Image Quality Criteria

Often used criteria:
Resolution: MTFs, Wavefront RMS, RMS spot size, Strehl Ratio, DPI……
Contrast
Color gamut,
Distortion
Noise.…

However
Artifacts are important and need optical and/or electronic correction
Banding artifact - laser printing and projection
Laser printing and the “banding” artifact

\[ \frac{dE}{E} = \frac{dP}{P} \]

Where P is the pitch and E is the exposure

The banding source:
Polygon pyramid error.
A 12 facets polygon will produce a modulation every 12 raster lines which will place it at the peak of the eye sensitivity curve.
Contrast sensitivity curve

POLYGON  PYRAMID ERROR CORRECTION BY CONJUGATION IS THE CROSS-SCAN DIRECTION
Optical layout of a high resolution laser printer
Continuous tone laser printers with pyramid error correction

**Motion picture film laser color printer**

**10,000 prints/hour photofinishing laser printer**

**Dry and wet medical laser printers**

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Aliasing and color aliasing

Solutions for aliasing and color aliasing in digital cameras:

• Do not under sample i.e. observe the Nyquist frequency. (for example: increase F/# when capturing)
• Use blur filters (= optical low pass filters = anti aliasing filters)
• Use mechanical dithering

Sensor Bayer pattern
Anti aliasing filter: 4 spots

1mm thick crystal quartz will separate the ordinary and extraordinary spots by 6 microns at the sensor.
MTF curves for a blur filter vs. defocus

Cosine MTF term of a blur filter
Antialiasing solution: Mechanical dither in an LCOS printer

Obviously for dithering not to reduce resolution: the pixels have to be underfilled.
Artifacts with Extended Depth of Focus (EDOF)

EDOF started with CDM (bought by Omnivision), GG&C, DBLUR (an Israeli company) Xceed Imaging (Israel) and others. Some smart phones are available with it (Nokia).

The idea is to introduce to the design of a fixed focus lens a known phase mask and then capture the image with no focusing and retrieve the image using algorithms over a large depth of field.

EDOF cameras while greatly improved still have problems with some imaging situations especially in macro imaging, lower light level imaging and text imaging (fringing) as compared with cameras using autofocus.

Good review: EDoF versus Auto-focus: Understanding the compromises involved
Published by Steve Litchfield at 20:12 UTC, April 17th 2011
Schlieren systems in partially coherent illumination

Condenser / illumination system

Projection / imaging lens

Degree of coherence
Schlieren systems and phase objects

- Schlieren systems are systems which convert object phase to intensity such as Zernike microscopes or the TI DLP projector.
- When the object phase is unwanted, it creates an artifact which needs to be suppressed.
  - Examples: cover glass imperfections on LCOS image sources or on CCD/CMOS sensors.
  - Anti friction structures on motion picture films.
  - Related to the traditional term: “scratch and dig”.

Kessler Optics & Photonics Solutions, Ltd.
Suppression of Schlieren artifacts: DataCine – a HD telecine

Object phase suppressed with an integrating cylinder producing incoherent line illumination
“Dirty windshield” artifact

Sunlight scattered off structures and discontinuities on the windshield.

This artifact is present in a number of systems with or without windshields.
Near to Eye display:
What does everyone want?

“Oakley look”. i.e., thin & small optics
Augmented imaging preferably an optical see-through channel
Low cost & small image generators (OLED, LCOS, …)
Wide field of view 30° deg to 110° full diagonal field
Large eye box >10 mm, for eye ball movement + loose alignment
Large eye relief > 20 mm, for lash clearance and prescription glasses
High resolution ~ SXGA (1280 x 1024) or higher
Low distortion < 2%
Bright hundreds of Cd/m²
Artifact free; no “dirty windows” ; no raster; no sunlight scattering
Low weight
Other: eye tracking; battery life; connectivity….
Optics of Near to Eye Displays (NEDs)

NEDs: categories of optical design forms

- Magnifiers i.e. eye piece + image generator
- Relay based NEDs
- “Bird’s bath designs”
- “Pancake” designs: on axis folded by polarization means
- Pupil splitting:
- Segmented (or tiled) NEDs:
- Other: Foveated; Fiber scanning; Retina scanners; etc.
Pupil splitting designs
(also: pupil expanders and dilated optics)

We want an optical system to project into the eye with:

* Low F/number (= high Numerical Aperture) for efficiency
* Large eye box
* Short focal length for large field and small optics

Image source:

\[
\text{NA} = \sin(\theta) \\
(\text{Eye Box}) = 2f \times \text{NA} \\
\text{FOV} = \frac{S}{f}
\]

However, short focal length means small eye box, so we use a short focal length and get a small exit pupil and then expand it by replication to fill the eye box.
LUMUS one dimensional Light-guide Optical Element (LOE)

inventor: Yacov Amitai
The Nokia technology

Problem: limited FOV since this is basically a Bragg reflector obeying the Bragg condition
Segmented or tiled NEDs

Patches of different size holograms dispersed over the combiner and interact with an array of laser beams.

High potential for sunlight “dirty window” scattering

Chaum et al.
US20120/0149073A
100 pages, 300 figures, 85 claims
Dirty windshield artifact: in cameras

Scattering from diffractive optics elements (DOEs)
(see Bob Fisher HNDBK of Optical Systems Design- the bloopers and blunders in optics section)

KODAK story of the DOE white and magenta flare. The optical designers incorporated a 1.6 mm baffle to kill the scattered sun light but this was removed by the camera designers for esthetic reasons. The production was cancelled.

The message”: beware of scattering from any discontinuities in the pupil.
Shimmering /swimming

The artifact:
The field of view seems to be swimming when the head or eye are moving within the system eye box. Also: convergence is affected and thus 3D perception.

Can be found in:
- In Near to Eye Displays
- Biocular systems
- Binocular systems
- Any system with eyepieces with large entrance pupils (eye boxes) within which the eye can move about.
Correcting for shimmering

See-through: SXGA; 50 degrees diagonal; 10 mm Eye Box; 23 mm Eye Relief; 0.78” OLED
Kessler and Bablani, USA 8094377

Two ways to design for low shimmering system:
1. to optimize use the full eye box- may be an overkill since the eye is a sub aperture of the eye box at any given position.
2. To use multi configurations for the sub apertures at different location within the eyepiece and include chief ray deviations in the merit function.
Beams registration in RGB laser systems

Similar to the lateral color aberration but the source is laser pointing errors.

The solution is to design the laser channels so pointing is minimized. This is done by designing the laser trains and handle simultaneously.

1. The Gaussian beam properties of the beams - mainly waist size and location.
2. The geometrical properties of the system so the planes of minimum deviation are optical conjugated to the image plane.

For this, there is design method called the YY diagram.
y̅y Diagram, a powerful optical design method for laser systems

David Kessler and Roland V. Shack

We present a new method for synthesizing and analyzing laser systems based on the use of the y̅y diagram. The diagram is commonly used to represent two rays, the marginal and the chief rays, as they propagate through an optical system. Since a Gaussian beam can be represented by two rays, it is possible to use the y̅y diagram to represent these rays. This results in a representation of the beam as a single ray line on the y̅y diagram with simple graphic interpretations for the beam parameters. An equivalent representation of the Gaussian beam on the u̅v diagram is also presented and discussed. Complex design problems may be reduced to simple graphic problems, which often lead directly to algebraic solutions. Examples of y̅y diagrams are given for beam transfer through simple optical systems, including gradient optics. Diagram transformations are discussed and design examples are given of a three-element afocal system and a three-element collimator.

Keywords: y̅y Diagram, laser beam, Gaussian beam, optical design, Delano diagram.
Representation of a laser Gaussian beam by a line and a point

\[ \omega^2 = \omega_0^2 + \left( \frac{\lambda z}{\pi \omega_0} \right)^2 = \omega_0^2 \left[ 1 + \left( \frac{z}{z_0} \right)^2 \right], \]

where \( z_0 \), the Rayleigh distance, is defined as

\[ z_0 = \frac{\pi}{\lambda} \omega_0^2. \]
Beam parameters on the Y-Ybar diagram

\[ \omega^2 = \omega_0^2 \left[ 1 + \left( \frac{\lambda Z}{\Pi \omega_0} \right)^2 \right] \]

\[ \omega^2 = \omega_0^2 + \left( \frac{\lambda Z}{\Pi \omega_0} \right)^2 \]
Example: Laser marking system: YY diagrams before and after

There is a small, non-zero waist size at the media.
Tiling artifacts

LED displays are usually assembled of 6” x 6” modules.
The Just Noticeable Difference (JND) for streaking is \(~ 0.1\%

Holds for long streaks even when below the resolution of the eye of about \(1'\).
(\( this is why we see the high tension wires from the airplane)

Tiling is doable spatially in projectors for example on screen with gain factor of 1 (i.e. Lambertian screen) using matching and blending algorithms.

**Tiling in both the spatial and the angular domains is difficult.** This is why in Times Square we see the 6x6" LED modules when looking at the display off axis)
Birefringence in the PBS and beam combiner and field lenses are indistinguishable from the LCOS image information.
The first LCOS theatre cinema projector.

Thermal stress birefringence is the central issue of such a design.

The design has to consider special glasses with low stress birefringence but unfortunately are also the glasses laden with lead like SF57.

**The Kodak Digital Cinema projector** for Digital Cinema ~12,000 screen lumens, ~2,000:1 contrast ratio.
SPECKLE

C = 0.0

C = 0.04

C = 0.5

C = 0.84

C IS THE SPECKLE CONTRAST

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SPECKLE reduction techniques


1. Introduce polarization diversity;
2. Introduce a moving screen;
3. Introduce a specially designed screen that minimizes the generation of speckle;
4. For each color, broaden the spectrum of the sources or use multiple lasers at slightly different frequencies, thereby achieving wavelength diversity in the illumination;
5. For each color, use multiple independent lasers separated spatially, thereby achieving angle diversity in the illumination;
6. Overdesign the projection optics as compared with the resolution of the eye;
7. Image a changing diffuser with random phase cells onto the screen; and
8. Image a changing diffuser with deterministic or orthogonal phase codes onto the screen.

Bottom line: to reduce the speckle – make the lasers look more like an incoherent lamp and
Intermediate image with a dynamic speckling reducing element
Electronic vs. optical correction

Image algorithms people have sometimes the tendency to apply them universally.

Some artifacts should be left for the optics to correct:
- Aliasing
- Focusing
- Schlieren artifacts
- Banding
- Ghost images
- Speckle

Some artifacts can be corrected well by electronics/processing
- Distortion
- Lateral color
- $(\text{Cosine})^4$ falloff
Lateral Color: optical vs. electronic correction

Uncorrected lens with a focal length \( f \) has a \textit{longitudinal} color of

\[
\frac{df}{f} = \frac{1}{\nu}
\]

where \( \nu \) is the Abbe number which is between 30 for flint glasses to 80 for crown glasses. After achromatization the achromat will have typically:

\[
\frac{df}{f} \approx \frac{1}{1800}
\]

Beyond that, for \textit{apochromats}, special glasses are needed and other issues need to be considered such as color variations of the aberrations especially spherocromatism.
Relative Partial Dispersions $P_{g,F}$
Vs. Abbe Number

Glass type range 2003 July

Relative Partial Dispersions $P_{g,F}$ vs Abbe Number

Abbe Number $\nu_d$
Example: lateral color in RGB laser projection or printing

Achromatic scan lenses or projection lenses can be readily designed to correct down to 2 or 3 pixels. Further reduction to ½ or ¼ pixel: “secondary color” correction with special glasses needed.

Electronic correction is extremely beneficial in bringing the correction down to half or a quarter of a pixel.
f-θ scan lens for motion pictures printer.

Achromatic design & “electronic secondary color” correction AND optical polygon pyramid correction.
Electronic secondary color correction

- Lateral color is basically change of magnification with color
- Processing thus can be used also in cameras and CCD/CMOS scanners
Electronic correction at this range of distortion values is beneficial. Beyond it, loss of pixels is an issue.
Artifacts, Non Sequential & Sequential modeling

Sequential modeling:
System described in terms of
- Fields
- Numerical aperture or aperture size
- Spot diagrams

Non Sequential modeling:
System described in terms of
- Sources dimensions
- Sources divergences
- Irradiance on detectors

Fast optimization
Wavefront analysis and diffraction & MTFs
Tolerances, plate and index fitting…..
Merit function construction should include artifacts

Solid modeling
Ghost analysis
Scattering/glare from optical & mechanical components
Summary

• Artifacts are important and should be considered from the start in the design of imaging systems.

• A variety of artifacts in imaging systems and correction means encountered by the author and colleagues were discussed.

• The correction of artifacts should be mainly in the optical domain

• “Curb your enthusiasm” for correction by algorithms or electronic means. Electronic and processing correction methods should be used “mildly” and mostly for chief ray corrections (lateral color and distortion).

• Thank you for the invite and for your attention