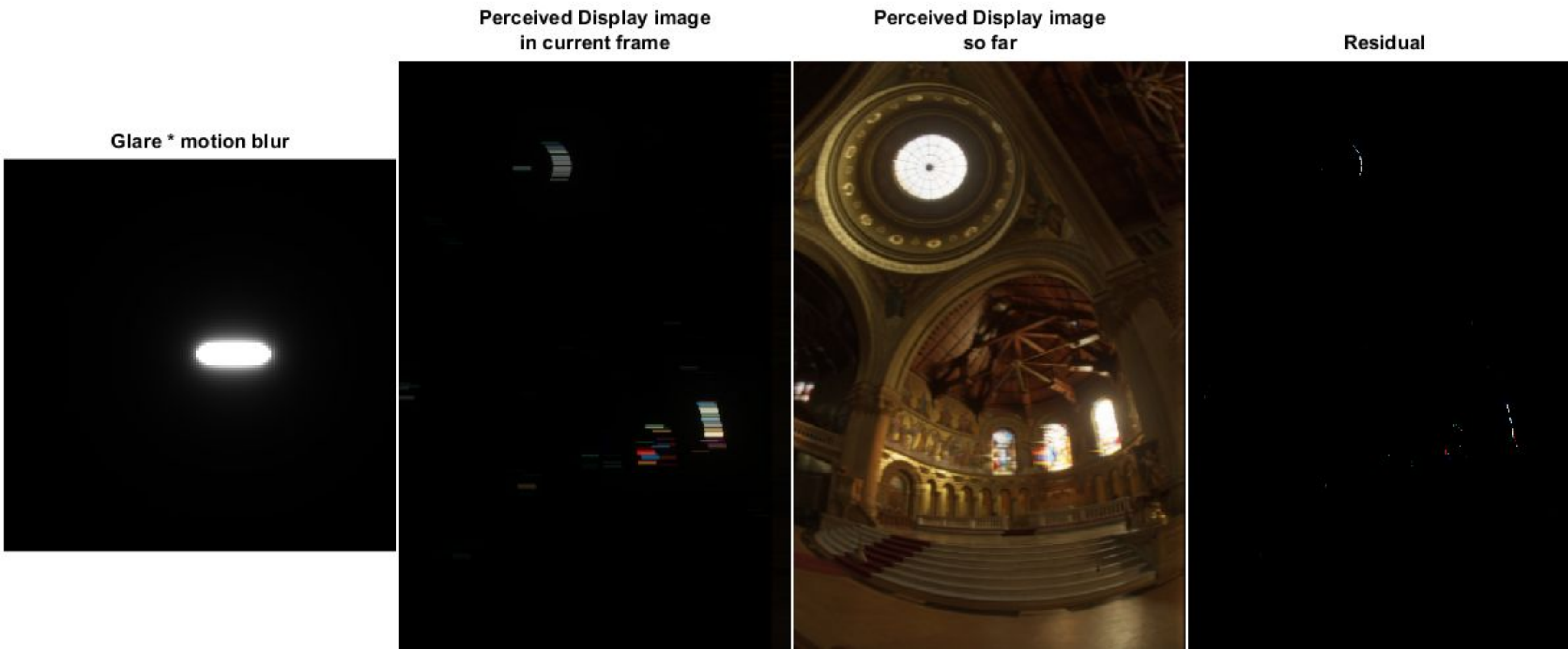
Simulations for PDM and Fixed Voltage; t = 4ms



Simulations for PDM and Fixed Voltage; t = 5ms

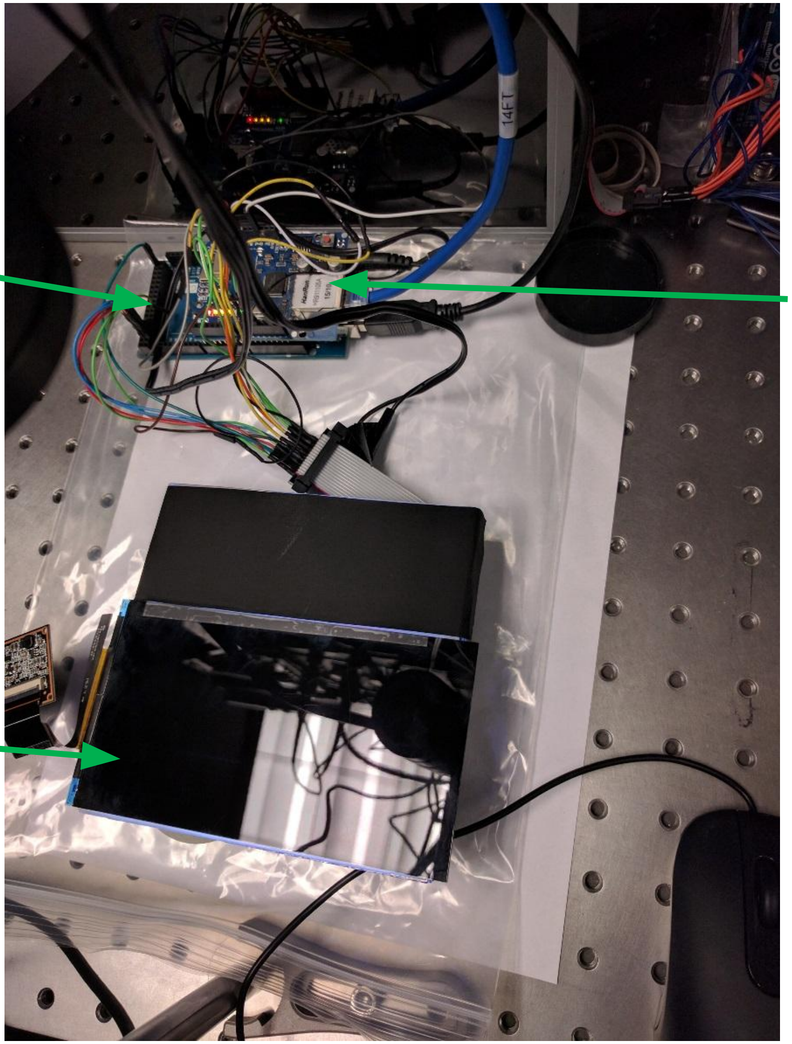


Simulations for PDM and Fixed Voltage; t = 6ms



Prototype

Arduino to drive LEDs



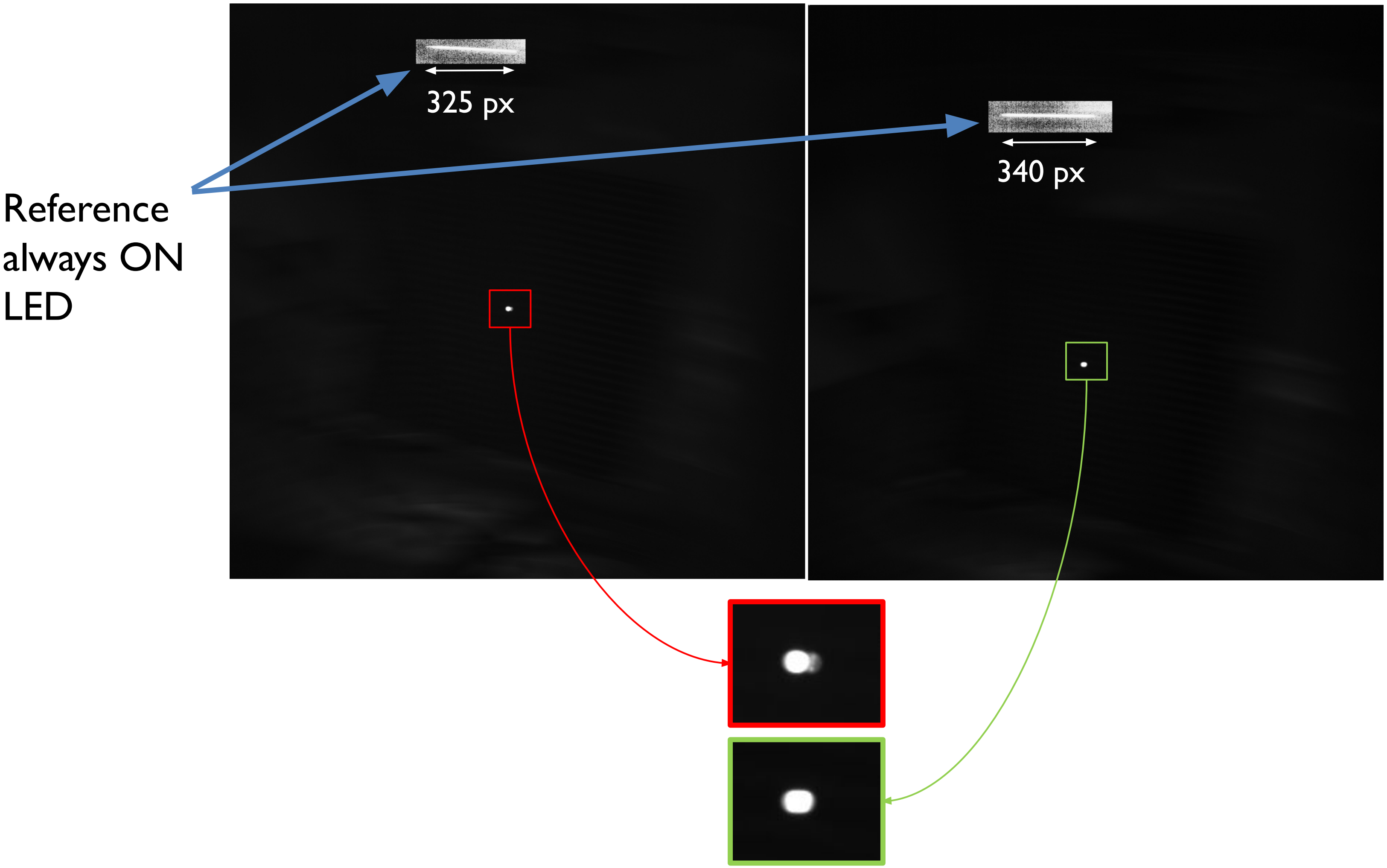
Ethernet shield for real-time update of backlight image

LCD panel and
LED array (underneath)

Memorial HDR scene

32 ms | 64 ms | 125 ms | 0.25 s | 0.5 s | 1 s

Prototype: Comparing BCM and PDM



Prototype: Comparing BCM and PDM

- Why is the difference so subtle?
  - LED array has 200 fps update
  - 1/16 scanning scheme
  - Max on time = 1/(200*16) = 0.3 ms

- Very hard to demonstrate normal/high persistence in current hardware
- Oculus Rift has around 3 ms persistence

Dynamic prototype

- Implemented dynamic update of backlight array
  - UDP
  - Data compressed, transmitted, and unpacked in Mega
- Image flickers
  - Unpacking data in Mega is expensive
  - Might improve with assembly code implementation

Limitations of current hardware

- Max Brightness of display
- LED update scheme: Static update vs 1/16
- Insufficient communication bandwidth
- Compute power

Summary

- Implemented HDR 2004 paper
- Simulated perceived images for HDR content (glare modelling)
- Demonstrated spatially varying persistence in simulations and prototype
- Developed methods to factorize target HDR image into dual layer modulation for various LED illumination schemes
- Implemented dynamic update of LED array

Future work

- Building better LED array addressable with an FPGA
- Explore variable voltage
- Eye-tracking:
  - Control maximum persistence
  - After-images
- Color optimization; RGB backlight
- Light shaping

Thank you