RADIANT VISION SYSTEMS

Latest in Virtual Reality Display Optics and Quality

Eric Eisenberg | October 15, 2024

Today’s Speaker

Eric Eisenberg
Director of Optics and Test Engineering

Eric Eisenberg has spent years developing solutions to help display manufacturers and their upstream suppliers ensure quality and improve efficiencies in both design and production. With extensive hands-on experience incorporating imaging and optical technology into diverse applications worldwide including AR/VR/MR, he has a deep understanding of the technical considerations required for successful implementation. Prior to joining Radiant, Eisenberg held Optical Engineering roles at Lockheed Martin and Terabeam. He is the inventor of multiple patents and has a B.S. in Laser and Optical Engineering from the Oregon Institute of Technology.

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A Konica Minolta Company

Light & Color

Automated Visual Inspection

Global Support

Today's Topics

- Current VR Market Landscape
  - Market demand drivers
  - Application drivers
- New Optics and Technologies
- VR Display Quality Challenges
- VR Measurement Solutions
- Summary and Q&A

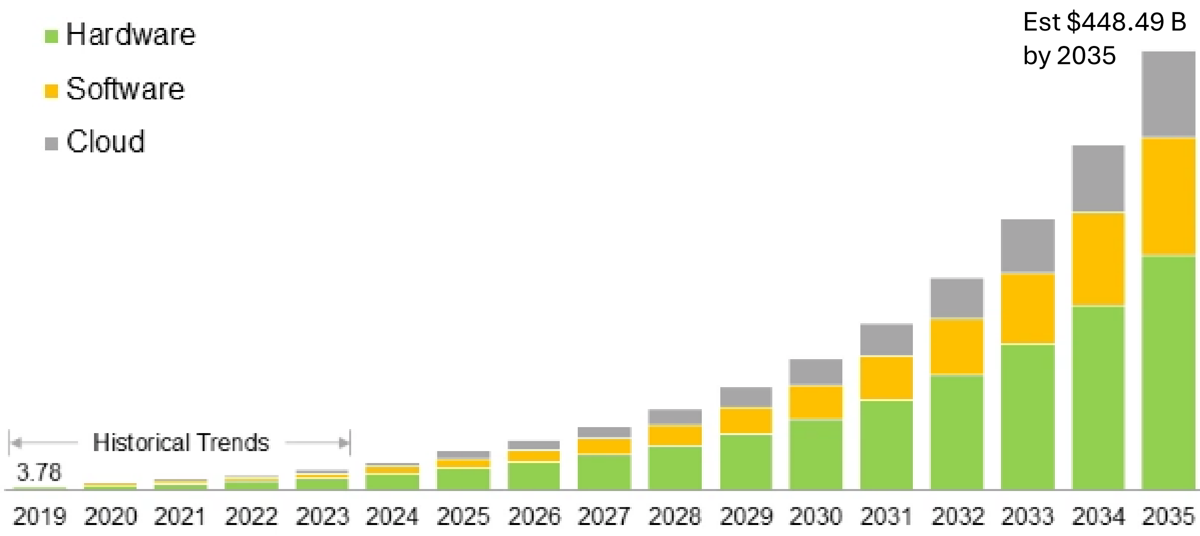
Current VR Market Landscape

Latest Trends and Applications Driving Growth

Virtual Reality Market Outlook

- Currently estimated US$22-25B 2023 global revenue
- Predicted growth ~29% CAGR to US$244B by 2032*
- 10.8 million VR devices sold in 2023

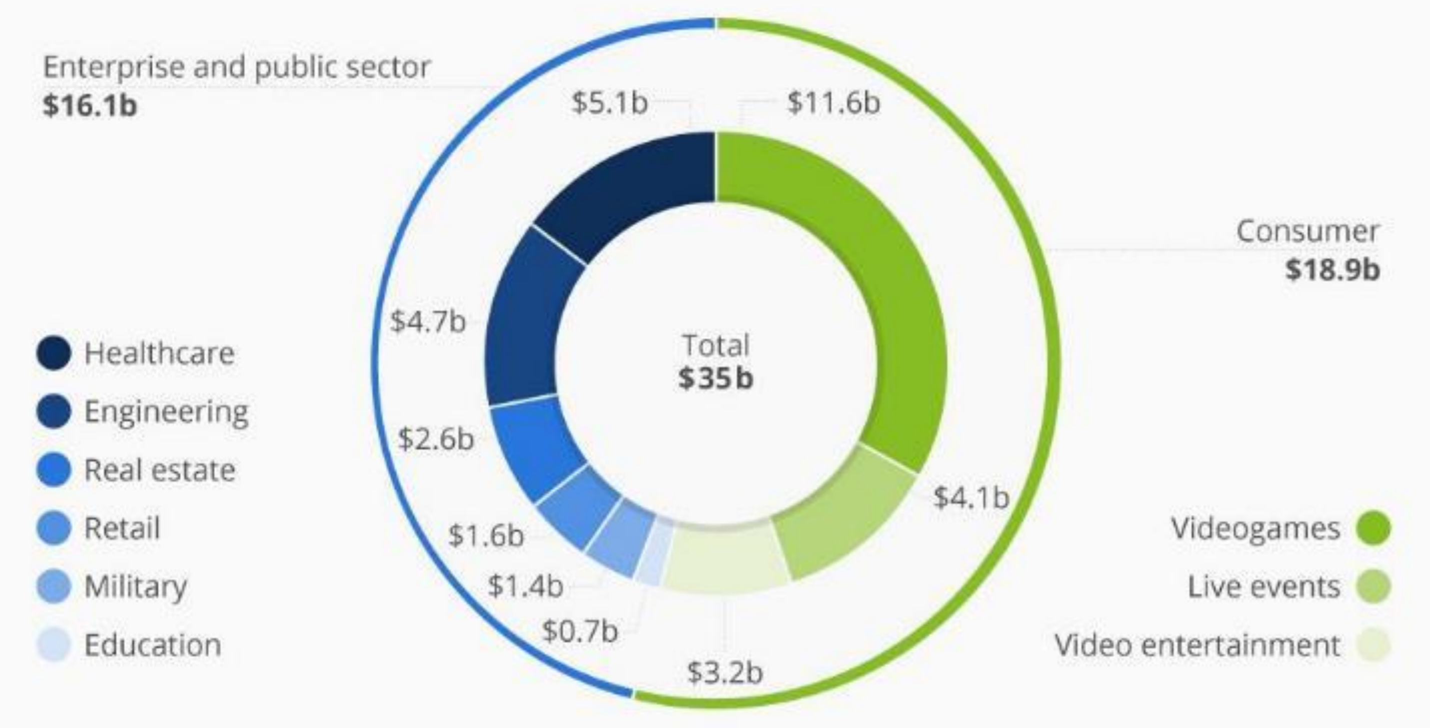
Virtual Reality Market by Type of Component



*SOURCE: Fortune Business Insights
IMAGE: Roots Analysis

Virtual Reality Applications by Industry

Predicted market size of AR/VR software for different use cases in 2025*



*Base case scenario
SOURCE: Goldman Sachs Global Investment Research
Image Source: Statista

VR in Medical/Healthcare Industry

Training

- Anatomy
- Skills training
- Simulated procedures
- Patient interface simulation

Surgery & Treatment

- Surgical prep/practice
- In surgery
- Robotic surgery
- Operative and post-operative services

Rehabilitation

- Rehabilitation
- Physical therapy

Pain Management

- During treatments
- Chronic pain
- Stress reduction

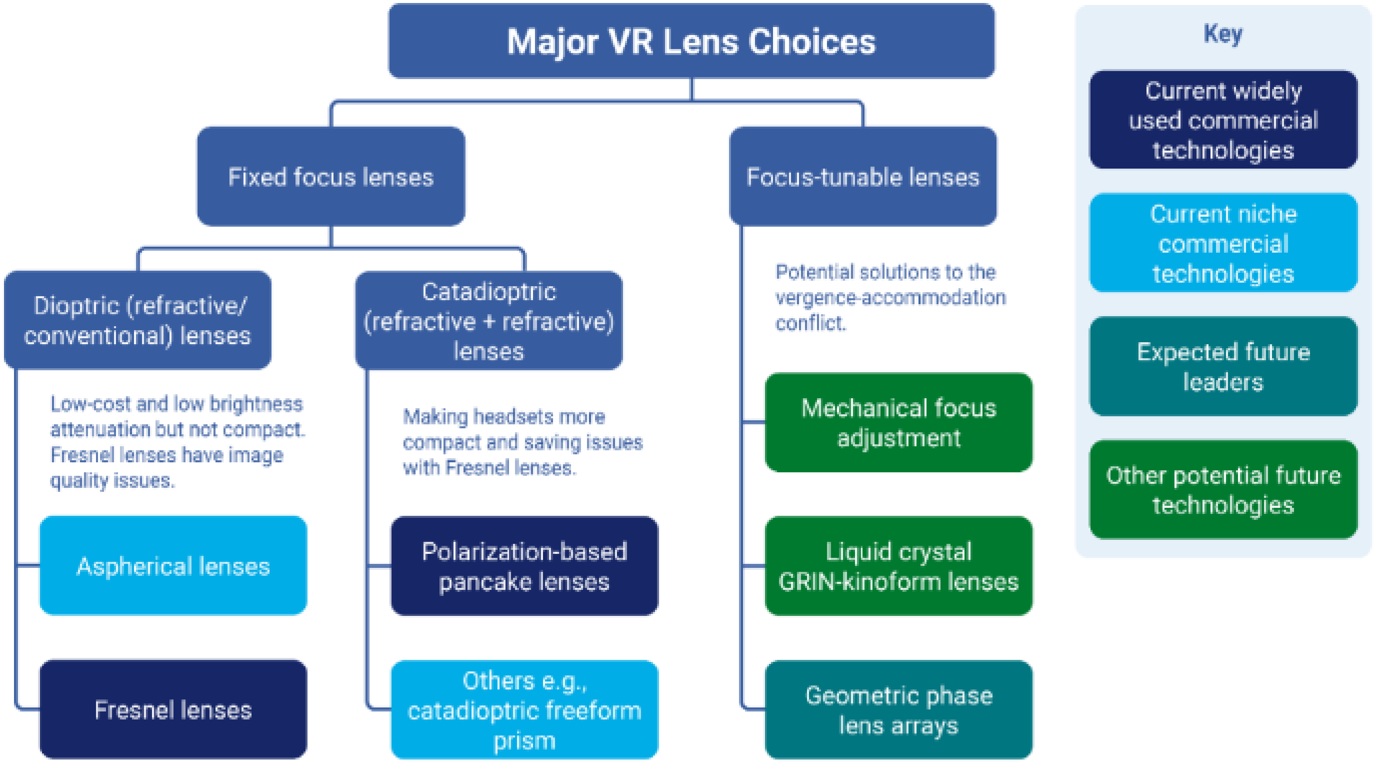
Mental Health

- PTSD
- Anxiety
- Phobias




New Optics & Technologies

VR Optics Landscape



SOURCE: IDTechEx

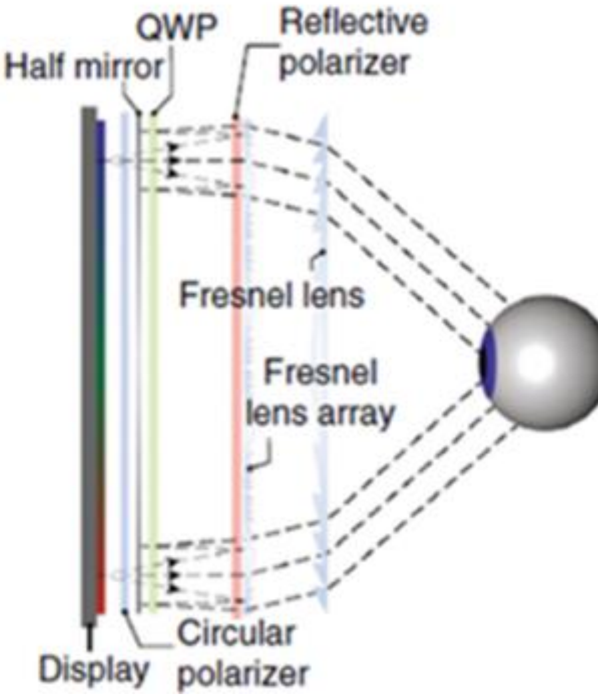
VR Optics "Holy Grail"

- User comfort / Low weight / not bulky
- FOV to match human vision
- Image clarity across the FOV
- Minimize vergence-accommodation conflict
- Energy efficiency
- Light efficiency
- Low cost

Fixed Focus Lenses: Fresnel

Pros
• Affordability
• Wide FOV

Cons
• Prone to image distortion (e.g., “God rays,” chromatic aberration
• Light cannot be focused on a single point
• Trade-off of beam focus and contrast vs. image sharpness



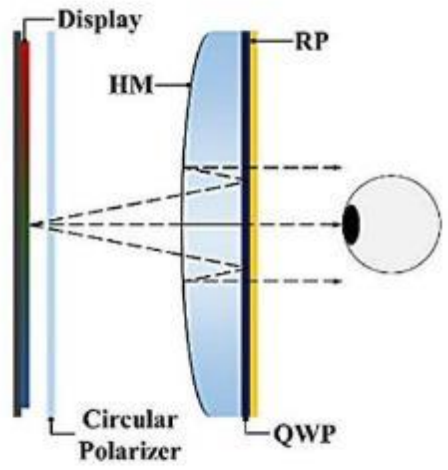
Fixed Focus: Pancake Lenses

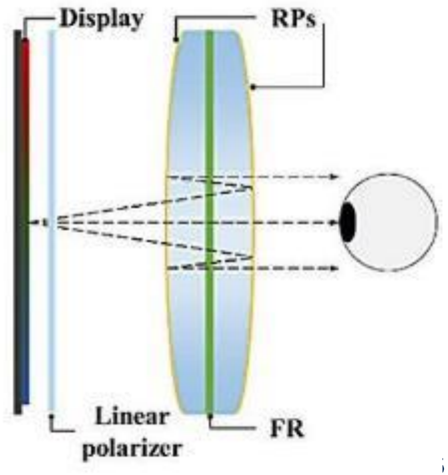
Pros

- Thinner and lighter
- Energy efficient, less processing power required
- Visual quality – eliminates “God rays” and chromatic aberration
- FOV closer to human vision

Cons

- Smaller FOV compared to Fresnel lenses
- Low light efficiency
- More prone to ghosting
- More expensive





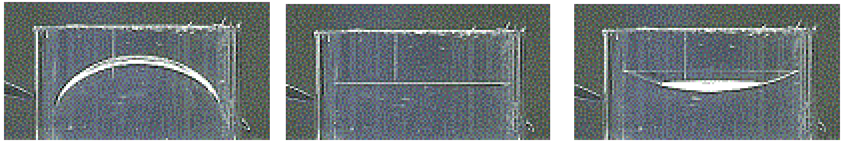
Foveated Rendering

- Focus follows human gaze (eye tracking) to mimic foveal region of the eye
- Multi-focal, varifocal, and foveated optics create a need to measure more than 1 focal distance or region with a single measurement system
- Focal distances may dynamically change over a wide range

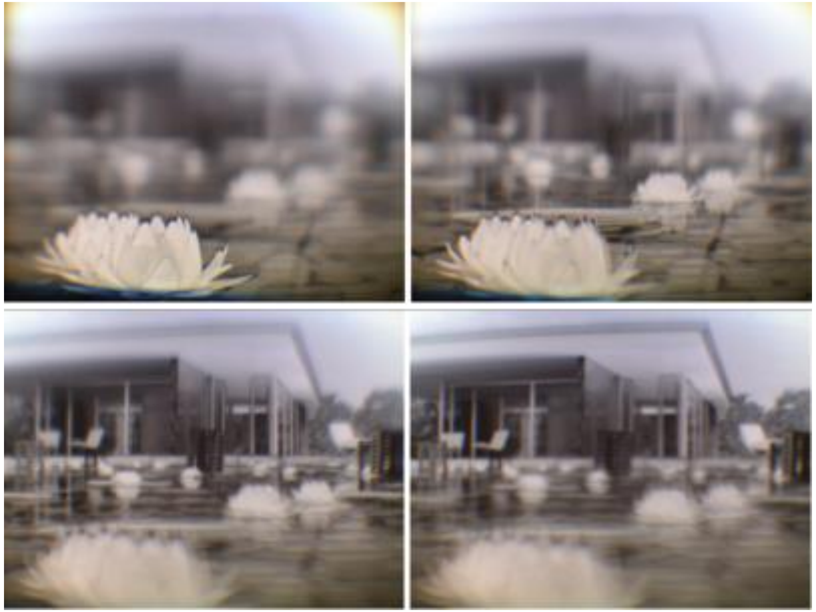
Example of foveated optics from Varjo using two displays and a rotating combiner to adjust focal point. Source: RoadtoVR

Variable Focus: Liquid Lenses

- Principle: changing the shape of a liquid changes its refractive properties
- Electrical charge is applied to change lens curvature



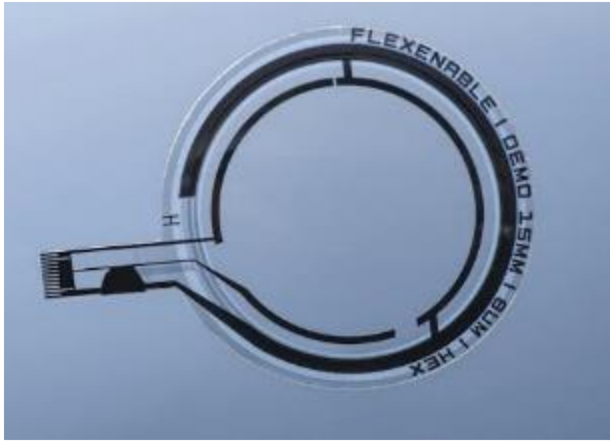
6 mm liquid lens at different voltages, from convex to flat to concave. (Image source: Phillips/Phys.org)



Example of images using a liquid lens to produce 'sweeping' focus (Image Source)

Variable Focus: Many Options

- Mechanical systems, e.g., move the lens closer/further from the wearer's eye. Downside: adds weight and volume to headset
- Alvarez Lens, e.g., using Pancharatnam–Berry phase LCD lenses stacked together to create a set of discrete focal lengths.
- Light field displays
- Ultra-thin LCD lenses on plastic substrates →
- Polarization-based optics
- Electrically tunable lenses
- Piezoelectric-actuated tunable lenses – transparent fluid encapsulated by two elastomeric membranes



(Image © Flexenable)

Additional Optics Challenge: Prescription Vision

- Roughly 65% of people wear prescription lenses of some kind – 4.2 billion globally
- Currently AR/MR headsets manufactured with custom lenses
- Currently for VR headsets:
  - Wear prescription glasses within headset
    - *Adds weight, discomfort, fit issues*
  - Purchase third-party custom inserts

Image: VRLensLab

The Challenges of VR Display Measurement

Latest methods to address the visualization parameters of VR devices

Fundamental VR Display Quality Challenges

Near-eye displays (NEDs) are:

- Viewed *extremely close up*
- Viewed *within head-mounted devices* (goggles, headsets, etc.)
- Viewed *by the human eye* (luminance and color perception)

→

- Defects are more noticeable
  - Uniformity issues, dead pixels, line defects, inconsistency from eye to eye
- Displays require higher PPI
  - Increases realism, but requires higher-resolution measurement device

VR Device Metrology Requirements

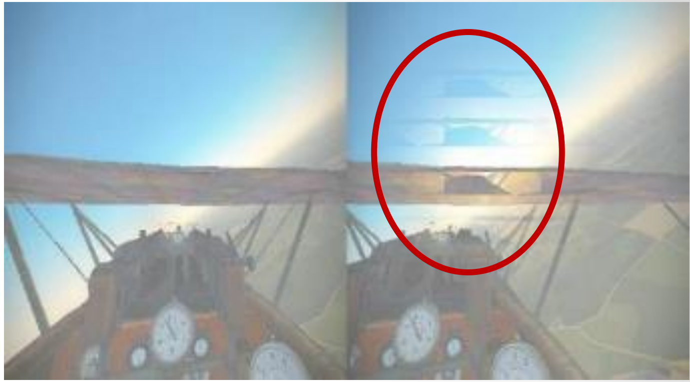
Embedded Displays

Immersive displays viewed with *wide FOV*

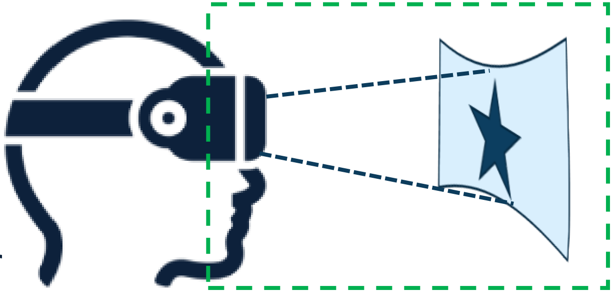
- With display in fixed position, horizontal FOV leveraged for immersion...
  - But requires wide FOV optics for complete evaluation
  - Display testing from position of the human eye while capturing full horizontal angular FOV
- Some VR devices replicate human binocular FOV (approx. 120° H),
  - Requiring equivalent measurement FOV
- Light & Color Measurement to match human visual perception

Visual Quality Issues

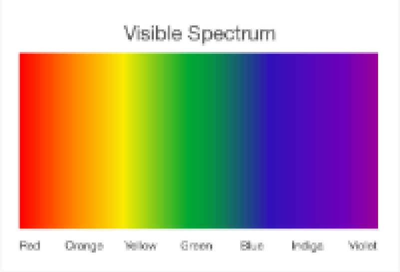
- Blurring
- Distortion
- Diffraction effects
  - Color separation
- Dimming
- Ghosting / double images
- Color non-uniformity
- Brightness non-uniformity
- Defects
  - E.g., pixel defects, lines
- Poor contrast
- Dual eye inconsistency



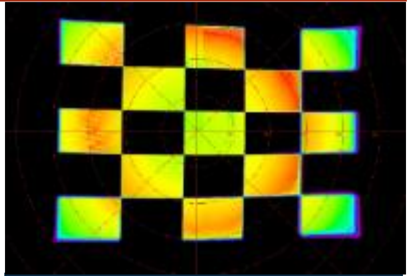
VR Displays & User Perception



Emulate user's visual perception of:

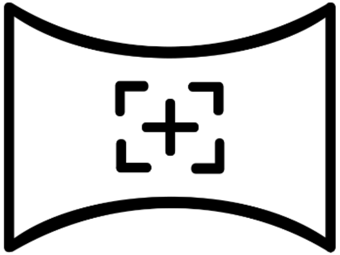


Visible Light



Spatial Images

Within the context of:



Angular FOV

Near-Eye Position

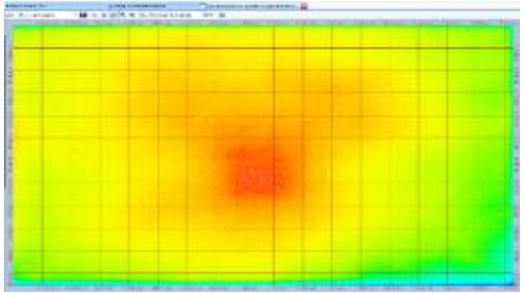
Human Vision Characteristics

Human Vision

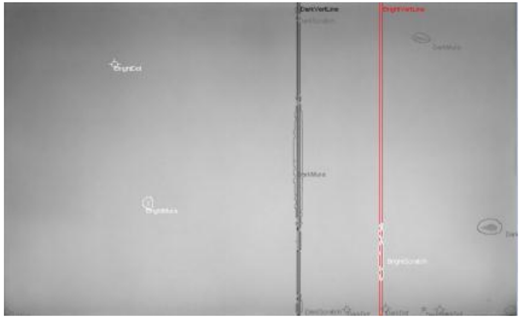
- Perception of light and color
- Size of human pupil
- Pupil location / position
- Human FOV
- Human visual acuity (resolution)
- Human foveal area (focus)
- Binocular vision and interpupillary distance

VR Display Measurement

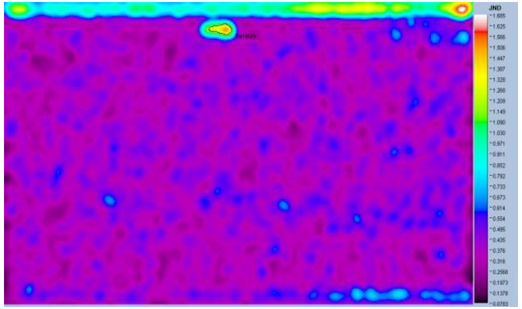
1. Brightness & Color
2. Pupil Location and Field of View (FOV)
3. Focus & MTF (Modulation Transfer Function)
4. Distortion
5. Display Resolution & Emissive Displays



Luminance Uniformity



Pixel and Line Defects

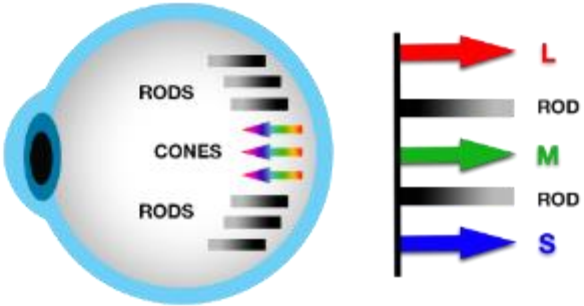


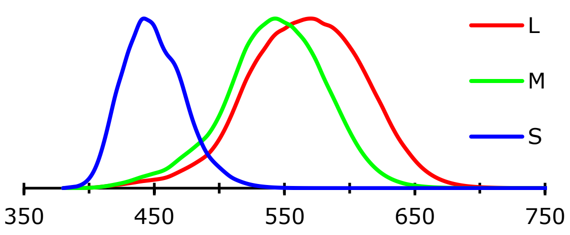
Mura Detection and JND

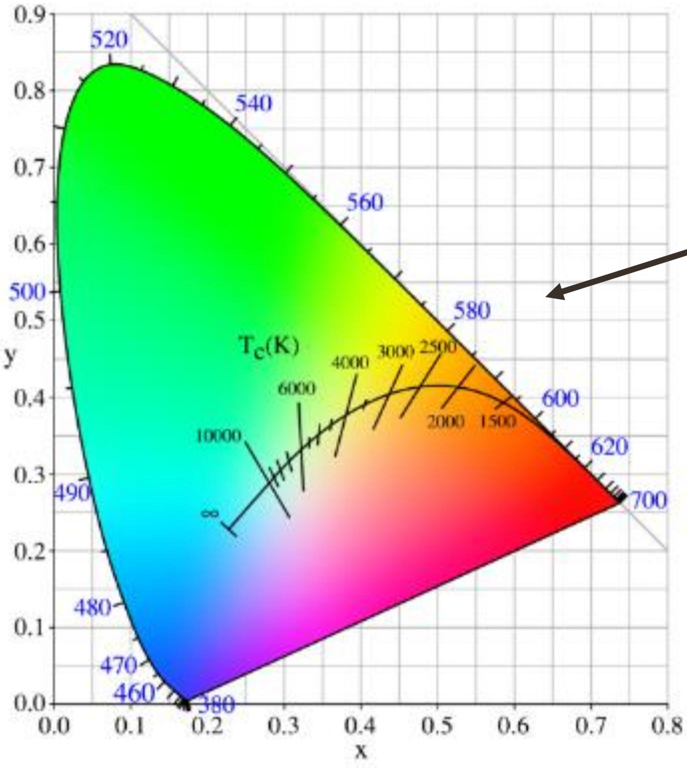
Brightness & Color

Human Perception of Color & Light

The human eye is sensitive to **COLOR** and **BRIGHTNESS**



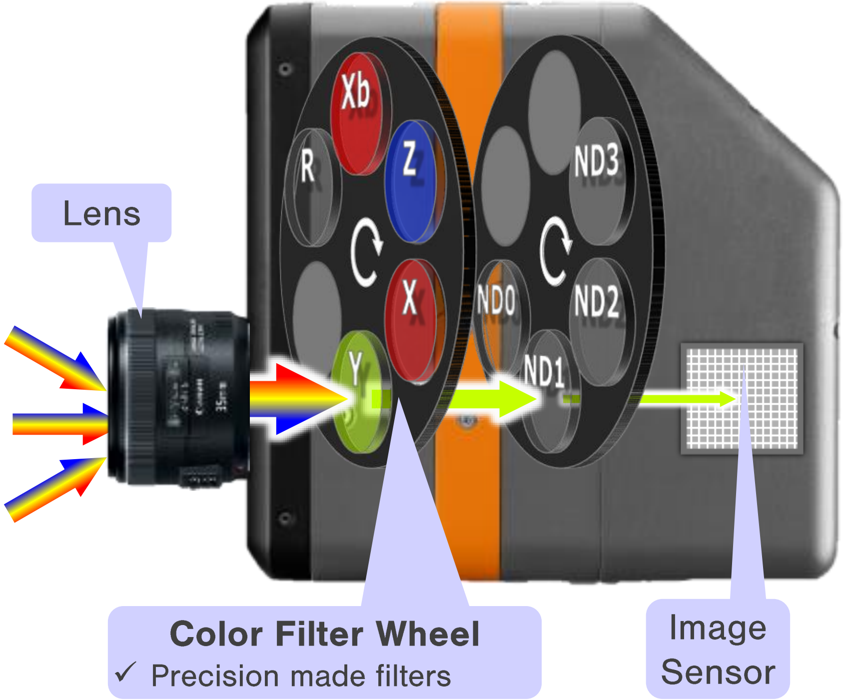




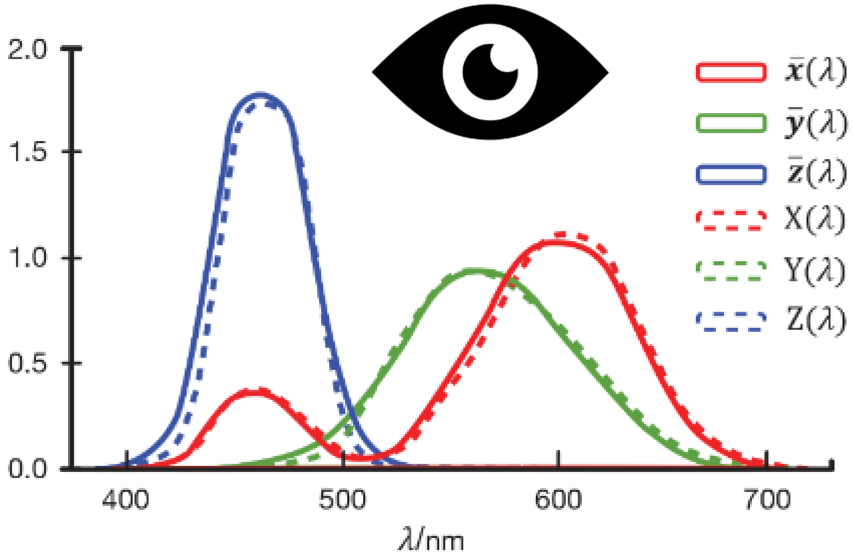
CIE Color Space:
Total visible colors (to the human eye)

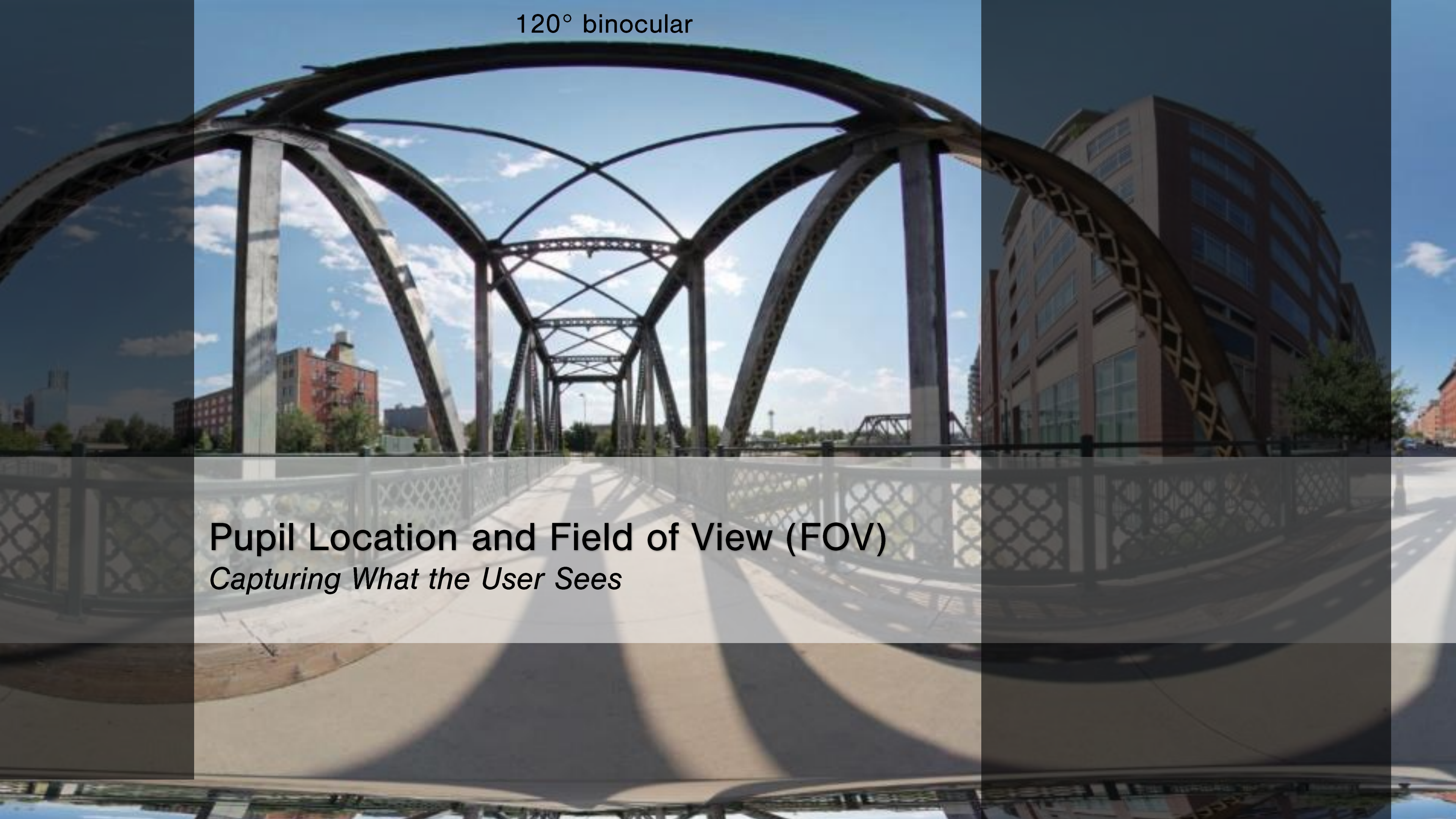
CIE Color Chart
(C_x, C_y)

Photometry & Colorimetry to Match Human Vision



ProMetric® Imaging Colorimeter





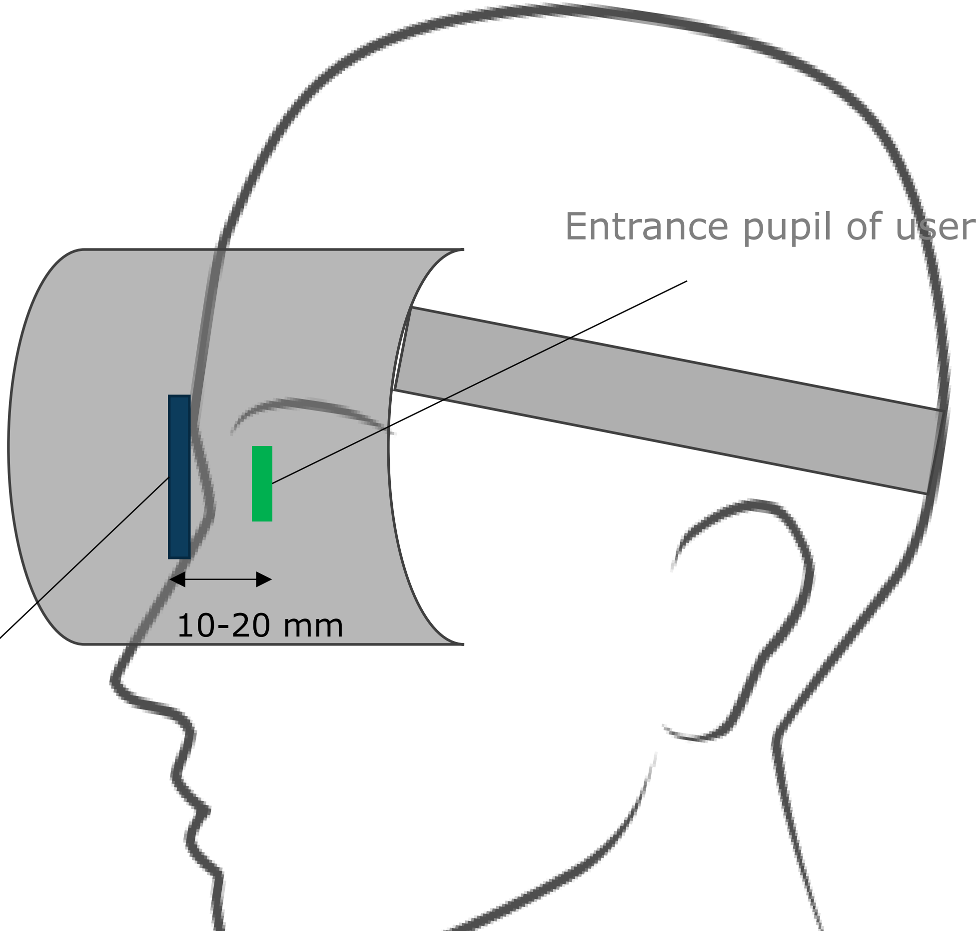
Pupil Location and Field of View (FOV)

Capturing What the User Sees

Pupil Location

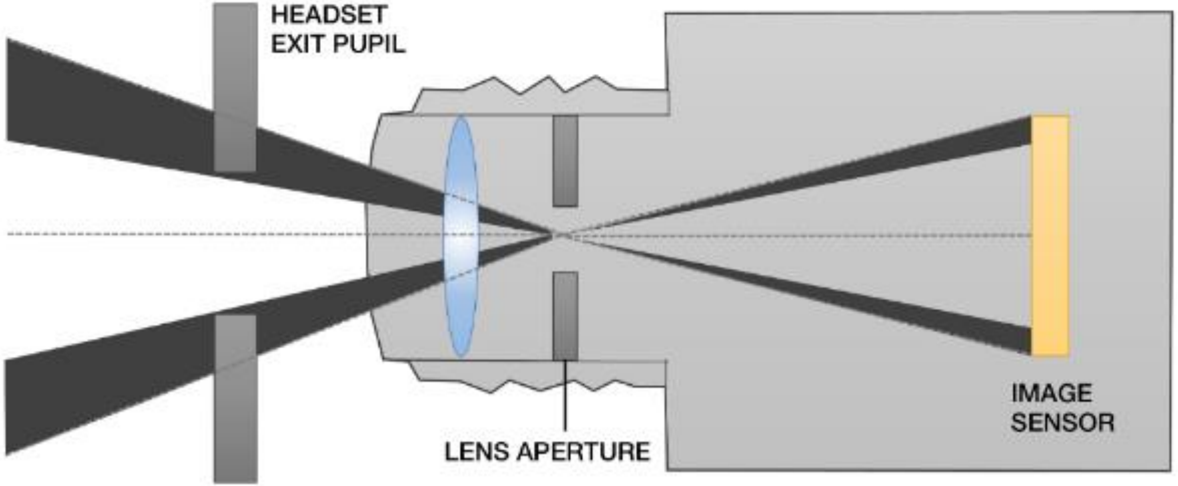
Importance of the Entrance Pupil

- Intended entrance pupil **position** (position of the human pupil) relative to the location of the exit pupil of the headset (headset eyepiece)
- Pupil **size** (aperture)
  - Average human pupil ~ 2-8 mm diameter



Solution: Match Human Entrance Pupil

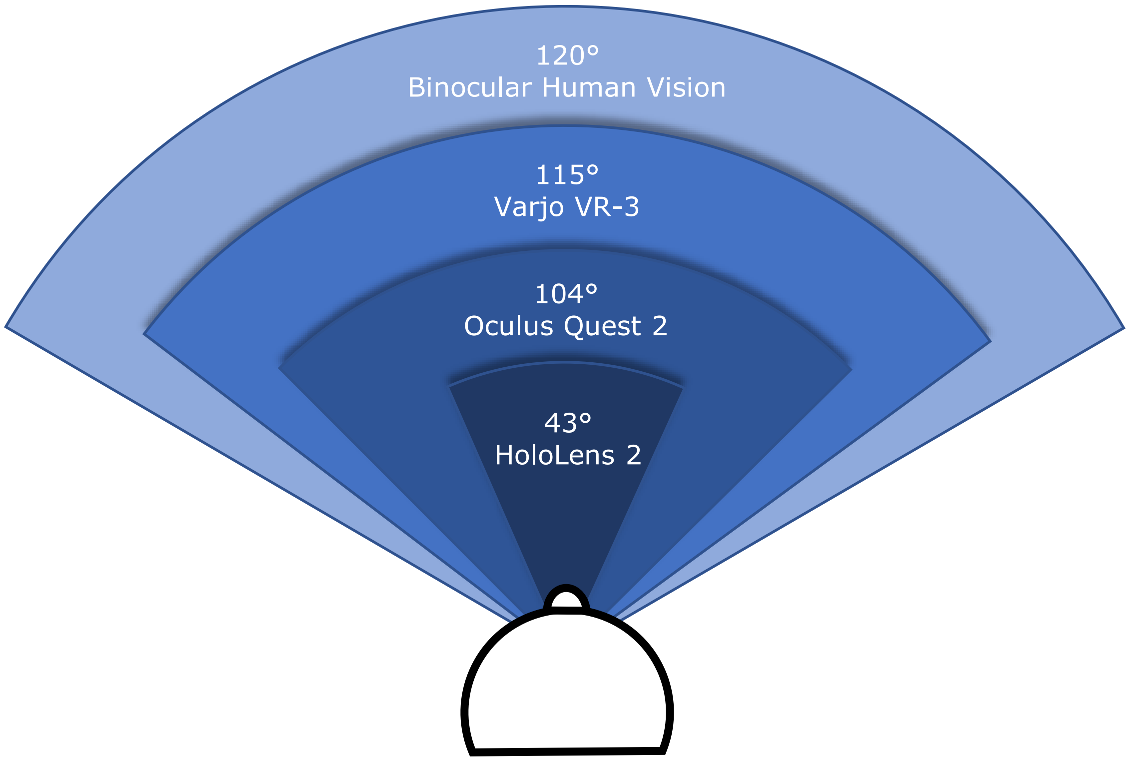
- Buried entrance pupil (aperture) of the imaging system results in “knothole effect”



Far from knothole – FOV is clipped

Close to knothole – wider FOV can be seen

Angular Field of View (FOV)

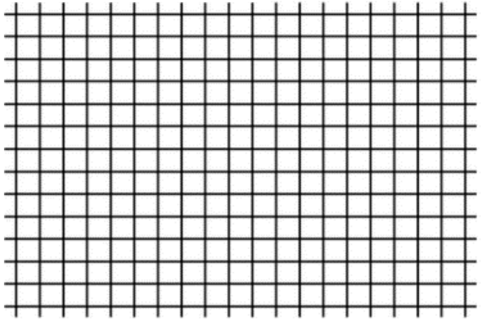


- Capture virtual elements (and their constituent light & color values) in their true angular positions
- Capture potentially wide FOVs in a single image
- Emulate human FOV of immersive display
- VR & AR devices all have different requirements

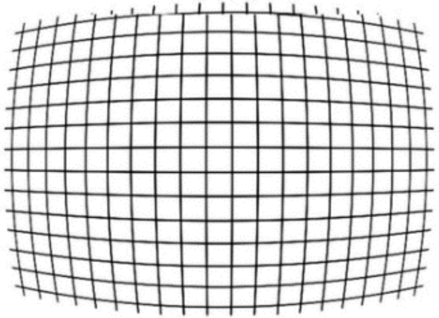
Distortion & Ghosting

3. Distortion

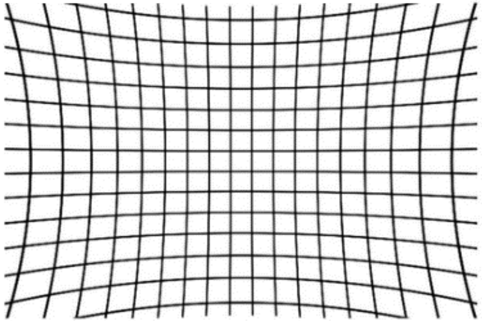
Normal



Barrel Distortion



Pincushion Distortion



Mustache Distortion

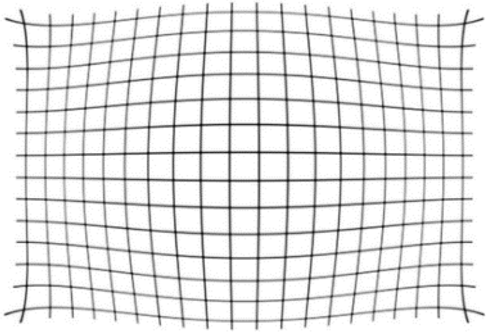
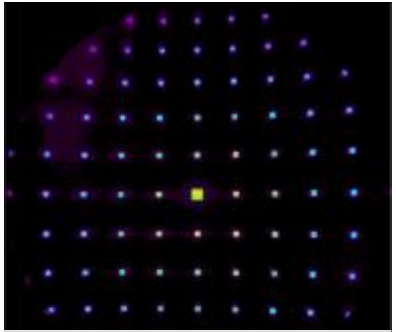


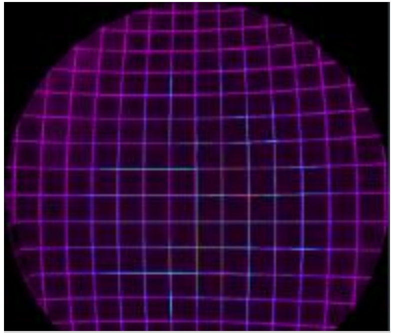
Image Source: International Journal of Advanced Robotic Systems, DOI 10.1177/1729881419896717

Solution: Distortion Correction

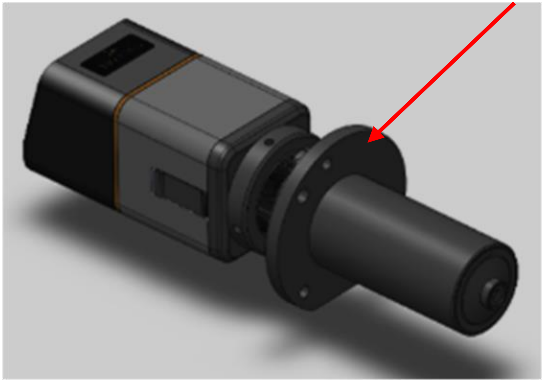
- Combine software distortion calibration with mechanical datum
- Calibration performed with system installed on datum, so it remains valid when deployed in a fixture mechanically compatible with the datum



Distortion Dot Grid



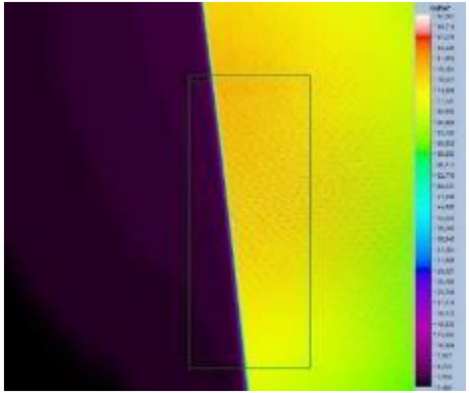
Distortion Line Grid



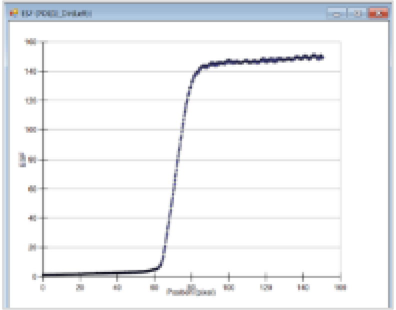
Focus & MTF

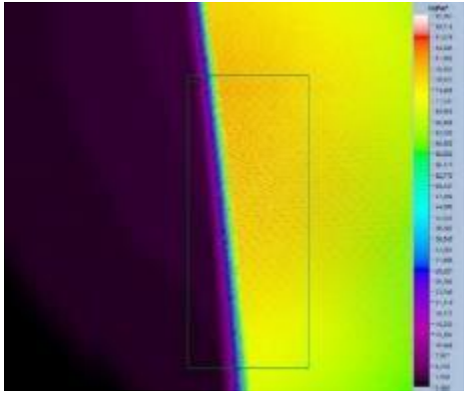
Requirement: Electronic Focus

- Manual focus is imprecise and inconsistent
- Poor focus introduced by the imaging system impacts measurement accuracy

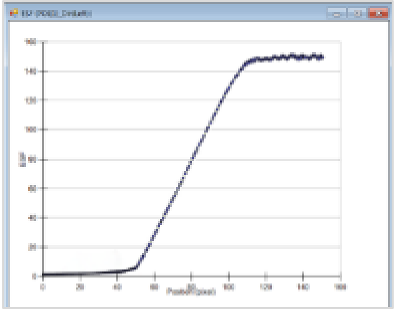


In-Focus





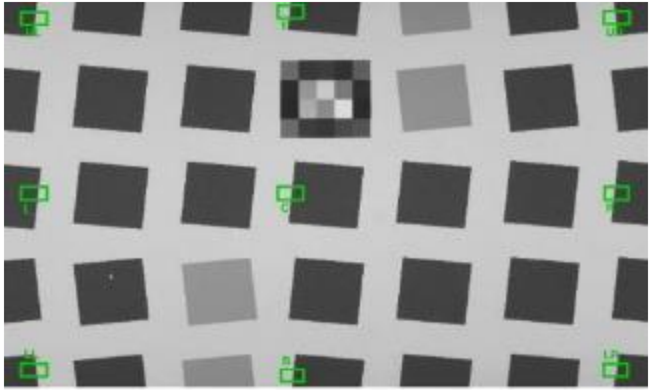
Poor Focus



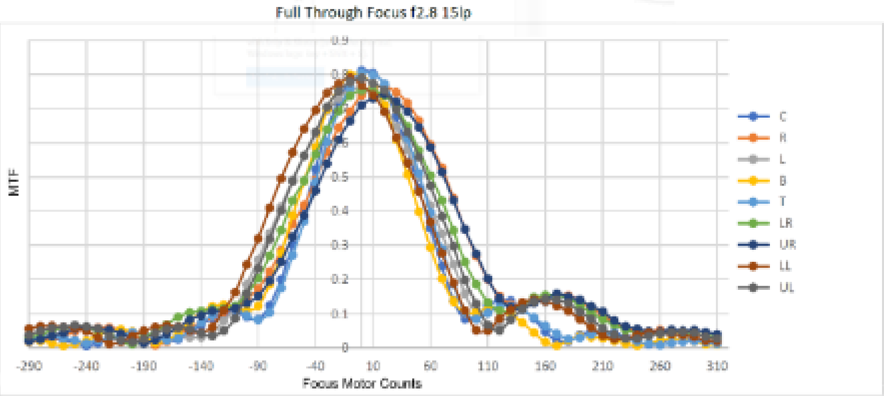
Poor focus on edge impacts MTF result.

Focus

- Through-focus MTF testing finds best focus for each region of the display (based on MTF)
- Lens focus is iterated to record MTF at each focal distance
- No effective way to test with manual lens
  - Range of focal distances too great
  - Optimal focus of each region unknown
  - Each focus change significantly increases measurement time and risk of error

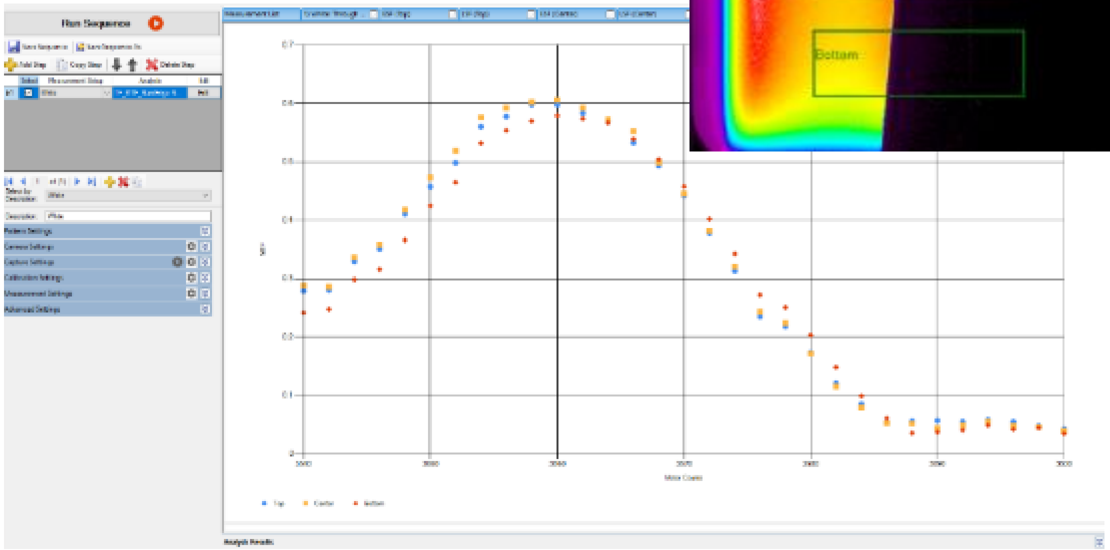


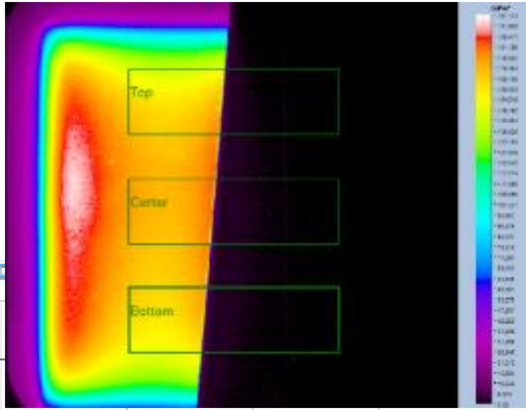
Key			
	UL = Upper Left	T = Top	UR = Upper Right
	L = Left	C = Center	R = Right
	LL = Lower Left	B = Bottom	LR = Lower Right



Electronic Focus: Through-Focus MTF

- Through-focus MTF test using XRE Lens system with electronic focus lens
- Lens barrel does not change length, so iterative measurements can be taken in rapid succession
- Focus changes are automated via software
- 30 focus settings for each measurement region completed in seconds

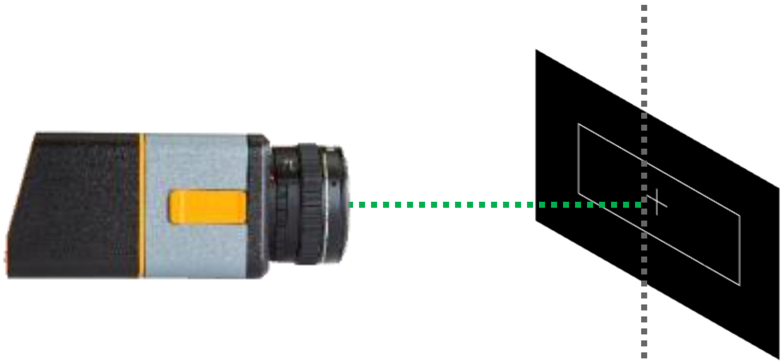




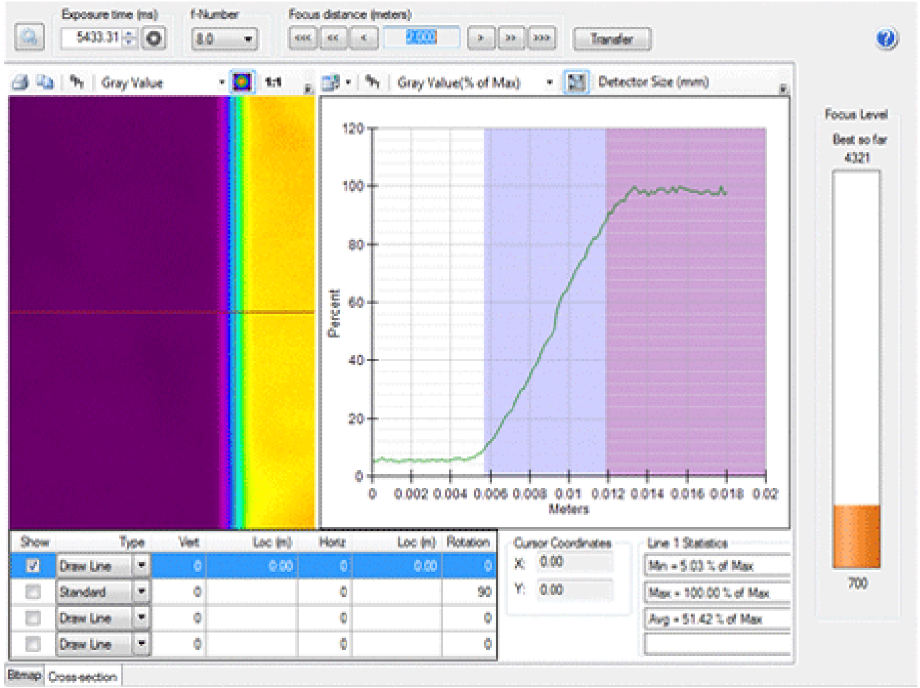
Measurements captured using the XRE Lens system and TrueTest™ Software from Radiant

XRE Lens: Electronic Focus

- Focus adjusted in software until best focus (crisp edge) is found



ProMetric® Imaging Photometer

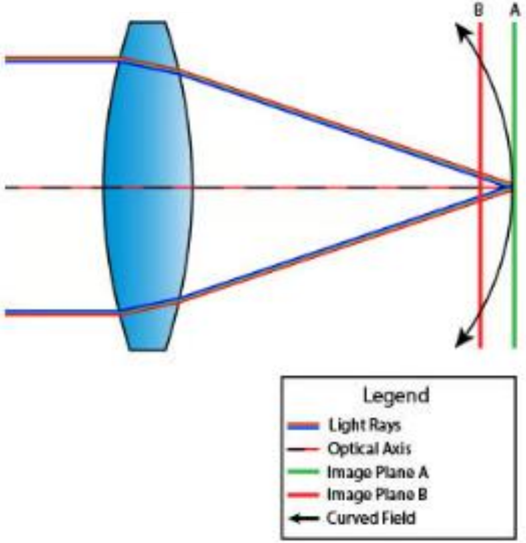


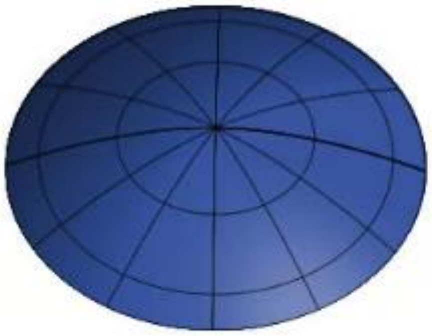
TrueTest™ Software

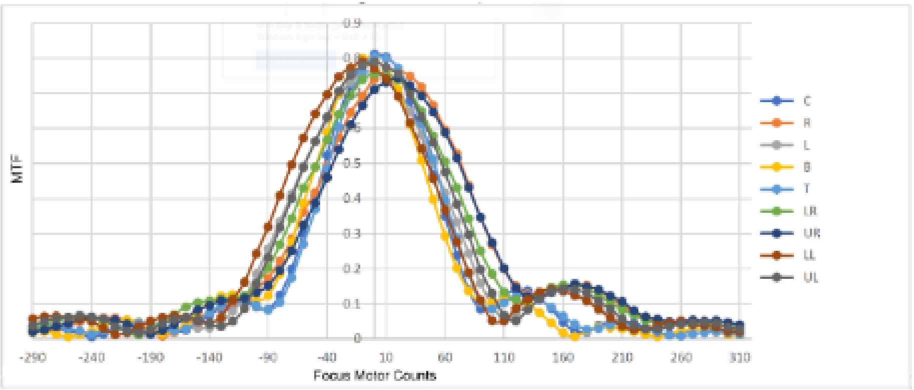
Field Curvature

- Object plane of imaging system may be curved
- The virtual image plane of the VR device under test may also be curved
- Though Focus allows for every field point to achieve best focus at one of the iterations of the scan

Simple Field Curvature

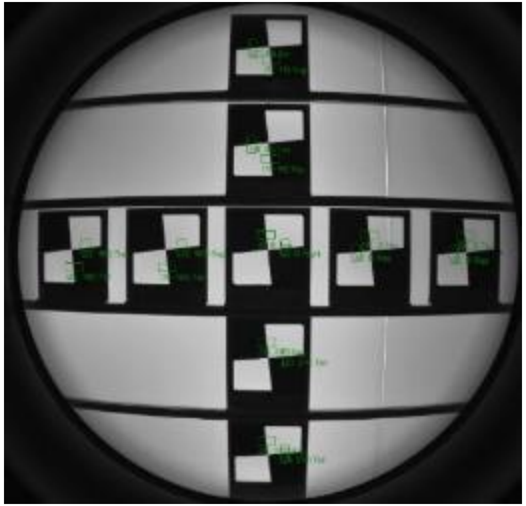


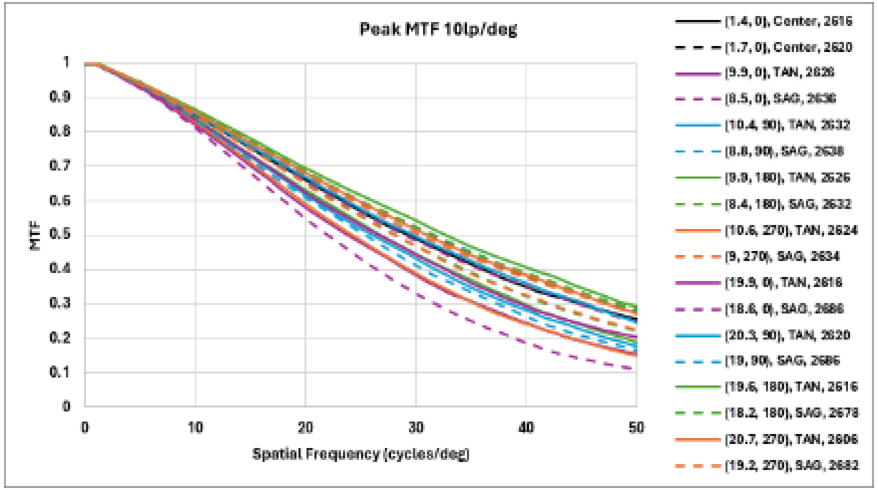




Focus

- Through-focus MTF testing finds best focus for each region of the display (based on MTF)
- Lens focus is iterated to record MTF at each focal distance
- Prescription Compensation (eyeglasses) requires variable focus and is more applicable to AR device inspection.
- Radiant's Patent Pending methods for prescription compensation measurement techniques are beyond the scope of this presentation.





High Resolution Displays

Pixel-level Measurement

Challenge: Display Resolution

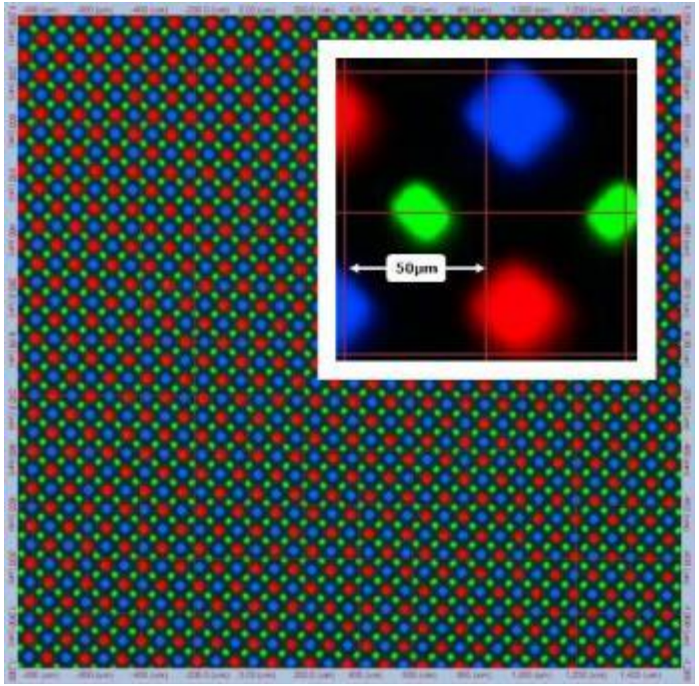
Headset	Resolution Per Eye
Valve Index VR Kit	1600 x 1440
Meta Quest 3	2064 x 2208
Occulus Rift S	1280 x 1440
Varjo VR-3	2880 x 2720
PIMAX 4K	1920 x 2160
HTC VIVE Focus	1440 x 1600
Samsung Gear	1280 x 1440

AMOLED AR/VR display and driver, 1280 x 960, 5644 PPI

Display Resolution

How can we measure high-resolution displays?

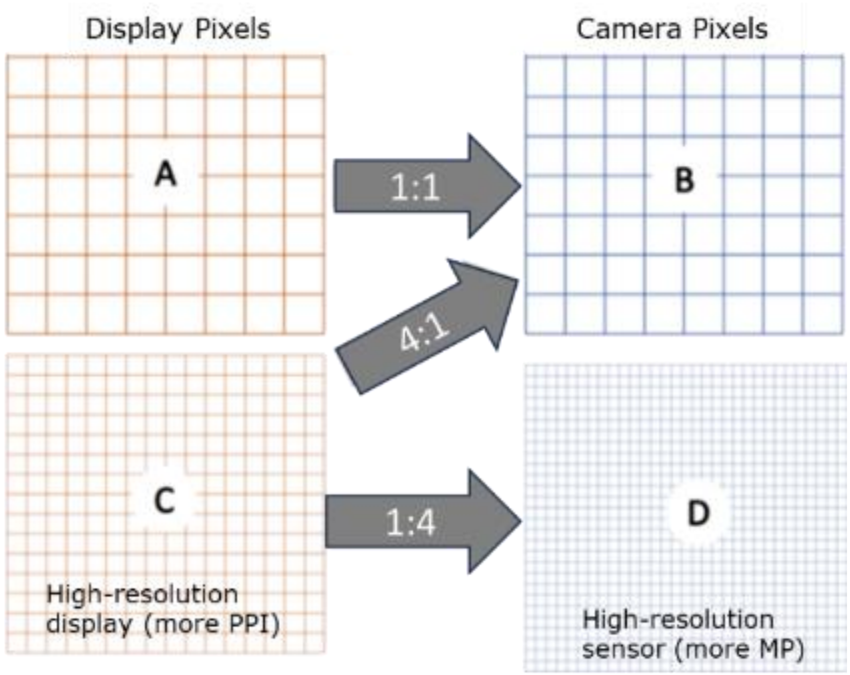
- High-resolution imaging system with high quality optics, e.g., 61MP or 151MP sensor:
  - More sensor pixels per display pixel—across any FOV
  - Accurate measurement of high-resolution, pixel-dense displays such microdisplays
  - Ability to discern individual subpixels to correct uniformity of emissive displays (OLED, microLED, microLED, etc.)
  - Efficient single-image capture for production testing
- Other specs to look for: high dynamic range, repeatability



Sub-pixel imaging of a microLED display using Radiant ProMetric® Imaging Colorimeter plus Microscope Lens

Sensor Pixels & Optical Resolution vs. Display Pixels

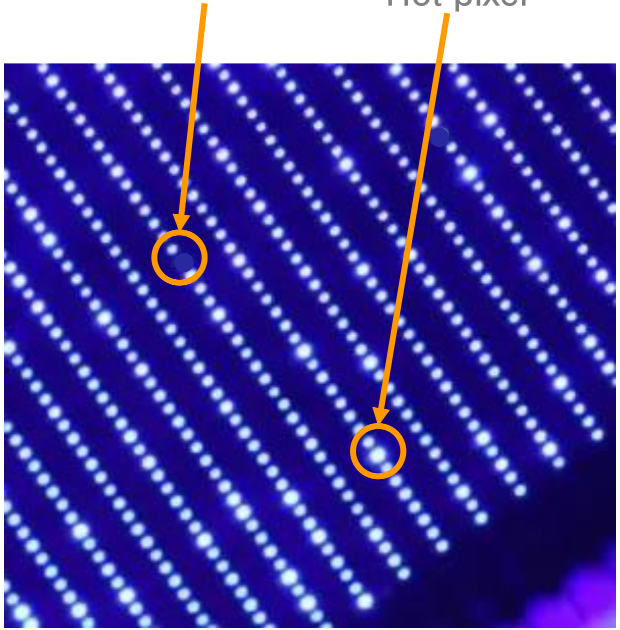
- High-resolution imager means more sensor pixels dedicated to each display pixel
- Able to capture precise detail of each display pixel and subpixel
- Single image is sufficient for faster measurement in production
- Optical Resolution (MTF) of the imaging system must be sufficient to effectively utilize the sensor resolution.



Emissive Displays

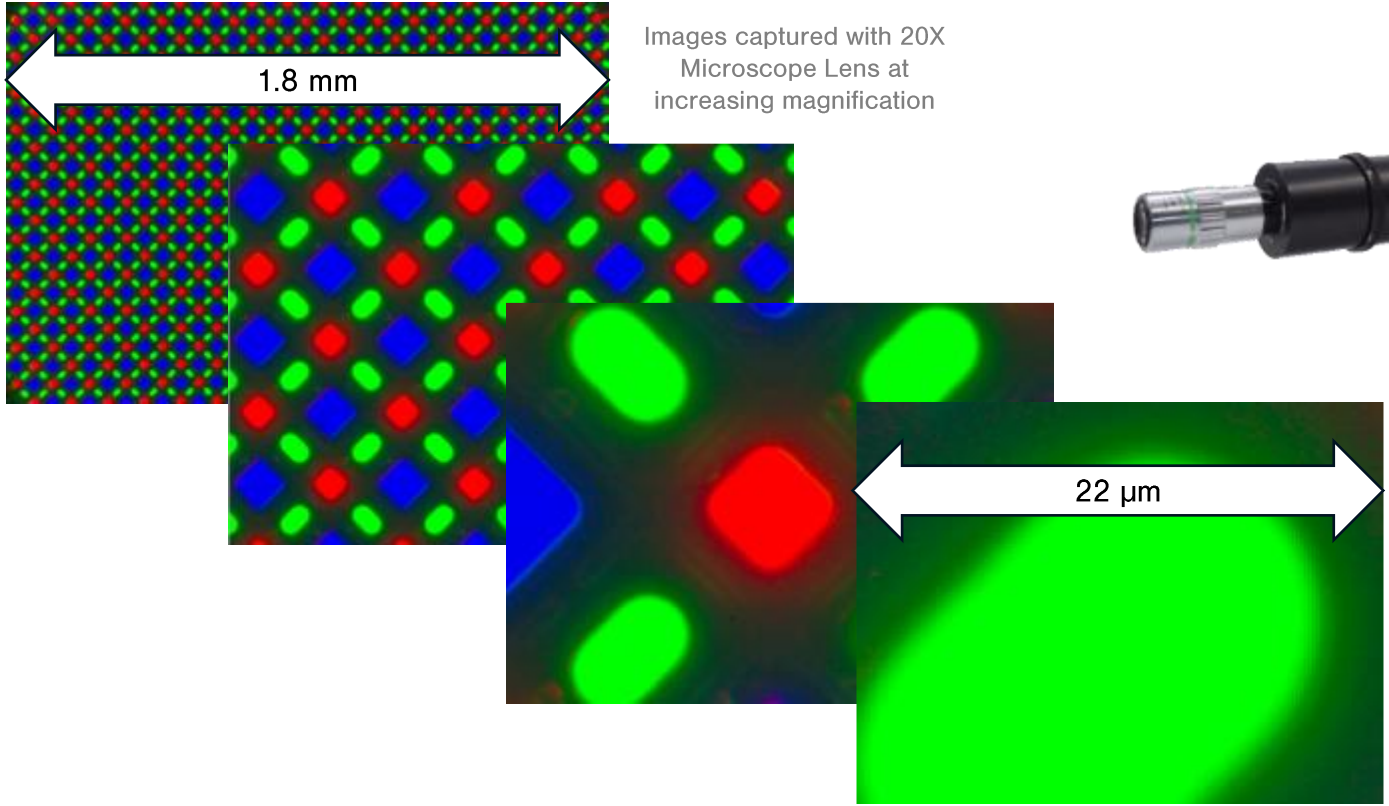
Quality Challenges

- Emitters are extremely small, densely populated
- Pixel-level variation from individual emitter state
- Color dependence on brightness
- Regional non-uniformity (mura) at low grey levels



Emissive display types include: OLED, AMOLED, microLED, microOLED, plasma

Display Measurement with Microscope Lenses

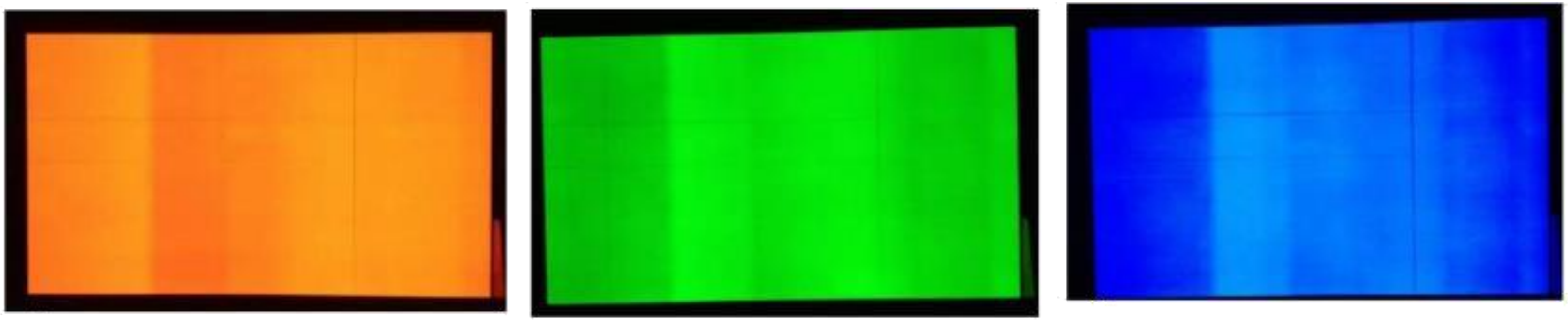


Images captured with 20X Microscope Lens at increasing magnification

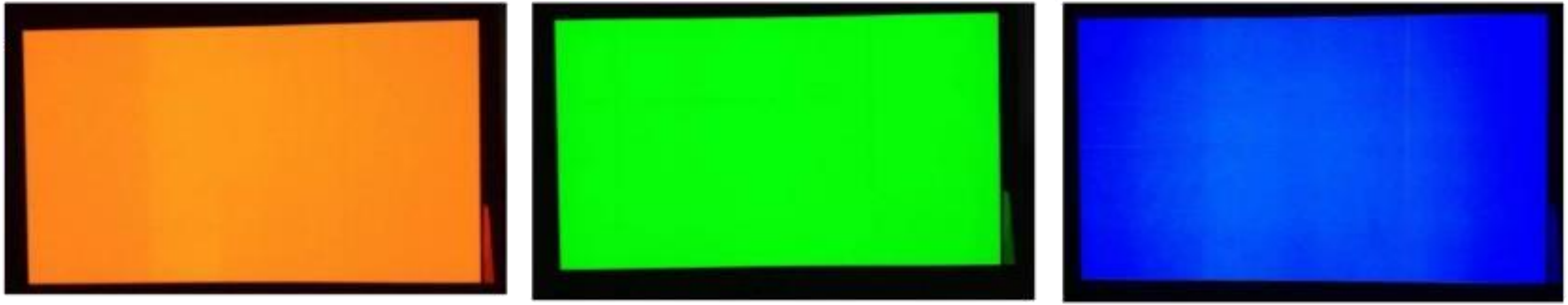
Radiant 20X Microscope Lens

Data Can Be Applied in Correction (Demura)

Before Correction



After Correction



VR Measurement Solutions Overview

Solution Design
System & Optics

Requirement:
Emulate Human Visual Characteristics

	Human Vision	Test Solution
1	Perception of light and color	Accurate measurement of luminance and CIE-matched chromaticity
2	Size of human pupil	Aperture size
3	Pupil location / position	Location of test system entrance pupil within the headset
4	Human FOV	System FOV
5	Human visual acuity (resolution)	Sensor resolution
6	Human foveal area (focus)	Adjustable focus / focal distances
7	Binocular vision and interpupillary distance	Ability to perform dual-eye testing

Brightness, Color & Spectrum

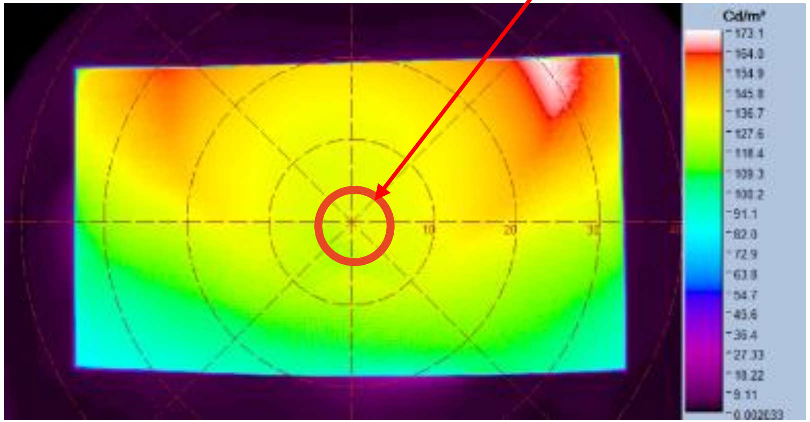
- Accuracy
- Uniformity
  - Version of Radiant Colorimeter combined with Instrument Systems CAS-140
  - Patented “pick off technology” allows for measurement of the spectrum of light
- I-SC works with Radiant ARVR Lens or XRE Lens

ProMetric® I-SC Solution: Imaging Colorimeter with Integrated Spectrometer

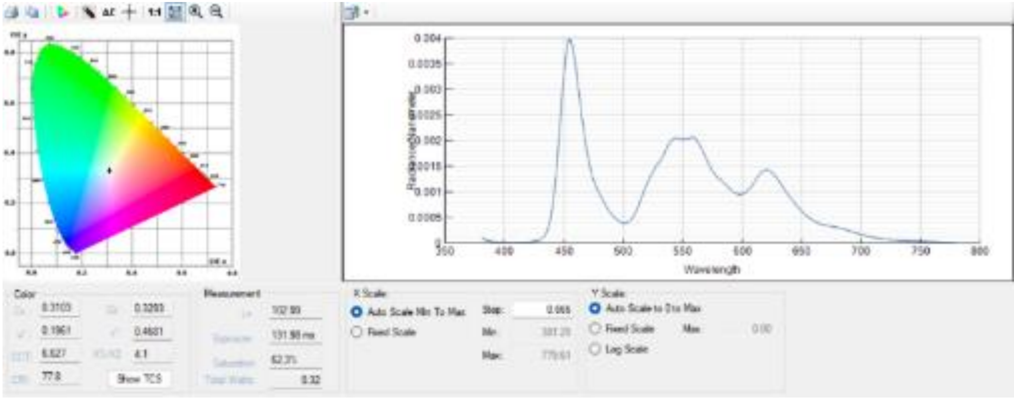
Spectral Content of a Specific POI

- A positionally calibrated Point of Interest (POI) within the colorimeter's FOV can be sampled with CAS-140 to measure the discreet spectrum

POI



POI Spectral Content



Radiant's AR/VR Lens

Unique Features:

- Aperture (entrance pupil) located on front of lens
- 3.6 mm aperture
- Designed to be positioned in eye relief location
- **Wide field of view** (FOV): 120° horizontal
  - Accommodates most AR/VR headsets
  - Distortion corrected automatically for accurate testing
- Full suite of TrueTest™ display tests

Radiant's XRE Lens Solution

ProMetric® I
Imaging Colorimeter + folded XRE Lens

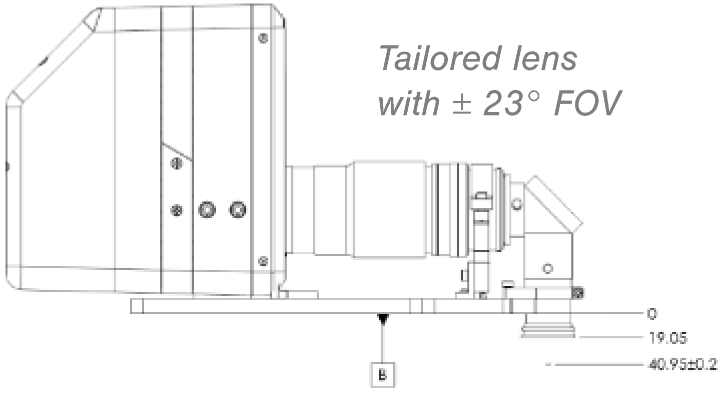
ProMetric® Y
Imaging Photometer + non-folded XRE Lens

Patent-pending Optical Technology
Invented by Radiant Vision Systems

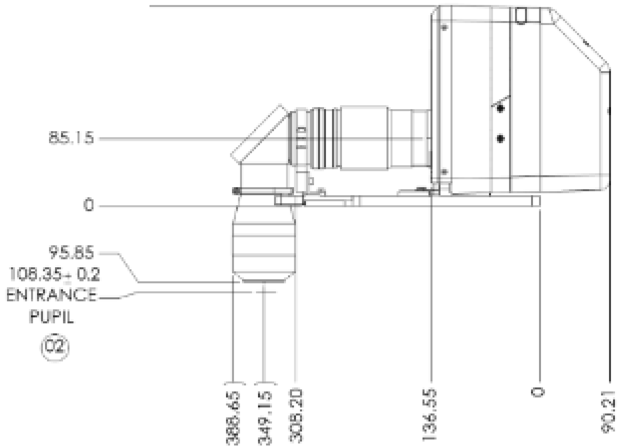
- Flexible optical solution for replicating human vision in a broad range of XR devices & display test scenarios
- Electronic focus
- Two Configurations:
  - Folded ("periscope")
  - Non-folded ("straight")

Tailored “XR” Modular Lens Solutions

- Folded or non-folded configurations
- Pair with ProMetric® Imaging Photometer or Colorimeter
- XR23 and XR57 Shown



Tailored lens with ± 23° FOV



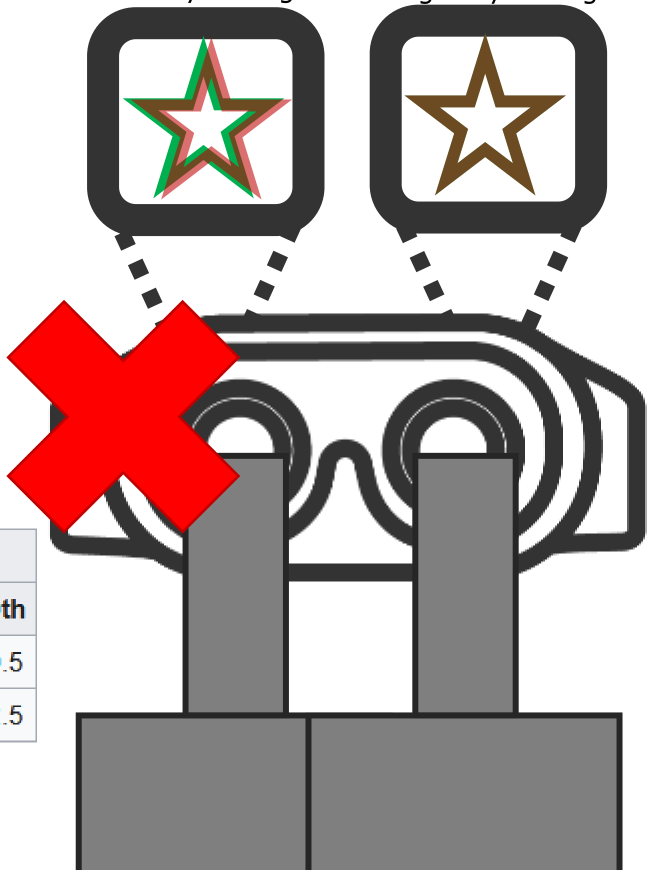
Tailored lens with ± 57° FOV

(Preliminary drawings, dimensions are subject to change)

Additional Challenge: Dual-Eye Measurement

How do we account for human binocular vision?

- Ensure consistency between left and right eyes
- Simultaneous measurement by 2 systems in the same headset



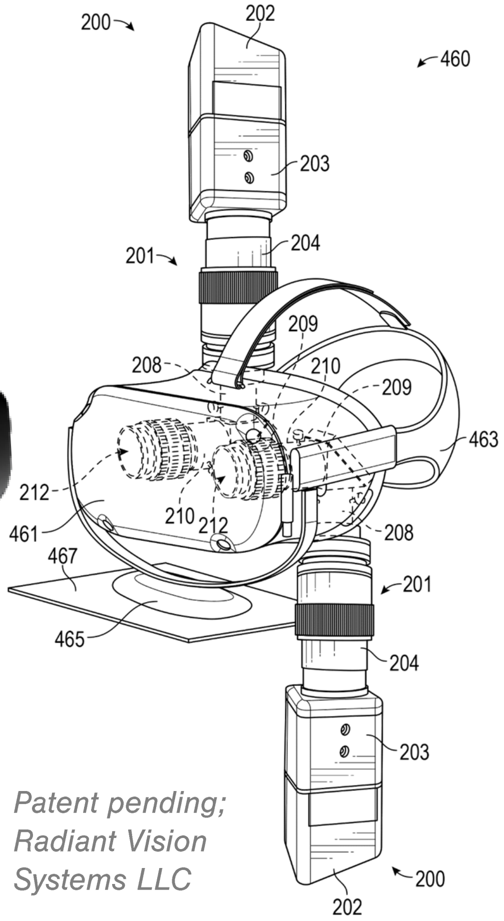
IPD values (mm) from the *2012 Anthropometric Survey of US Army Personnel*

Gender	Sample size	Mean	Standard deviation	Minimum	Maximum	Percentile				
						1st	5th	50th	95th	99th
Female	1986	61.7	3.6	51.0	74.5	53.5	55.5	62.0	67.5	70.5
Male	4082	64.0	3.4	53.0	77.0	56.0	58.5	64.0	70.0	72.5

XRE Lens: Folded Optics

- Folded optics provide more angles of approach to the desired imaging position
- Dual-eye (stereoscopic) measurement of left- and right-eye positions
- Two systems fit in the headset at once while continuing to avoid headgear

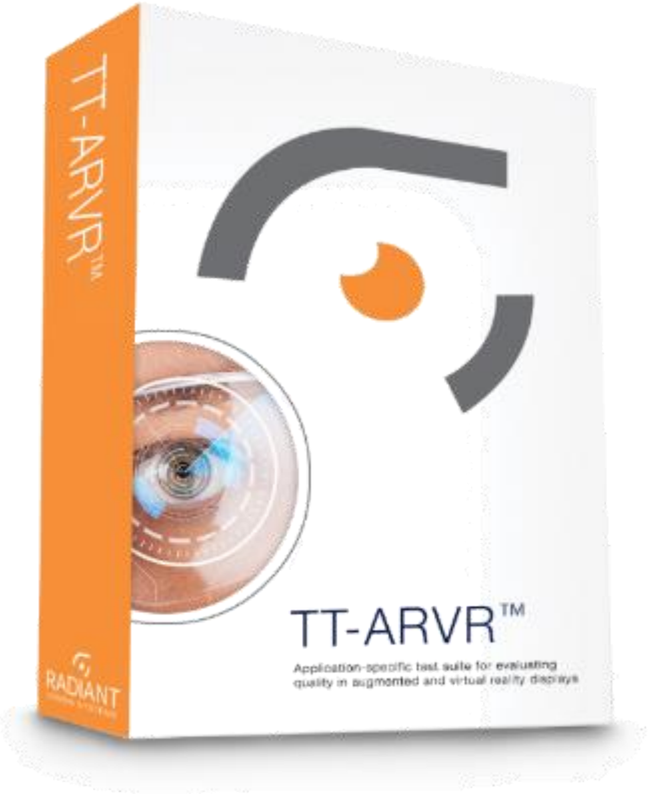
XRE Lens
Sample dual-eye configuration



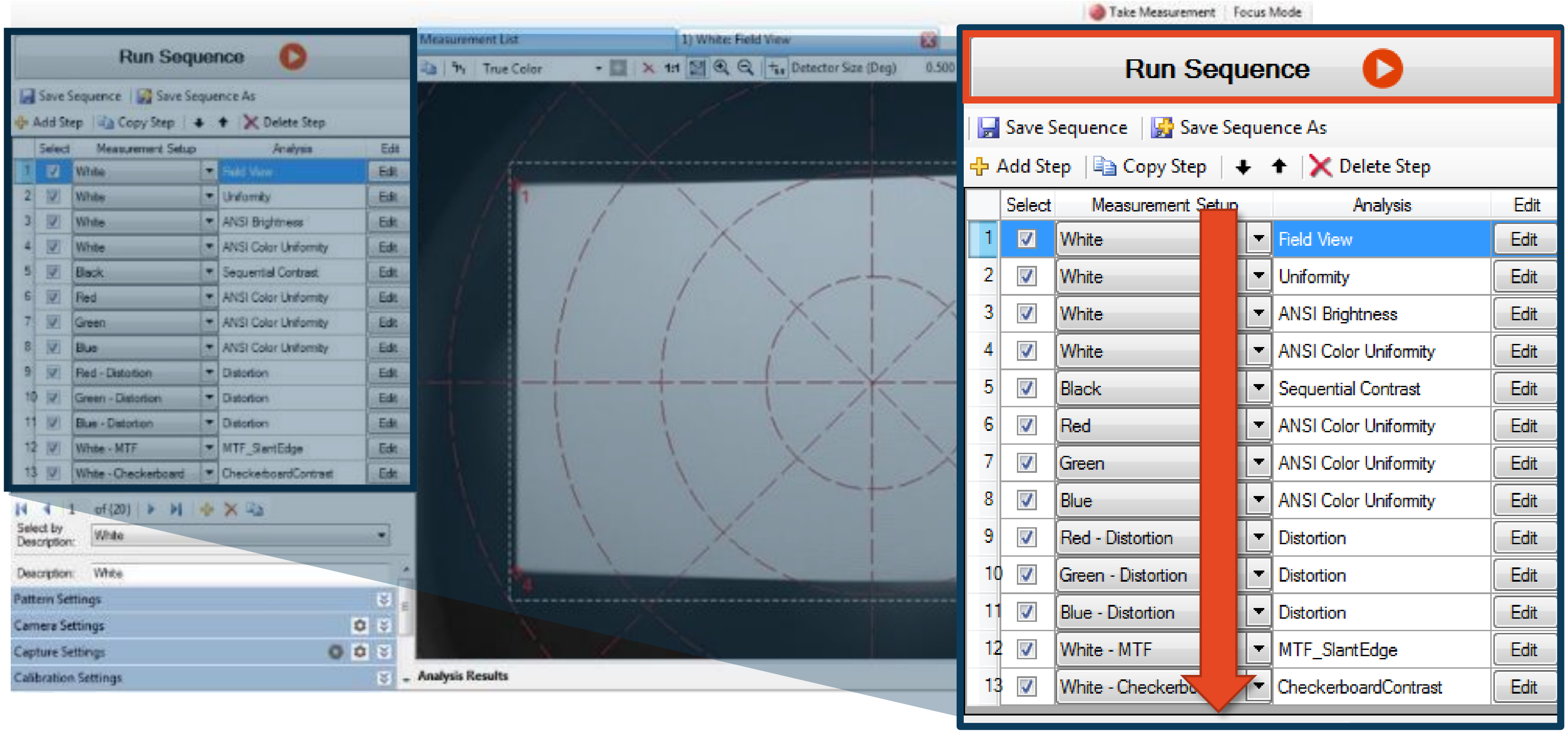
Patent pending; Radiant Vision Systems LLC

TT-ARVR™ Analysis Software

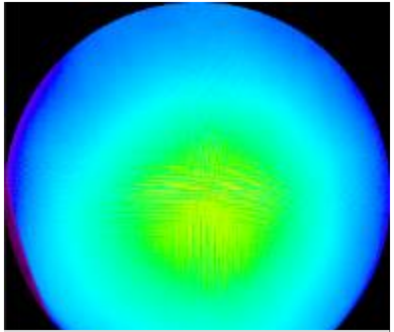
- Measurements and analyses:
  - *Luminance*
  - *Chromaticity*
  - *Uniformity*
  - *Contrast*
  - *Distortion*
  - *Focus Uniformity*
  - *MTF (Line Pair, Slant Edge, LSF)*
  - *Through Focus MTF*
  - *Mura & defects*
  - *Warping*
  - *Display FOV*
- Controls test images on headset
- Synchronizes tests with images
- Rapid, automated evaluation of all visual qualities with pass/fail results
- API and SDK for integration with fixtures and control systems



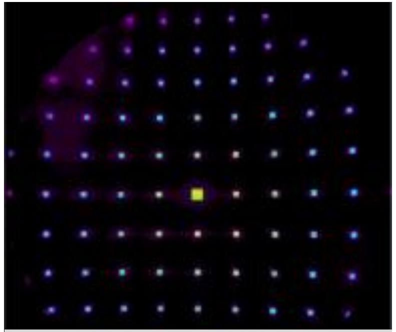
Automated Test Sequencing



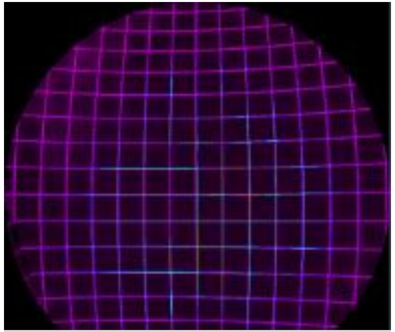
Application: In-Headset XR Display Testing



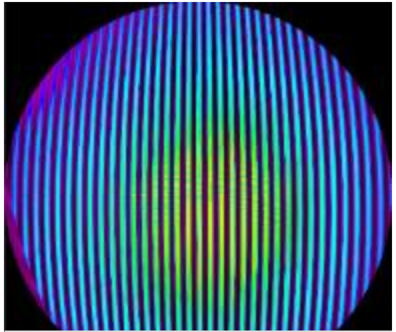
ANSI Brightness



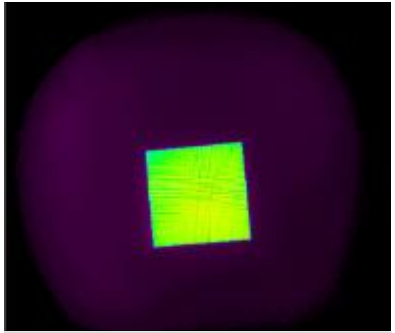
Distortion Dot Grid



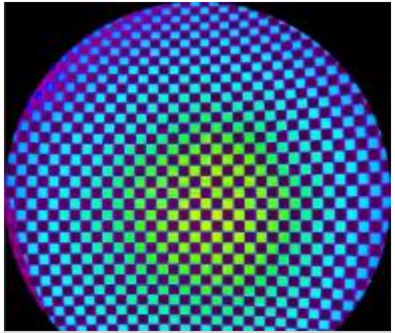
Distortion Line Grid



MTF Line Pairs

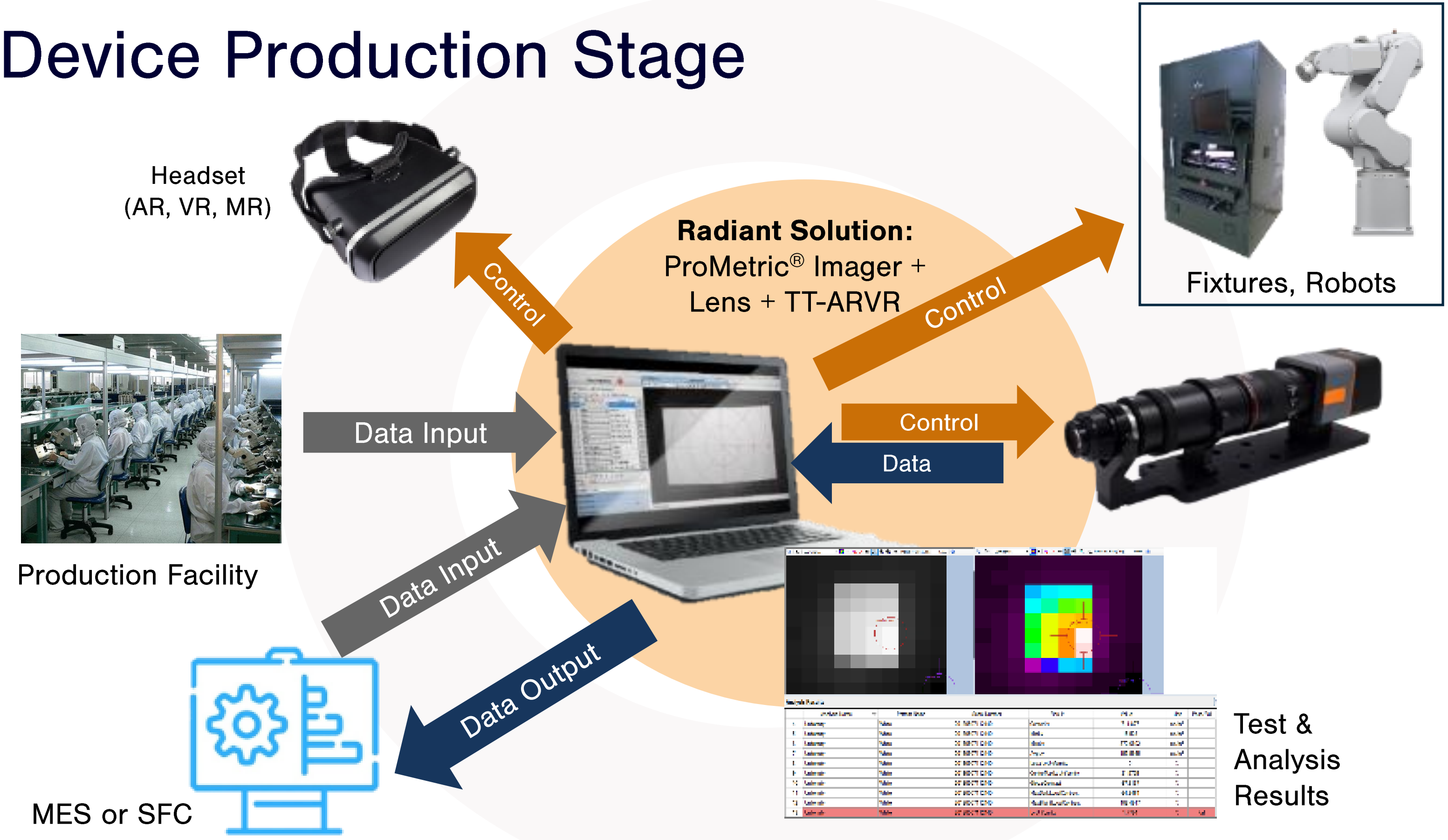


MTF Slant Edge



Focus Uniformity

Device Production Stage



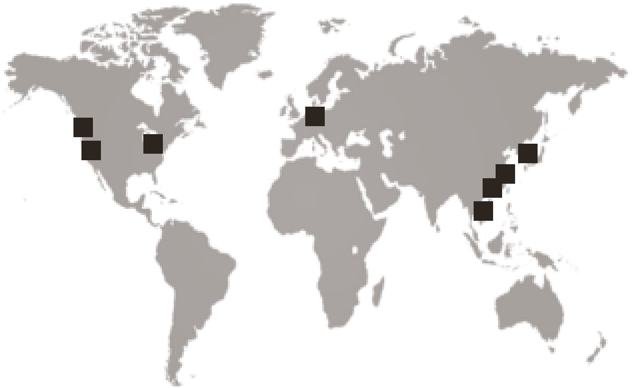
Summary and Q&A

Summary: Meeting The VR Metrology Challenges

RADIANT VISION SYSTEMS

Radiant's VR testing solutions provide unique optical measurement capabilities that:

- ✓ Replicate the human pupil size and position
- ✓ Match human visual perception
- ✓ Capture and evaluate a range of FOVs
- ✓ Correct for distortion
- ✓ Effectively measure through-focus MTF
- ✓ Measure high-resolution displays for luminance, color, and uniformity
- ✓ Offer multiple configuration options
- ✓ Are backed by our global service and support teams



Q&A

Additional Questions? Contact Info@RadiantVS.com
www.RadiantVisionSystems.com

RADIANT
VISION SYSTEMS

Thank you!