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Measuring What's Hard to Describe: *The Latest Research on "Flicker"*

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San Diego Convention Center
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Agenda

- Introduction: What is Flicker and TLA?
- Challenges of measurement metrics
- New industry efforts
- Where do we go from here?

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Introduction and Background

Definition: Temporal Light Artifacts (TLA)

Flicker

Perception of visual unsteadiness induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a static observer in a static environment.

~0-80Hz

Phantom Array

Perception of a spatially extended series of light spots when making a *saccade* (image transition across the retina) across a light source that fluctuates with time

~50Hz-2kHz

Stroboscopic Effects

Change in motion perception induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a static observer in a non-static environment.

~50Hz-2kHz

Definition: Temporal Light Artifacts (TLA)

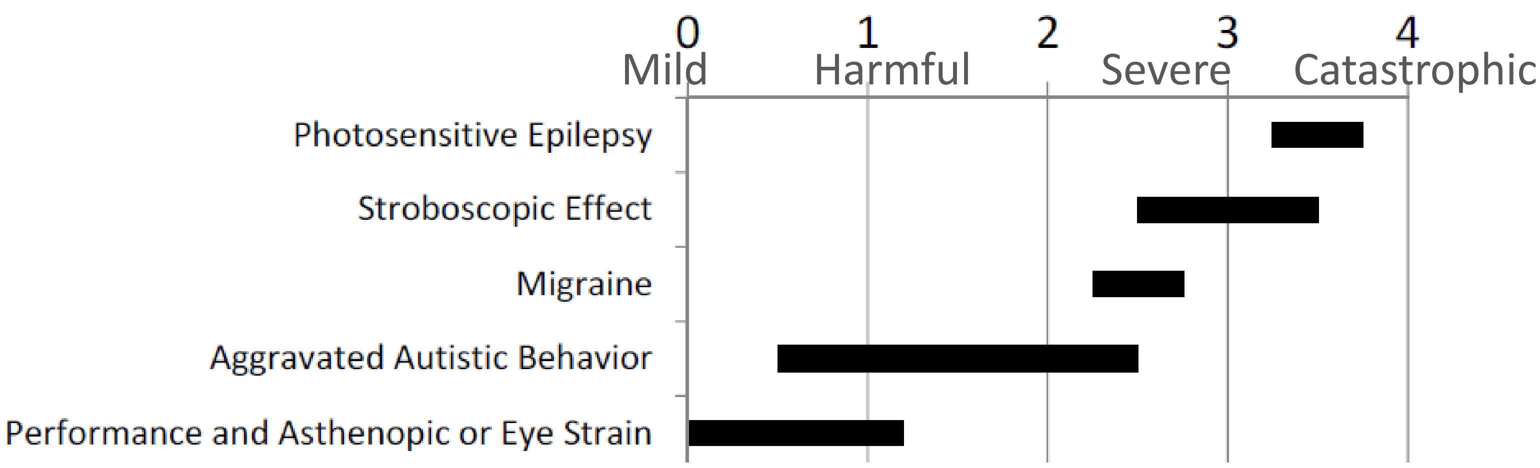
Temporal Light Artifact (TLA)
An undesired change in visual perception, induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for an observer in a certain environment.

or

or

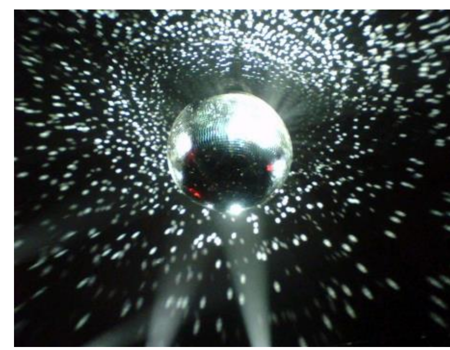
Why is TLA bad?

- May cause eye strain or headaches
- May impair visual or cognitive performance
- Distracting
- May trigger medical conditions *(in severe cases)*
- Interferes with optical equipment (cameras, etc.)
- **Could slow adoption of LED lighting due to perceived poor performance**



Not all TLA is bad!

- Sunlight through trees
- Reflections off of water
- Motion pictures
- Emergency vehicles
- Attention-getting signage
- Entertainment



(Although TLA in general lighting probably is bad…)

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Why do LEDs flicker?

- They don't! *(inherently…)*
- They faithfully reproduce light based on the amount of current flowing through them

Electrons in

Light out

Why do LEDs flicker?

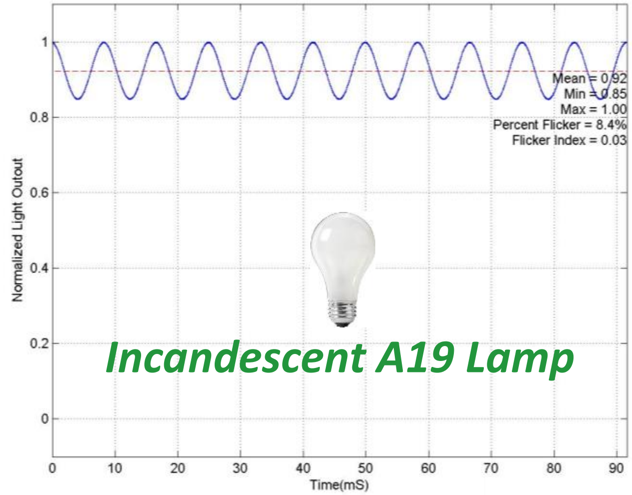
- An LED driver's job is to regulate current to the LEDs
  - Simpler drivers have a harder time avoiding current fluctuation, and are more prone to causing flicker
  - Voltage changes to the input of the driver (power line or control noise) can cause changes to the output

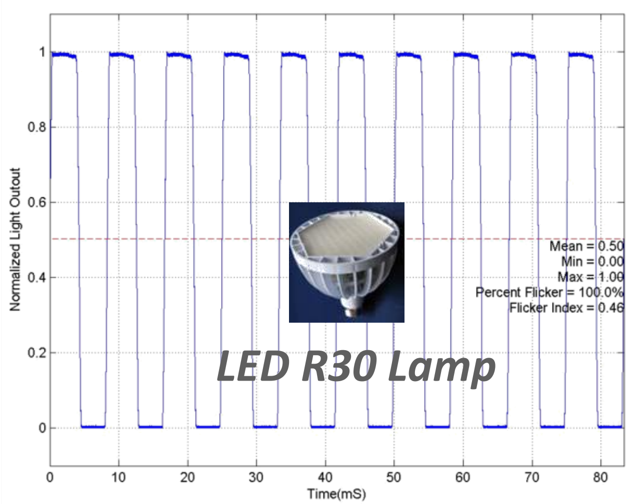
Electrical distortion in

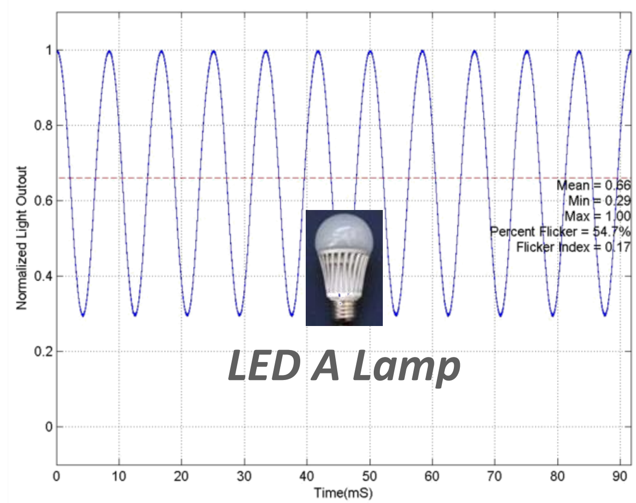
Optical distortion out

Why do LEDs flicker?

- LEDs respond QUICKLY to changes in current
  - No intrinsic filtering (unlike incandescent)

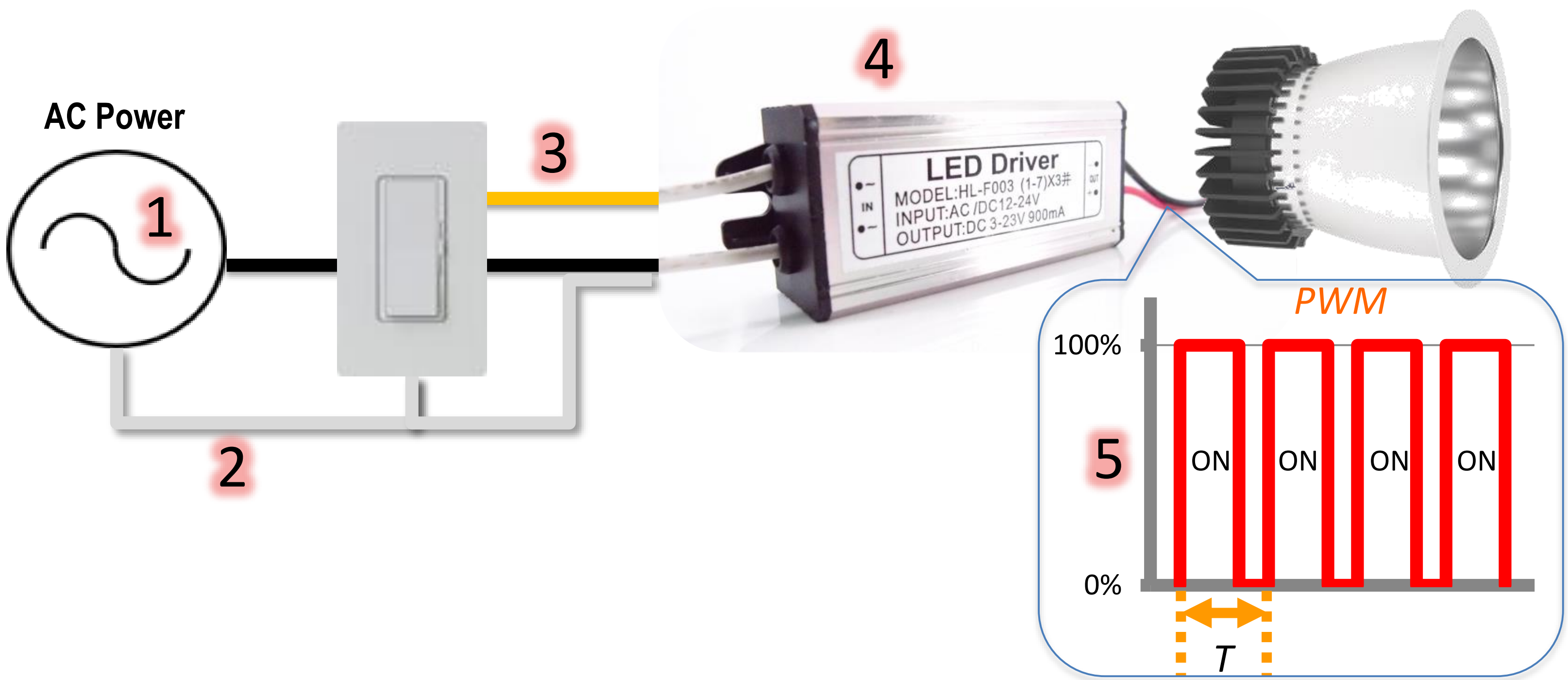






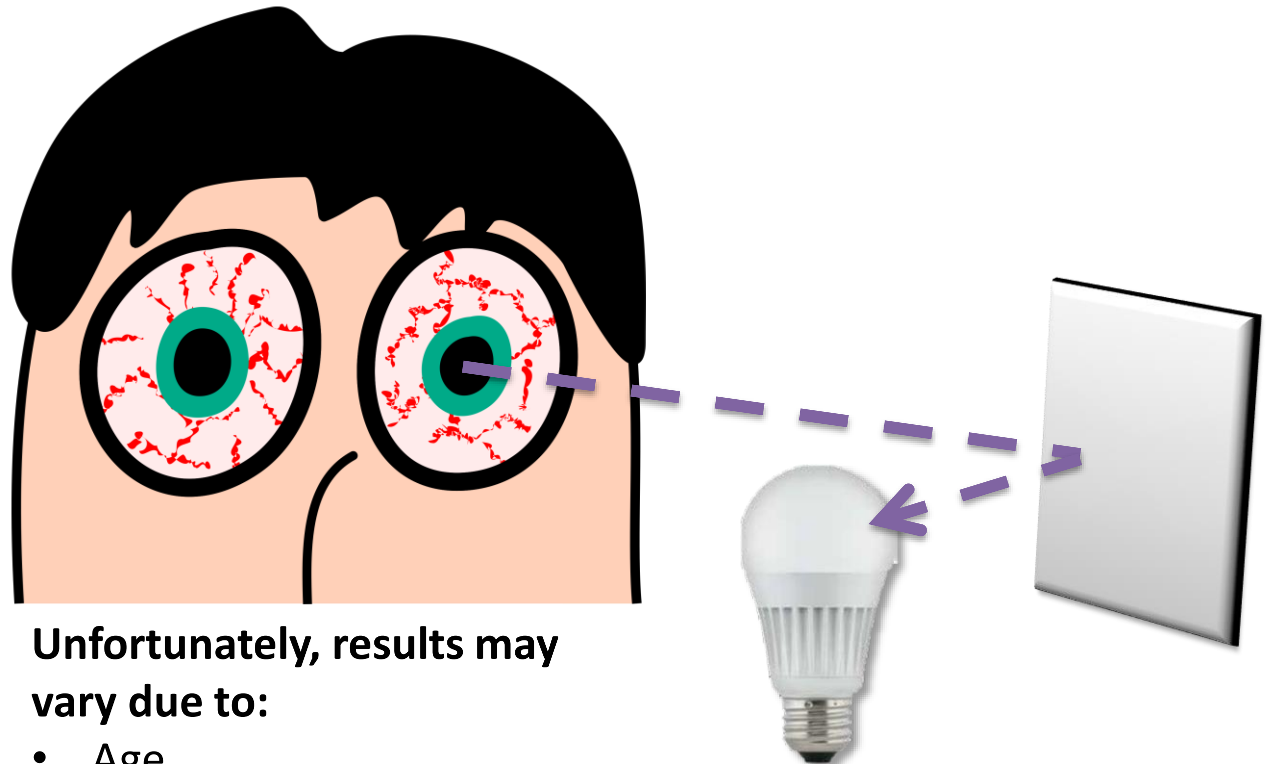
Sources of TLA

1. Source voltage changes (noise)
2. Externally coupled noise sources
3. Dimmer phase angle instabilities (when dimming)
4. Driver instabilities
5. Driver (intended) operation



Current state-of-the-art in TLA measurement

- Today's best equipment for measuring flicker:



Unfortunately, results may vary due to:

- Age
- Visual acuity
- Fatigue
- Ambient light
- Experience
- Viewing angle
- Brightness…

Flicker is best perceived off of a reflected surface, not directly viewing the source.

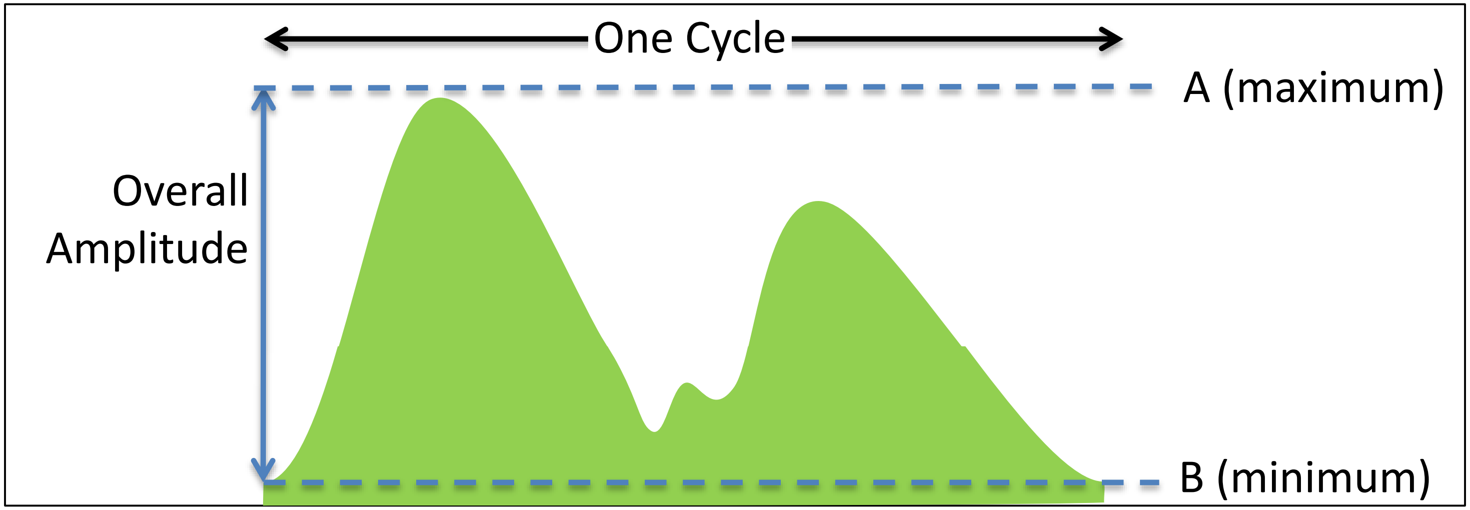
Current flicker metrics

- Simple
  - Percent Flicker
  - Flicker Index
- Complex
  - RPI LRC ASSIST
  - IEC PST
  - SVM
  - IEEE

Percent Flicker (or % Modulation, or Modulation Depth)

- Easy to understand
- Easy to calculate
- Assumes periodic waveform
- Does not account for wave shape
- Does not account for frequency
- $PF = 100\% \times \frac{A-B}{A+B}$

No relation to human perception!



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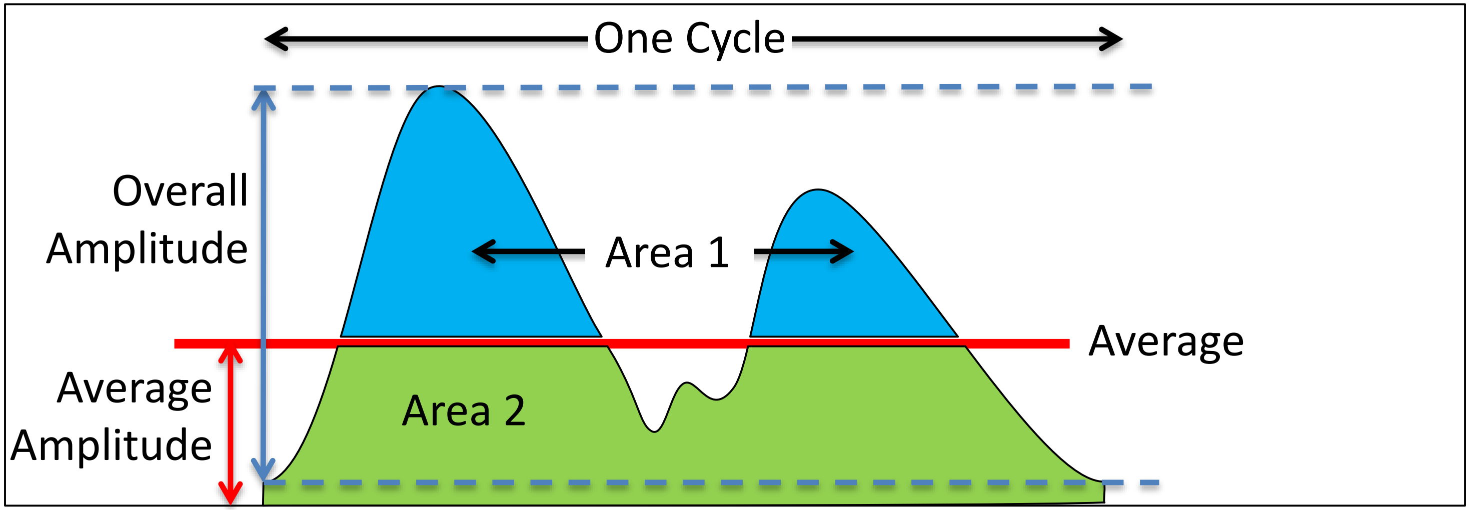
Flicker Index

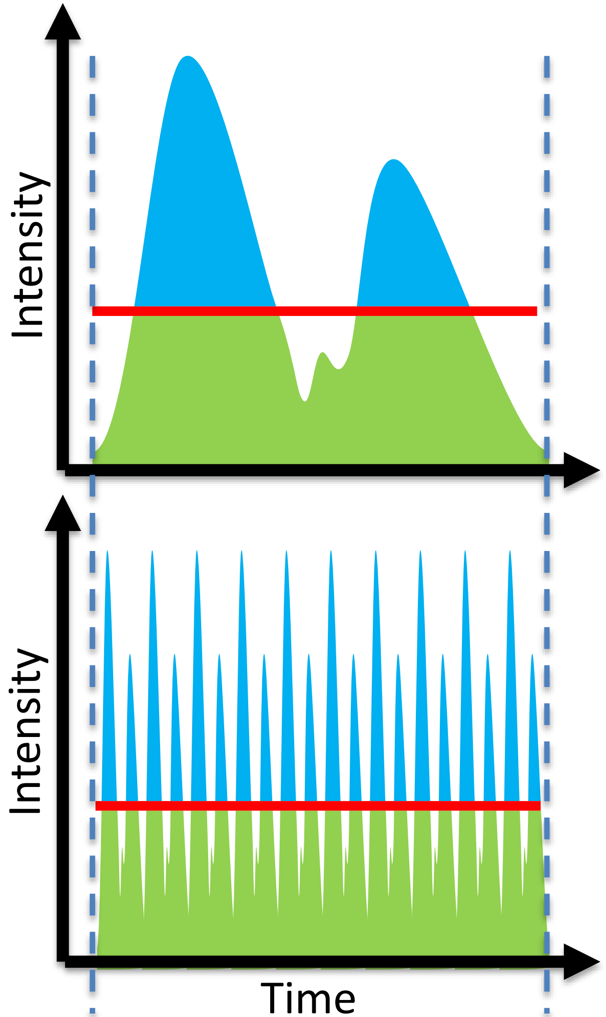
- Easy to understand
- Assumes periodic waveform
- Does not account for frequency
- $FI = \frac{Area\ 1}{Area\ 1 + Area\ 2}$

No relation to human perception!



Frequency independence

- Both graphs have same Flicker Index and Percent Flicker:
  - Same maximum
  - Same average
  - Same minimum
  - Same areas
- They will appear very different to an observer
  - 1Hz vs. 10Hz?
  - 10Hz vs. 100Hz?



Uses of Flicker Index and Percent Flicker

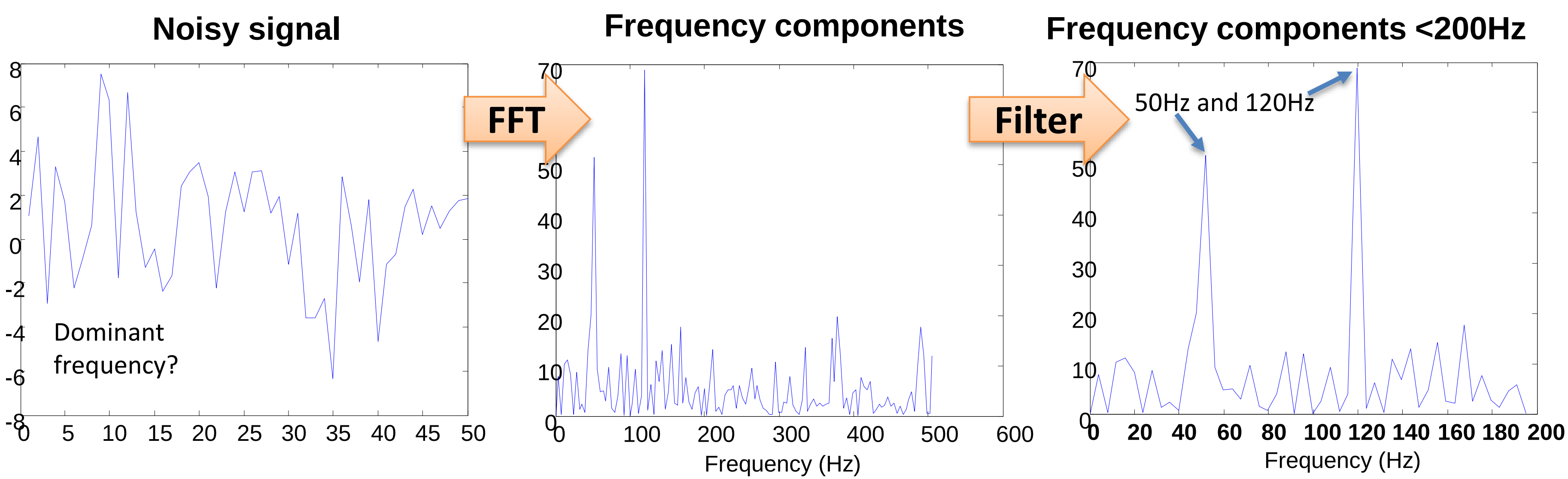
- Poor indicator of perceivable flicker
  - But, could be used to compare lamps with similar characteristics (operating frequency)
- Energy Star Lamps specification
  - Values are to be reported only; no limit
- California Title 24 Joint Appendix (JA) 8
  - Percent Flicker must be <30% at <200Hz

Better ways to measure TLA

1. Examine frequency components
2. Determine which frequencies are of interest (and how "interesting" they are)
3. Sum the result together
4. Compare that against a baseline or standard

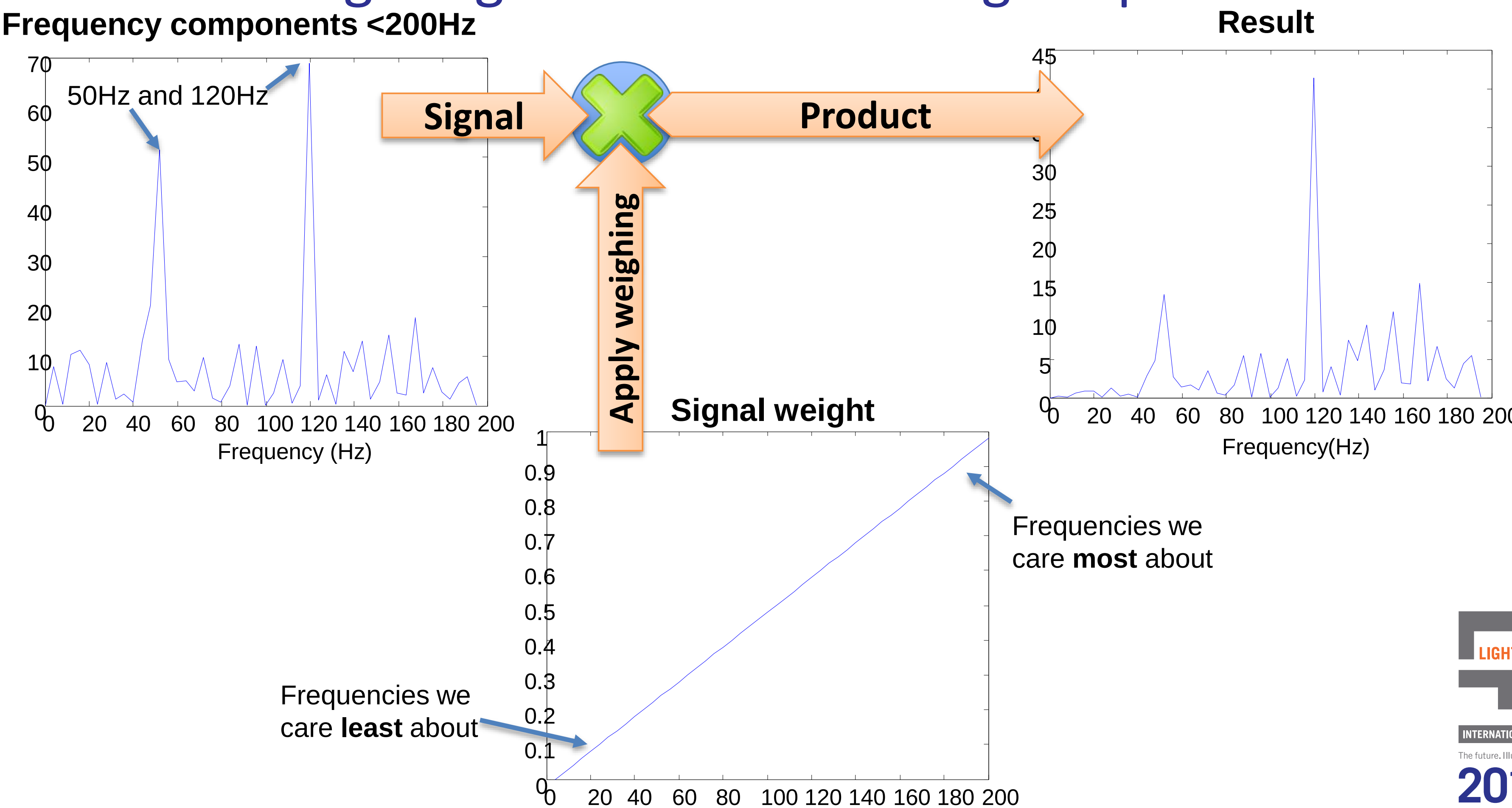
1. Examine frequency components

- Most "real" waveforms (light, sound, etc.) can be mathematically represented by a combination of several simpler (sinusoid) waveforms
  – Like a chord is a combination of musical notes
- The mathematical operation to determine these source waveforms is the *Fast Fourier Transform* (FFT)



2. Determine interesting frequencies

- Remove (filter) frequencies that are irrelevant
  - For example, those above human perception
- Add a weighting factor to remaining frequencies



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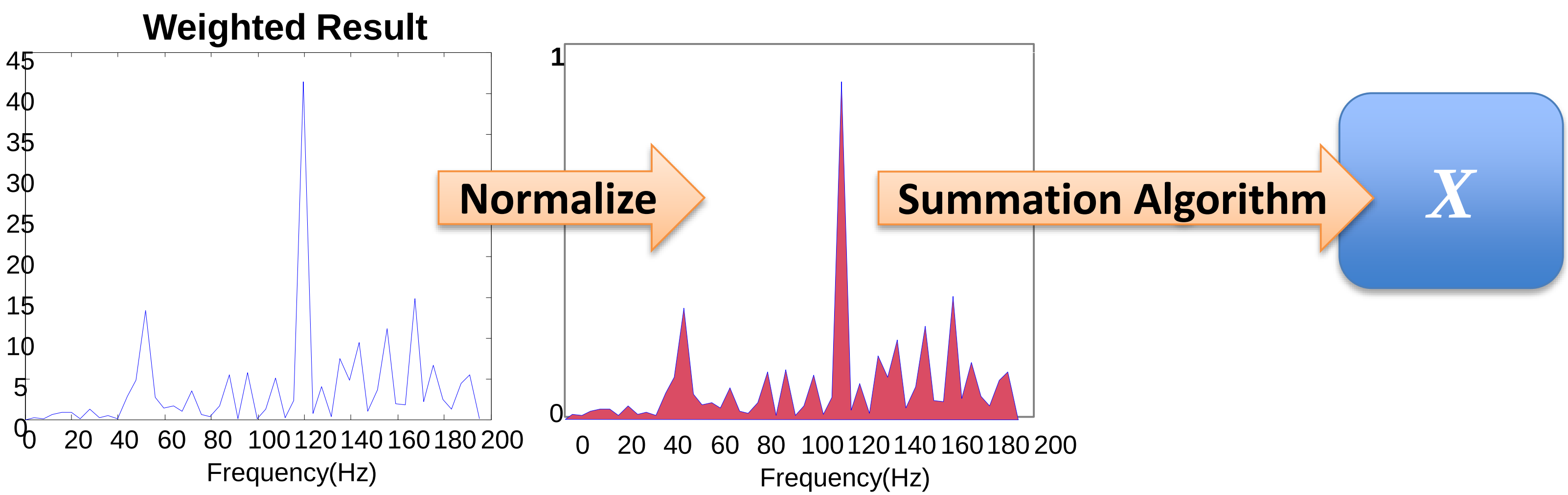
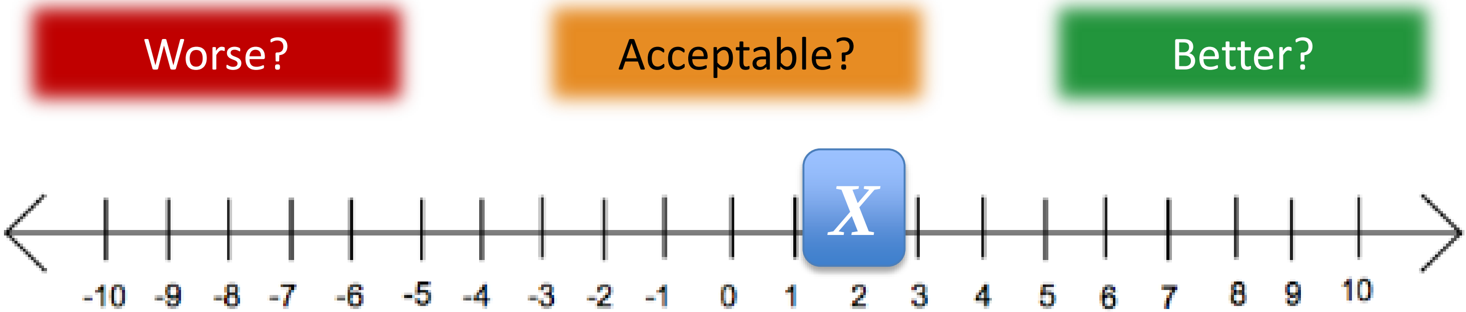
3. Add result together

- Normalize and perform a summation algorithm over the resulting (weighted) frequencies
  - Sum-of-squares, etc.
- Result is an integer value



4. Compare result against a standard

- Is lower or higher “better”?
- What’s an acceptable range?
- Does it vary based on application?



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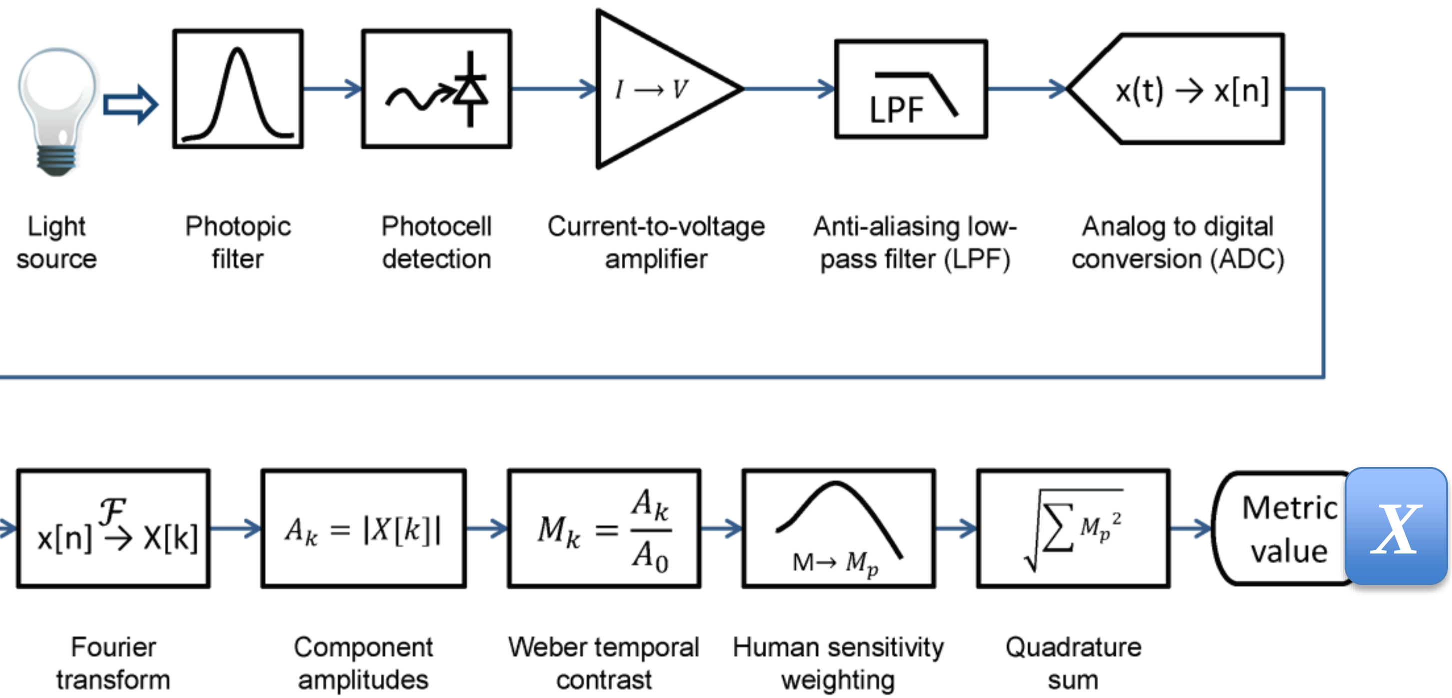
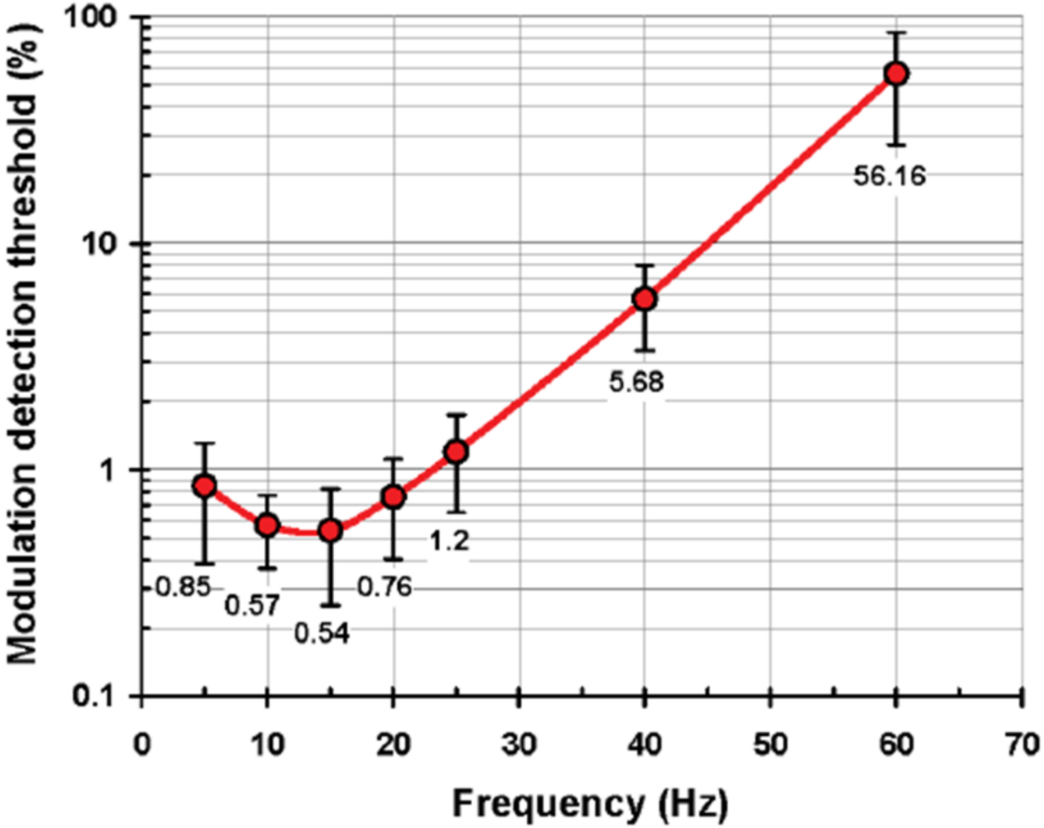
RPI LRC ASSIST metric

- Accounts for wave shape and frequency
- Based off of (limited) human perception trials
- Focuses on *perceptible* flicker: <100Hz
- Complex measurement and analysis:



Source: http://www.lrc.rpi.edu/programs/solidstate/assist/recommends/flicker.asp

RPI LRC ASSIST weighting curve



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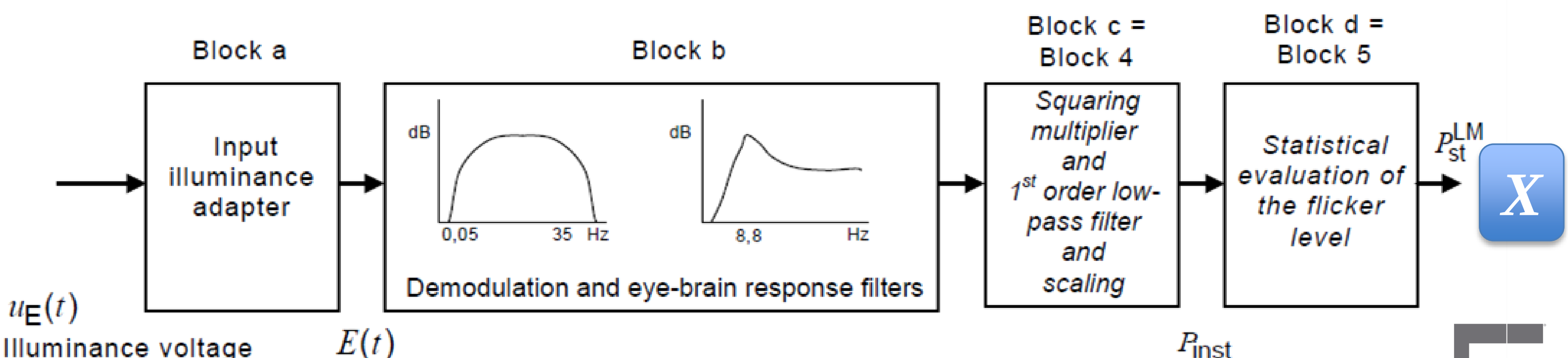
IEC flicker testing (P_{st})

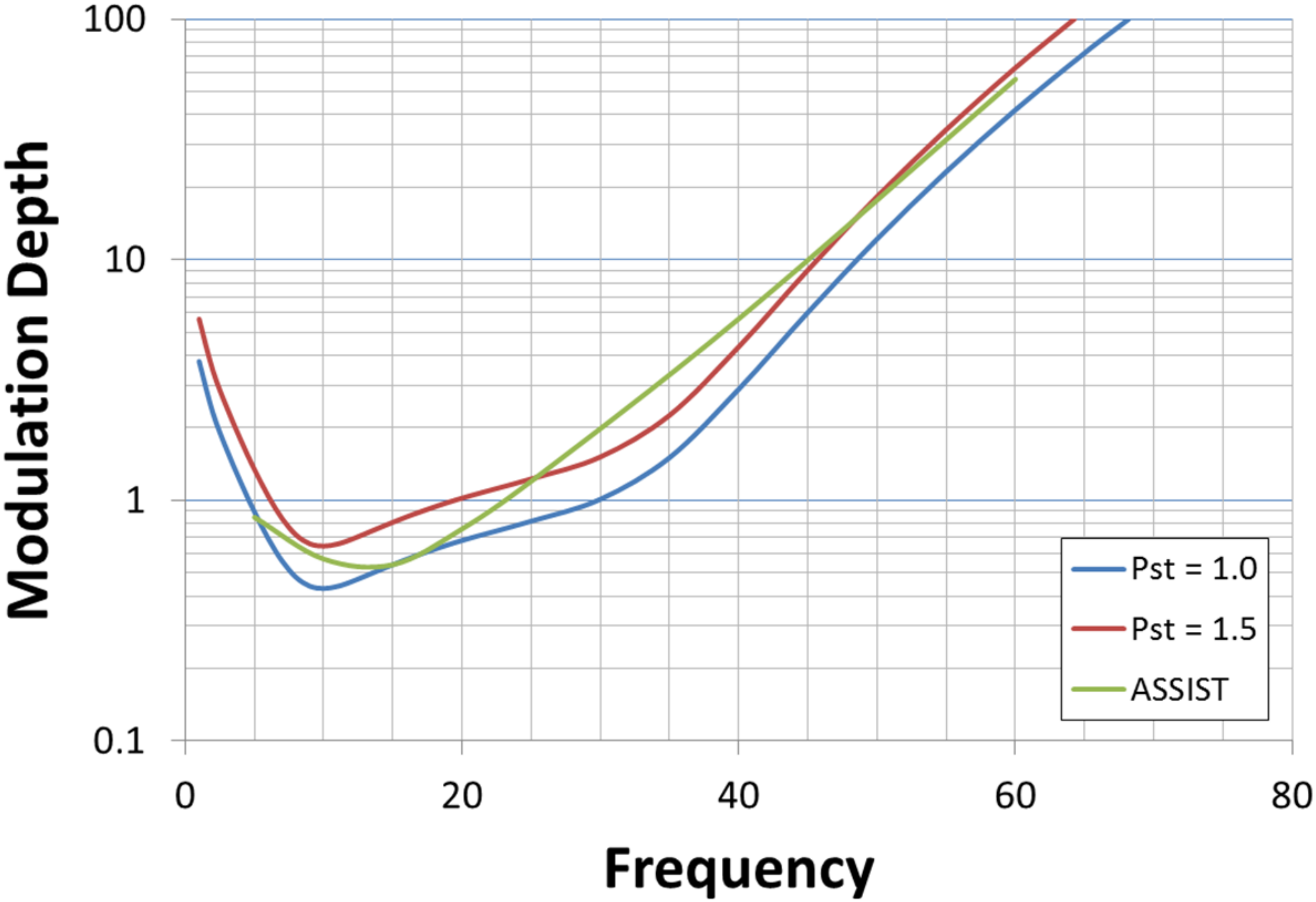
- IEC 61000-4-15
  - "Flickermeter – Functional and design specifications"
- IEC 61000-3-3
  - "Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems"
- IEC TR 61547-1 (Adopts IEC 61000 for use with light)
- Complex; originally developed to quantify power line quality



Structure of the IEC light flickermeter

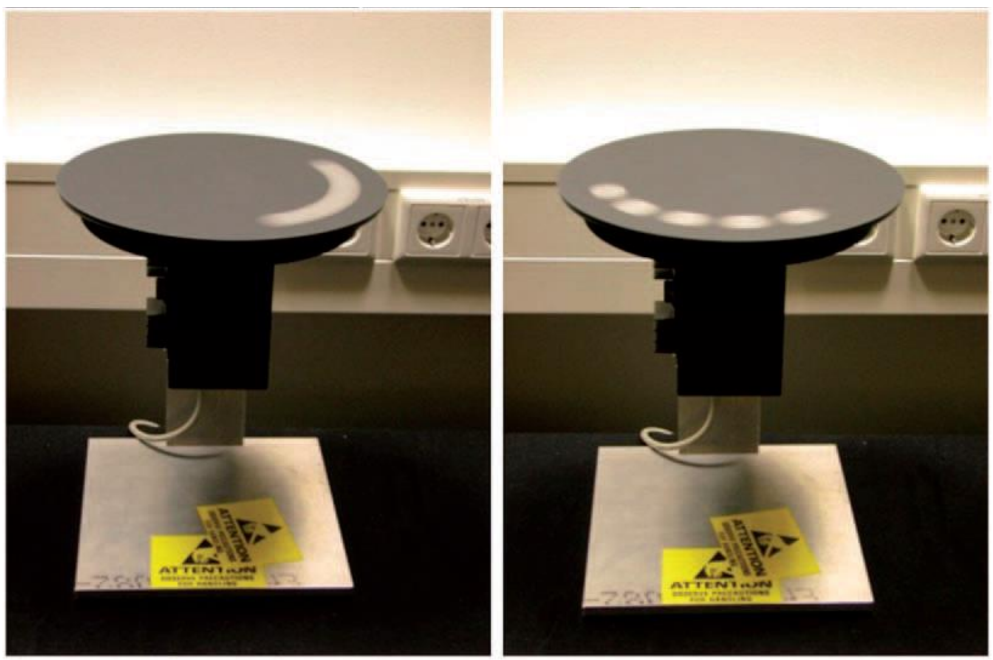
Sources: https://webstore.iec.ch/publication/4150 , https://webstore.iec.ch/publication/4173

IEC PST result curve



Stroboscopic Visibility Measure (SVM)

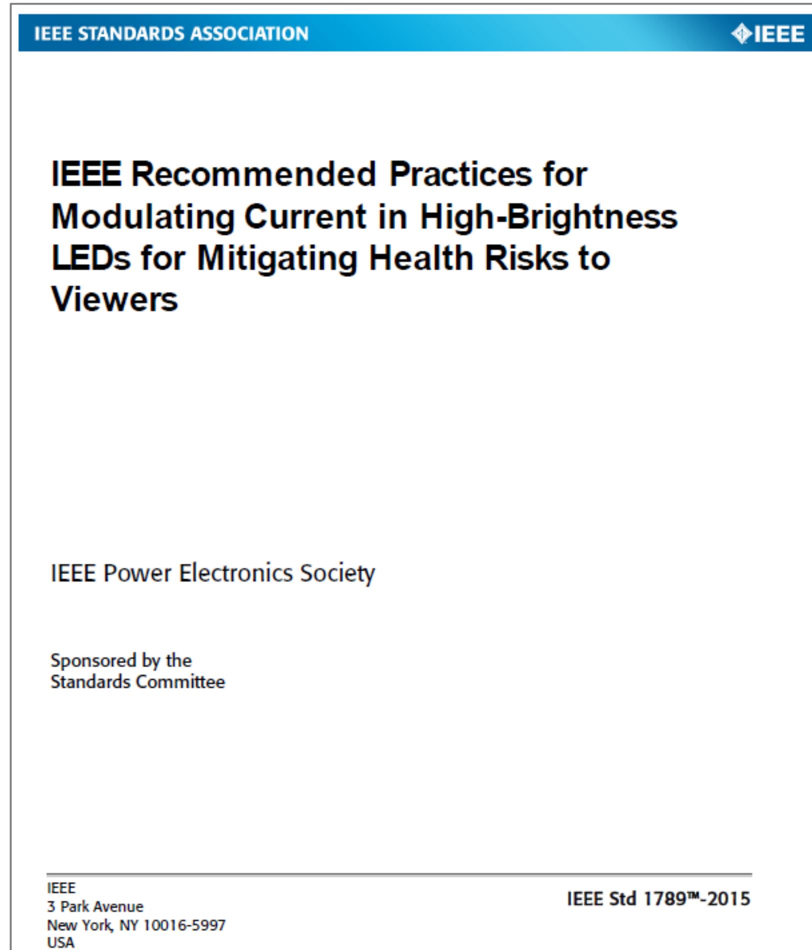
- Measures primarily stroboscopic effects >80Hz (for moving objects), not necessarily static flicker
- Not yet well known or widely used in industry
- Based off of human perception trials



Source: *Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems*
http://lrt.sagepub.com/content/early/2014/05/12/1477153514534945.full.pdf?ijkey=GcQ3UW7Qz2UwqtM&keytype=ref

IEEE 1789-2015

- "IEEE **Recommended Practices** for Modulating Current in High-Brightness LEDs for Mitigating **Health Risks** to Viewers"[1]
- Results drawn from multiple studies
- Results were somewhat controversial[2]



IEEE STANDARDS ASSOCIATION ◆IEEE

IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers

IEEE Power Electronics Society

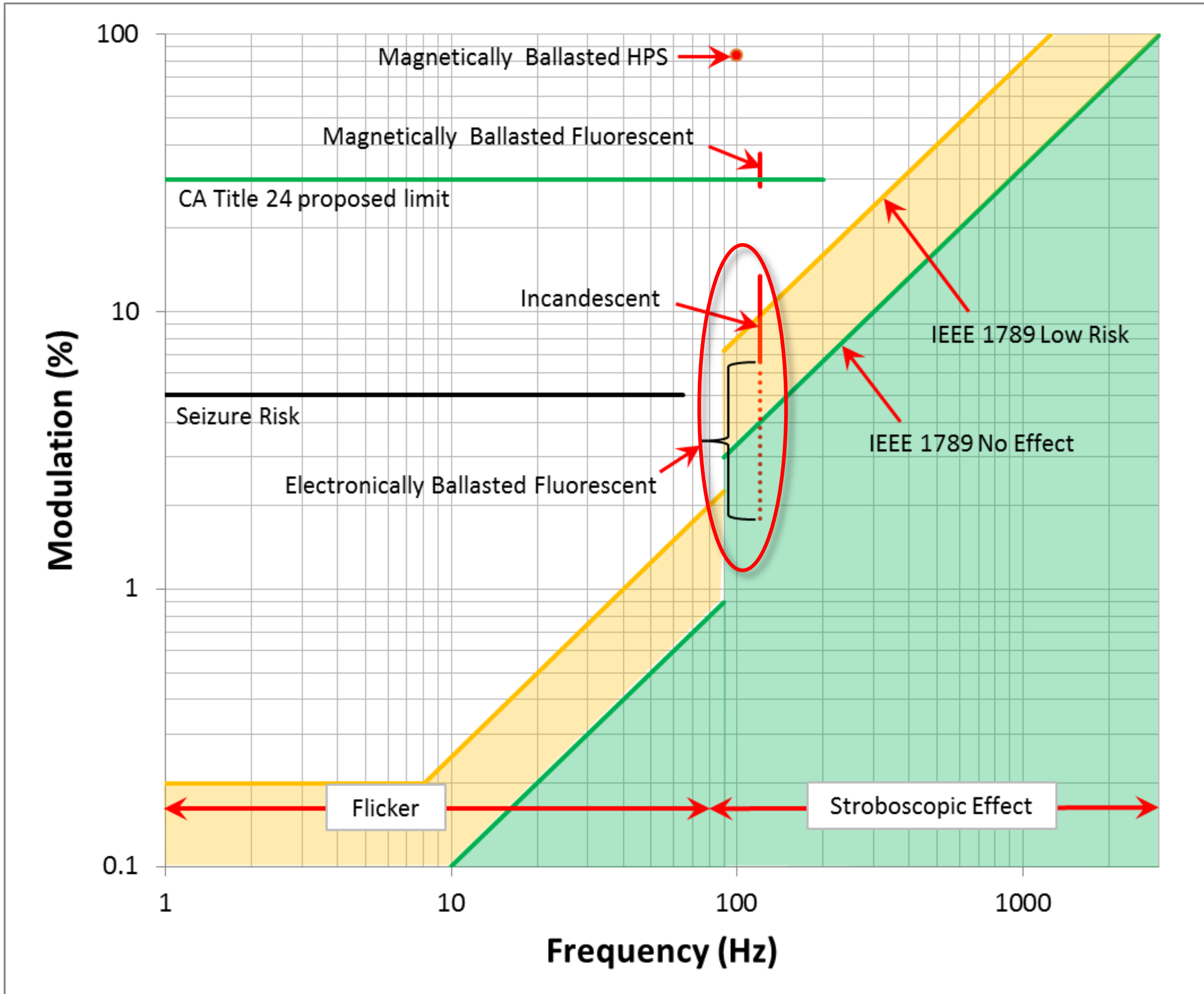
Sponsored by the
Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1789™-2015

Sources: [1]http://standards.ieee.org/findstds/standard/1789-2015.html
[2]https://www.nema.org/Standards/Pages/Temporal-Light-Artifacts-Flicker-and-Stroboscopic-Effects.aspx

IEEE 1789-2015 and common sources



Source: IEEE Std 1789-2015, Figure 18 "Low Risk Level and No Observable Effect Level"

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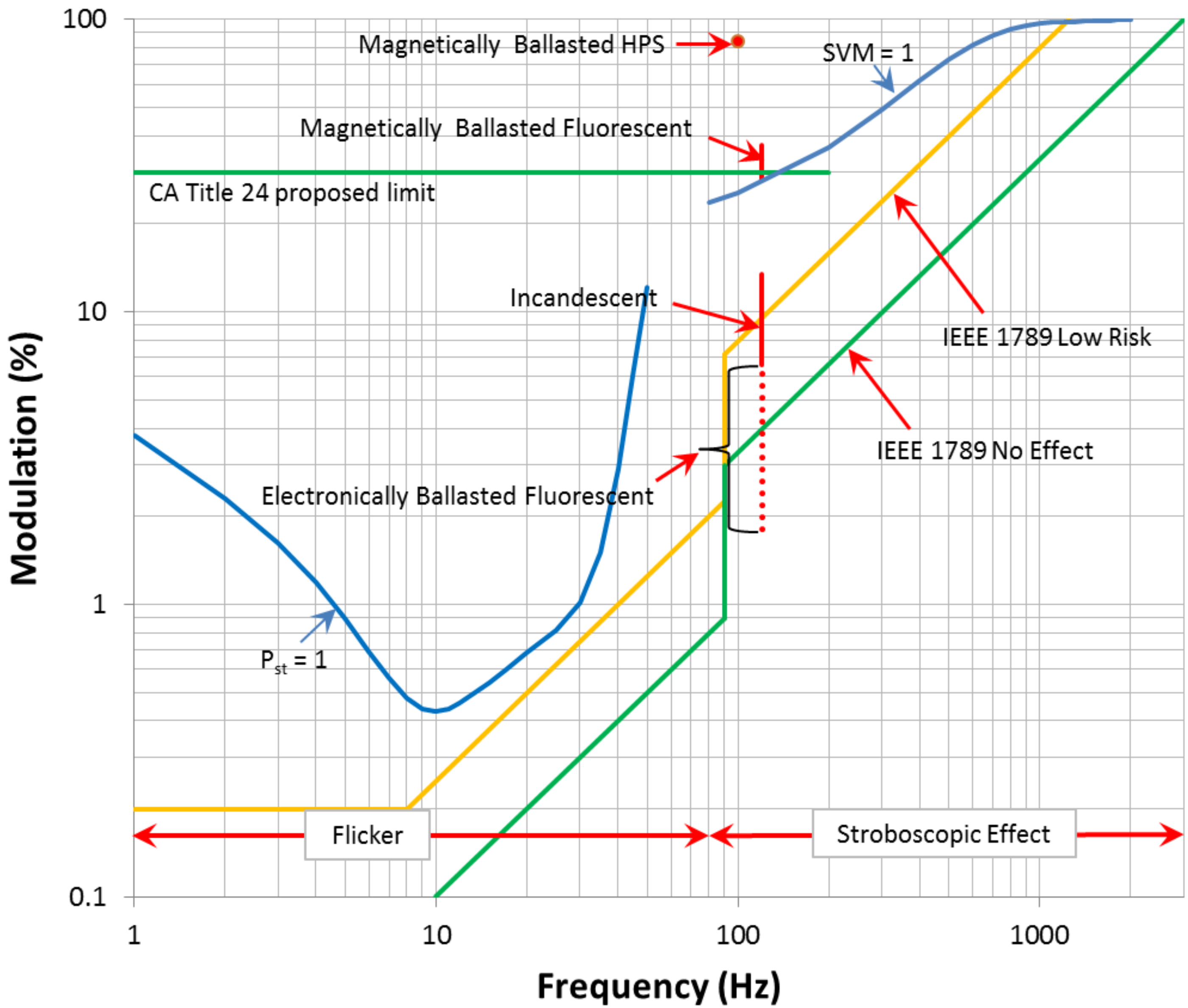
Comparison of several TLA metric limits



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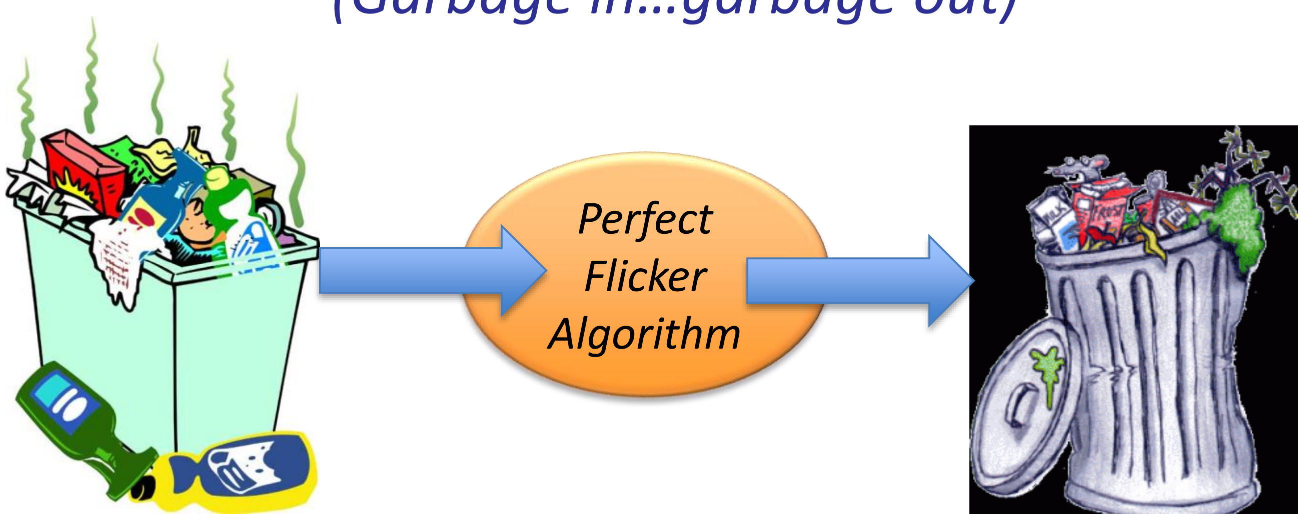
Challenges of measurement metrics

Measurement nuances: Equipment

- Spectral response of sensor
- Bandwidth and linearity of sensor
- Sampling frequency of recording device
- Vertical resolution of measurement

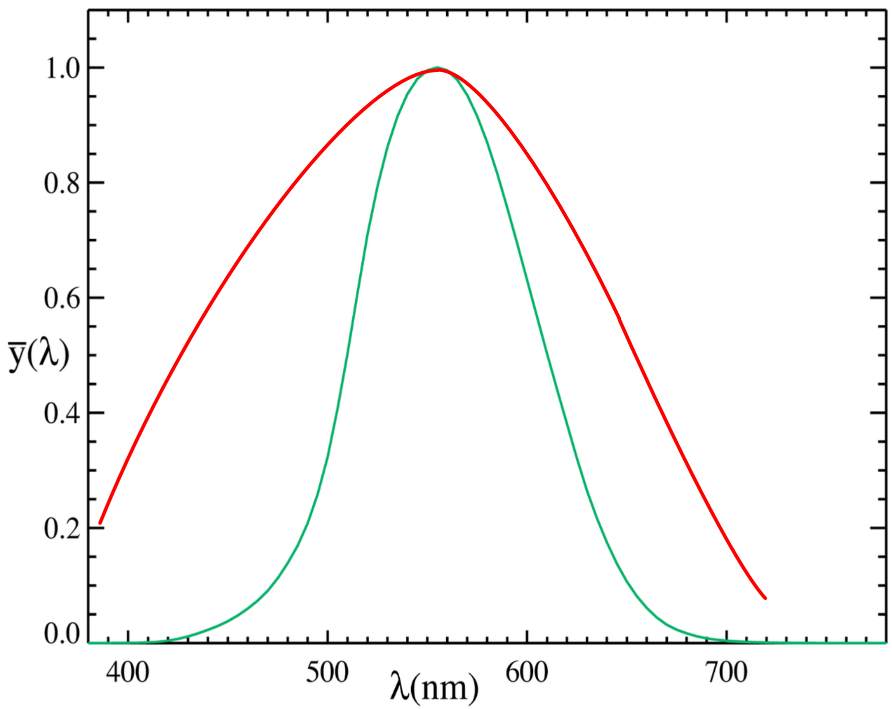
An algorithm is only as accurate as the data provided to it!

(Garbage in…garbage out)



Spectral response of sensor

- Energy Star: "Should match Commission Internationale de l'Eclairage (CIE) spectral luminous efficiency curve"
  - (Should respond to the same frequencies of light in the same manner as the human eye)

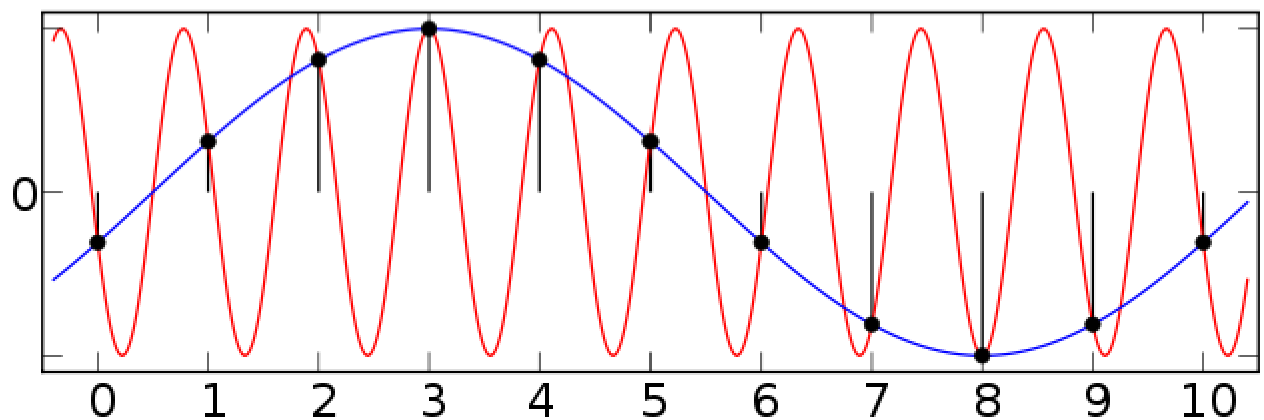


Green: photopic human eye response curve

Red: typical photodiode

Bandwidth of sensor

- If a sensor has intrinsic filtering (by design or otherwise), it may ignore higher-frequency signals
- Common light meters or commodity devices may only measure signals at a few hundred Hz (or less)
- Bandwidth that is TOO high may pick up undesired noise



Two different sinusoids that fit the same set of samples.

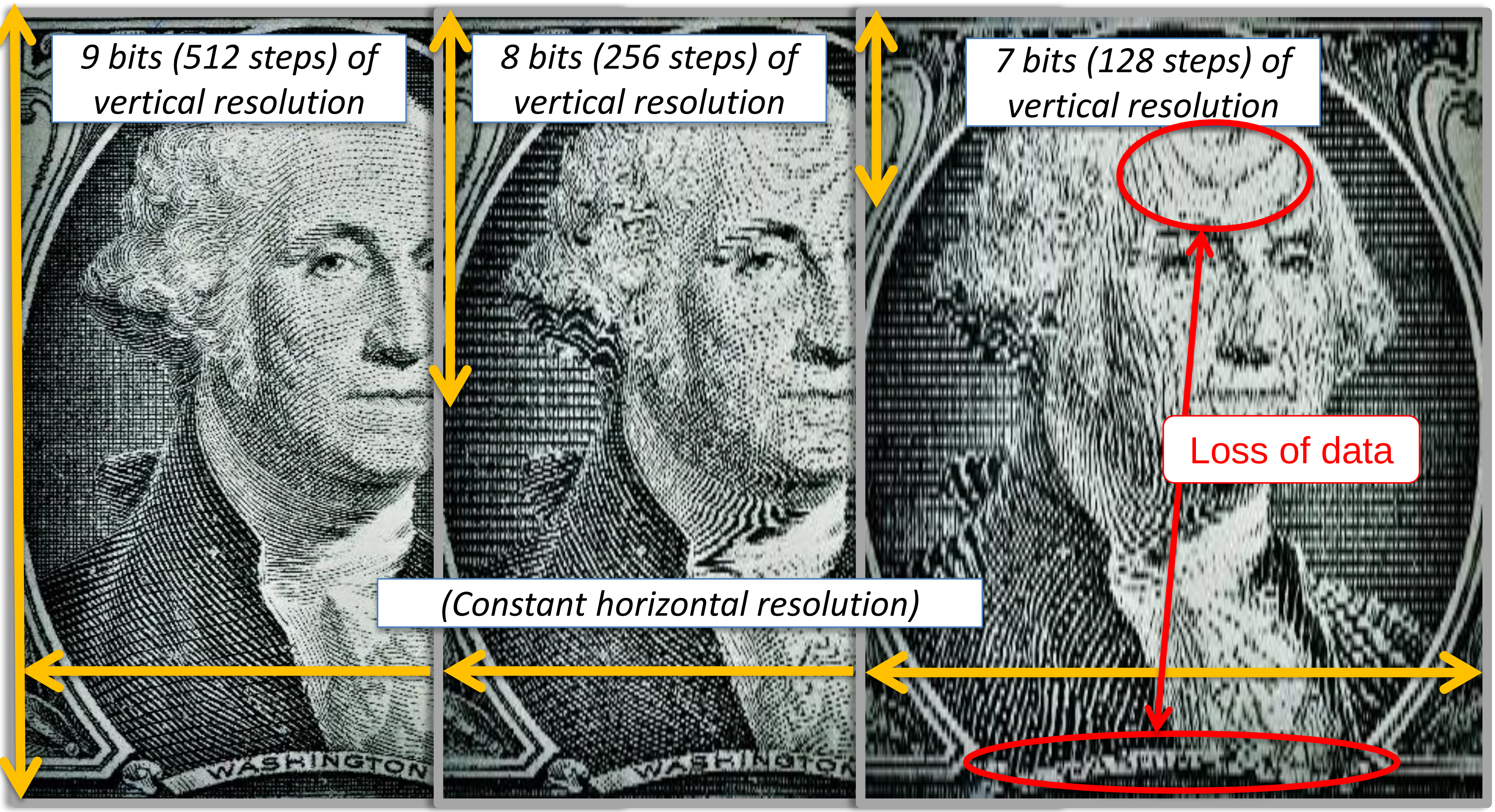
Source: https://en.wikipedia.org/wiki/Aliasing

Sampling frequency of recording device

- Energy Star: "The equipment sampling rate used shall be ≥ 2 kHz [samples per second]."
- Minimum: sampling frequency must be 2x the maximum frequency of interest (Nyquist rate)
  - Better: sampling frequency should be 10x the maximum frequency of interest
- Sampling that is too slow distorts the measurement of the signal and can miss higher-frequency components
  - Sample frequency is one of the differences between analog phone-quality and CD-quality audio

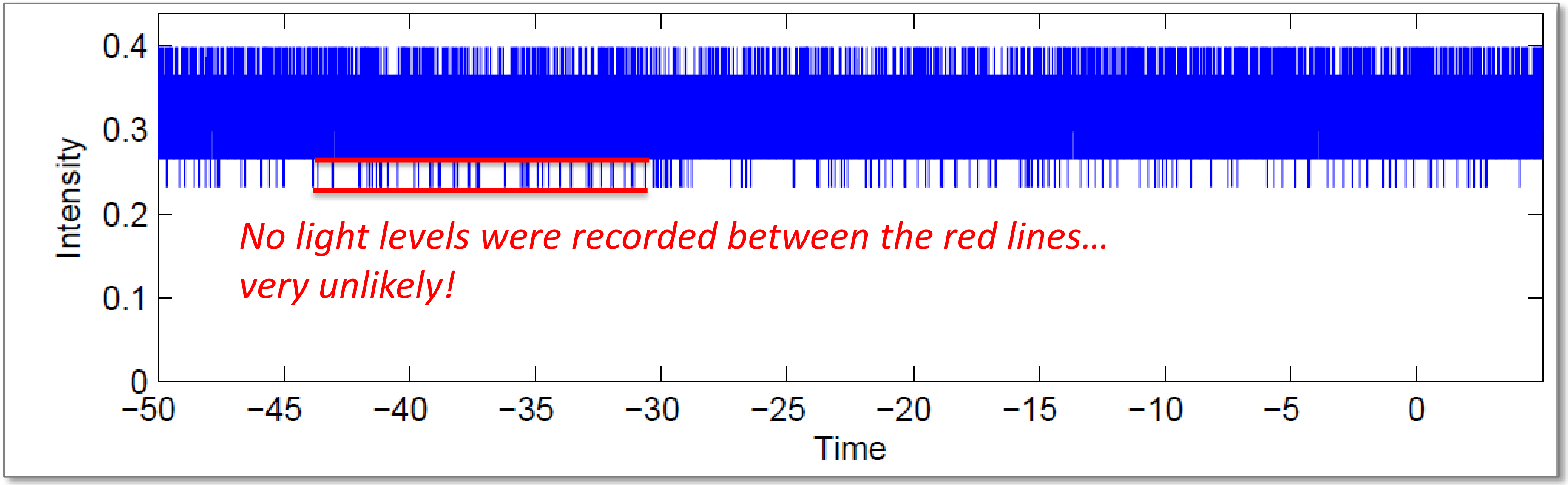
Resolution of measurement

- Typical oscilloscopes have only 8 bits of resolution
- For very small signals, data gets steppy (*quantized*)



Resolution of measurement

- Undesirably-quantized data can be seen on a light level graph
- This indicates the amplitude of the signal should be increased and retested



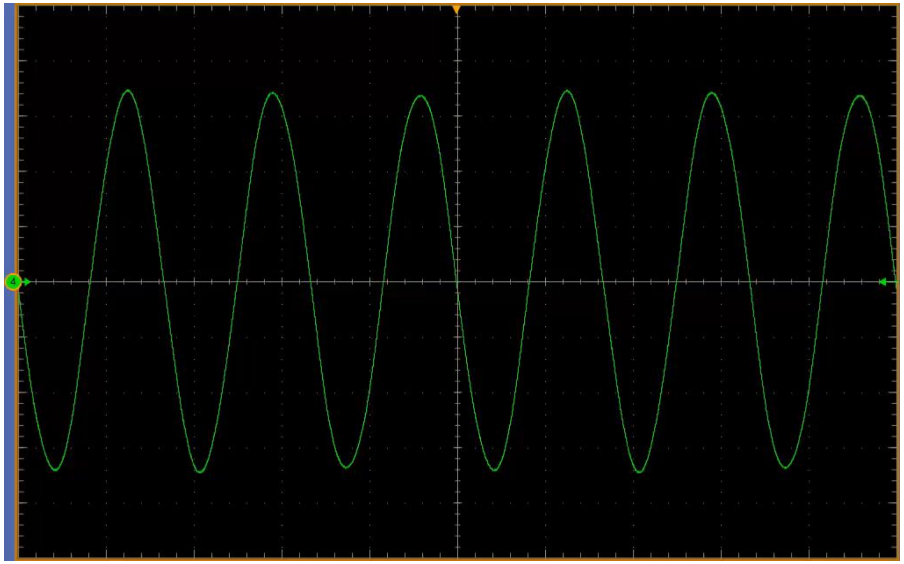
Measurement nuances: Test conditions

- Power source
- Mechanical stability
- Ambient light
- Sample length
- Stabilization

Power source

- Power sources that are "too perfect" (inverters, power supplies) may mask poor real-world behavior
- Normal building power may have specific noise sources (motors, elevators) that are impossible to duplicate
- An ideal source reliably and repeatedly reproduces common noise; for example:

$$y(t) = 120 \times \sqrt{2} \times \sin(2 \times \pi \times 60 \times t) + 2.25 \times \sin(2 \times \pi \times 200 \times t)$$



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Mechanical stability

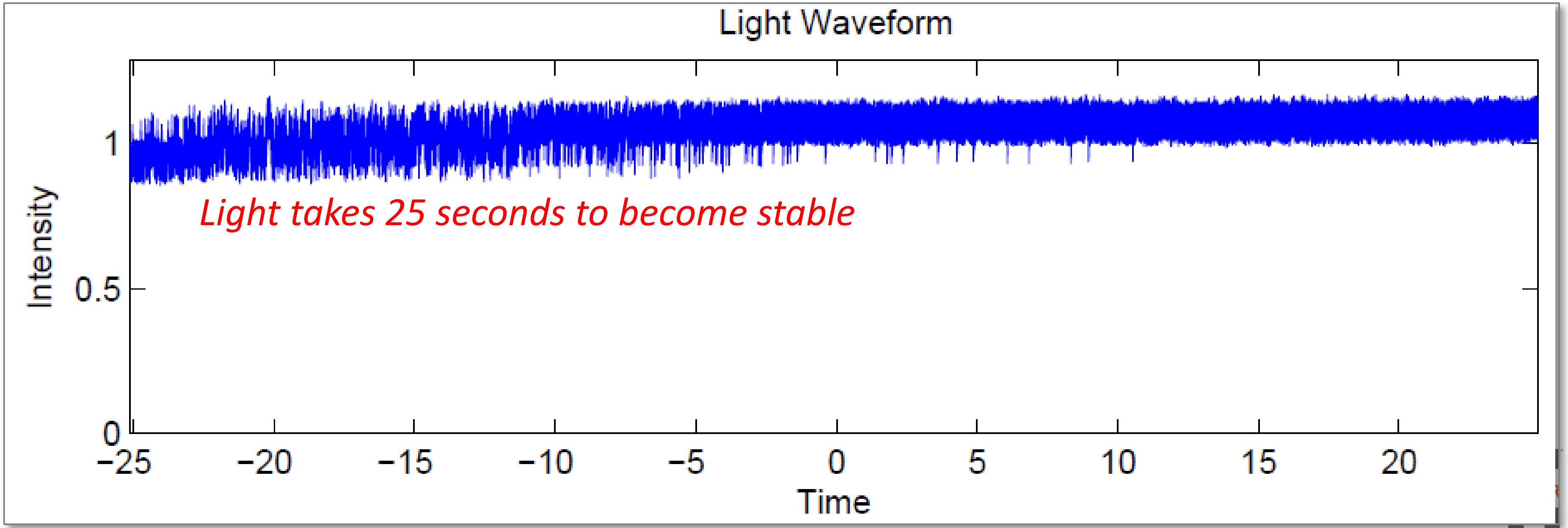
- Mechanical vibrations may result in detected modulation of light (especially with light gradients)
- This can be coupled in from nearby equipment or even footsteps
- Test samples and measurement probes should be securely attached to the test chamber, and isolated from vibration

Ambient light

- External light sources can suppress or corrupt proper flicker measurement
- Measurements should be taken in a dark box
  - A total integrating sphere is unnecessary; relative light levels are sufficient
- Zero light = zero signal

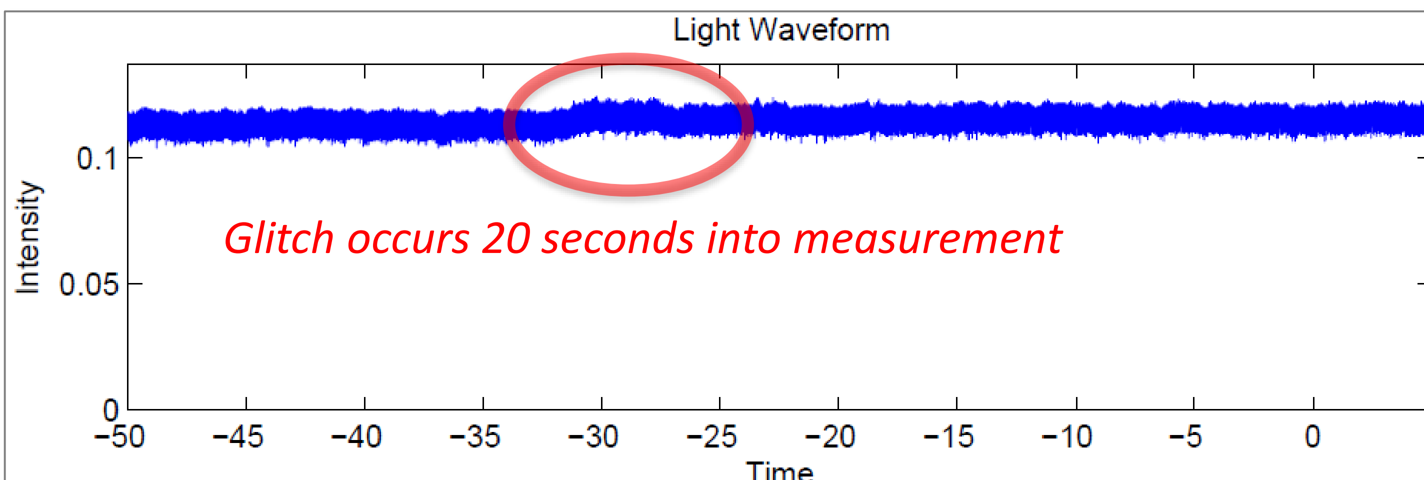
Stabilization

- Lamps may behave differently during their first few seconds or minutes of operation
- When should the measurement be taken?
- How long should a user wait for stable light output?



Sample length

- Energy Star: "The equipment measurement period shall be ≥ 100 ms"
- What if flicker is seen only every 2s? Every 20s?
- Large measurements at high resolution create large files
  - 20k samples/second * 60 seconds = 1.2M samples
  - Some equipment or software cannot handle such large files well (Excel)



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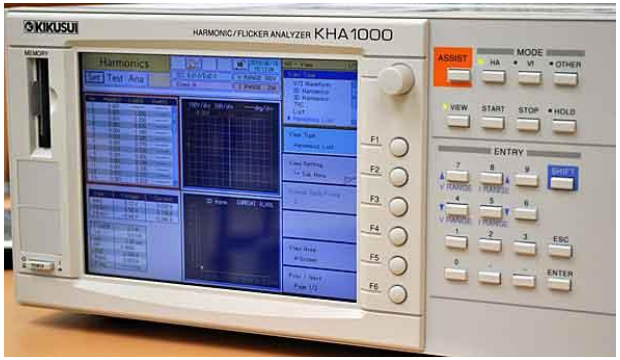
New Industry Efforts

NEMA TLA work

- NEMA has a TLA working group developing a method of reproducible measurement focused on general purpose LED lighting
- Pass/fail limits can be set by external standards-setting bodies (such as IES) on an application-specific basis
- It will involve a digital measurement and mathematical frequency-based analysis



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NEMA TLA scope

The purpose of the standard is:

1. Recommend a method of quantifying the visibility of temporal light artifacts (TLA), and
2. Propose application-dependent limits on TLA

The NEMA group will most likely propose initial application-dependent limits, which will later be refined by IES.

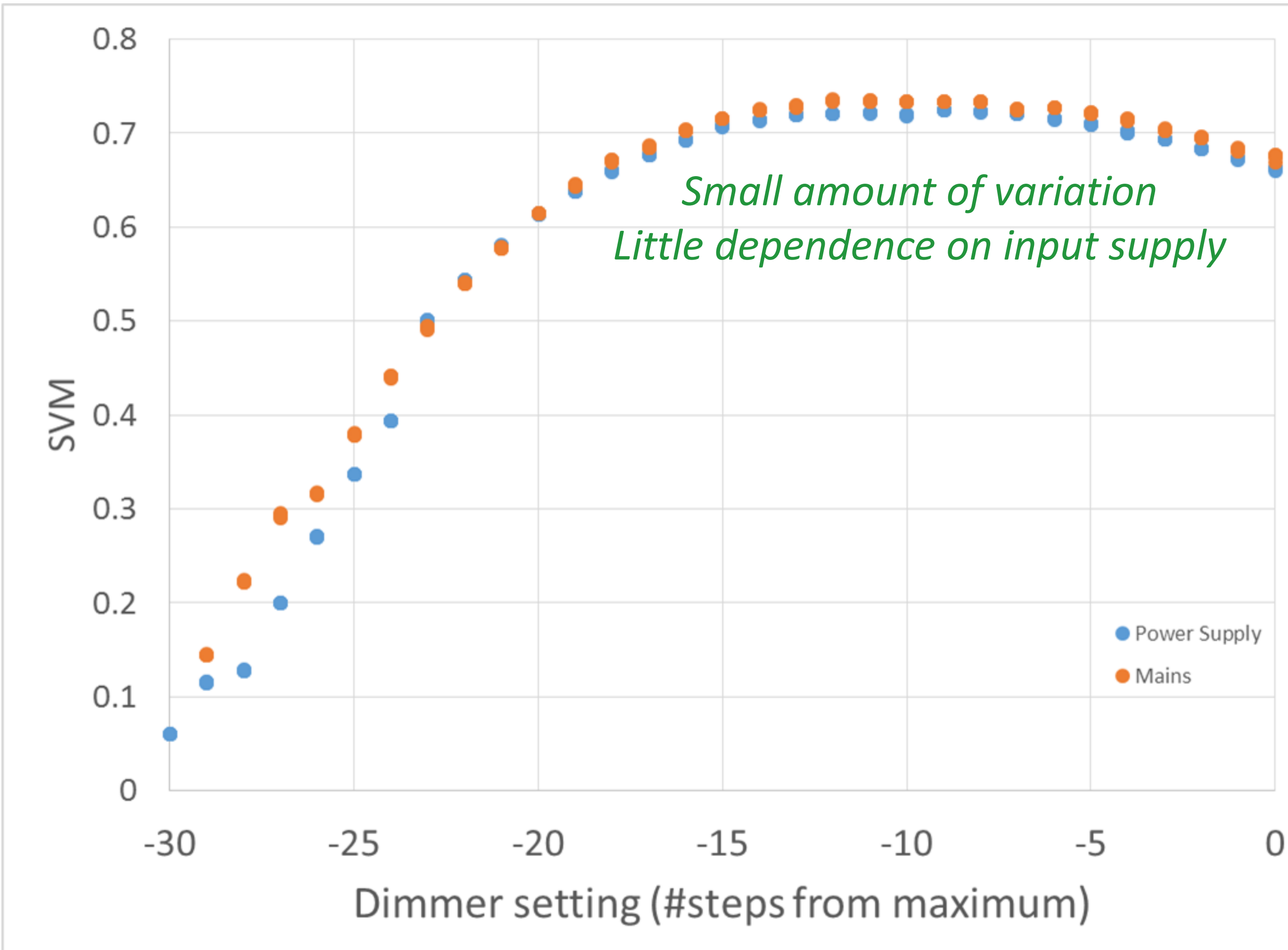
NEMA TLA results (so far)

- Data has been collected through a Round Robin study
  - 3 dimmer models
  - 7 light source models
  - Measure each combination, with no dimmer and at three different settings with dimmer
  - Note cases where TLA may have been observed

Summary from one manufacturer:

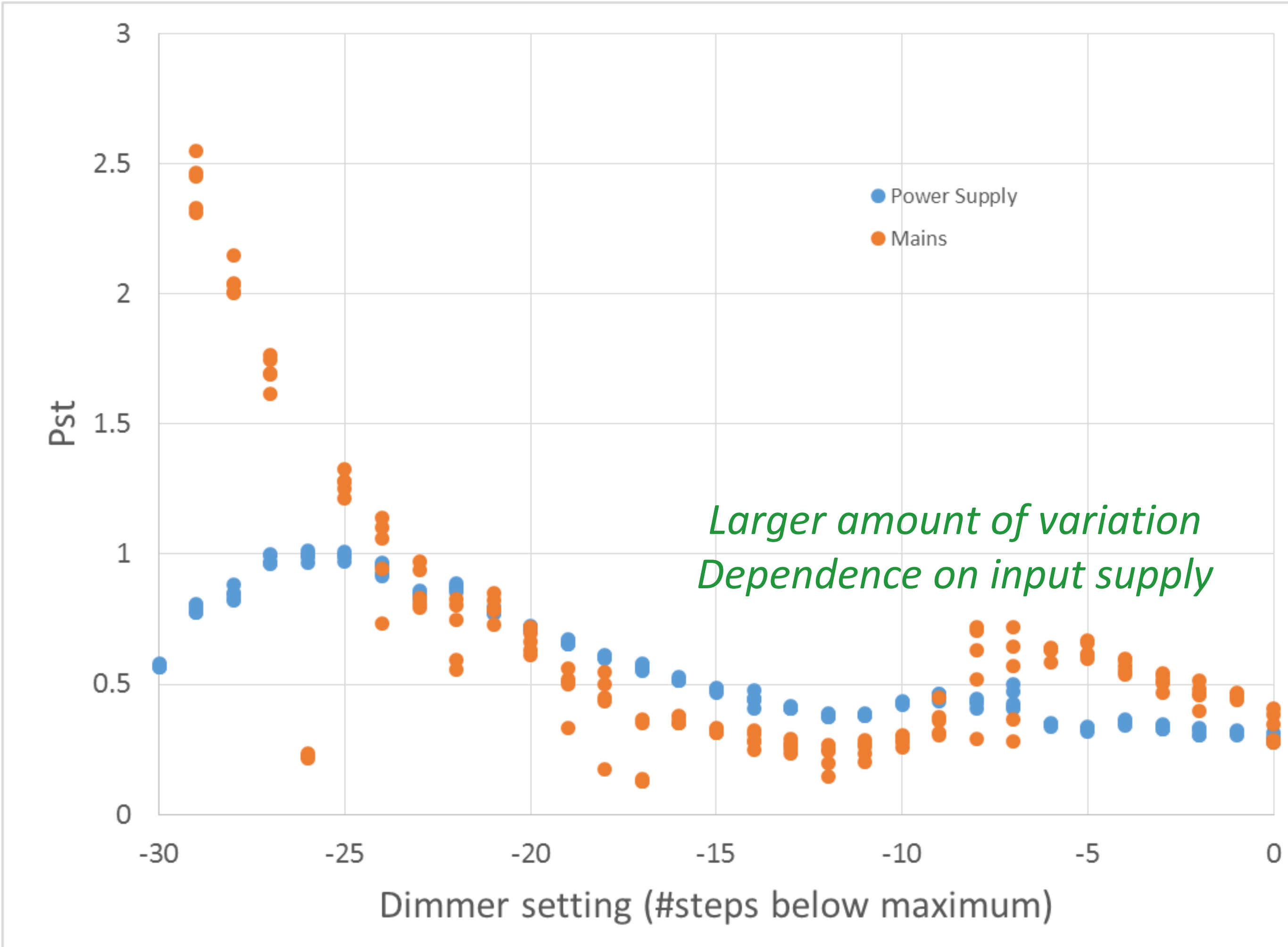
Metrics with Dimmer					
Level	% Flicker	Flicker Index	LRC	SVM Metric	Pst Metric
High	29.4	0.077	0.368	0.294	0.637
Medium	39.0	0.097	0.442	0.390	0.547
Low	30.0	0.075	0.576	0.300	1.028

Round Robin: Detailed look at one dimmer/lamp (SVM)



Each point measured 5 times.

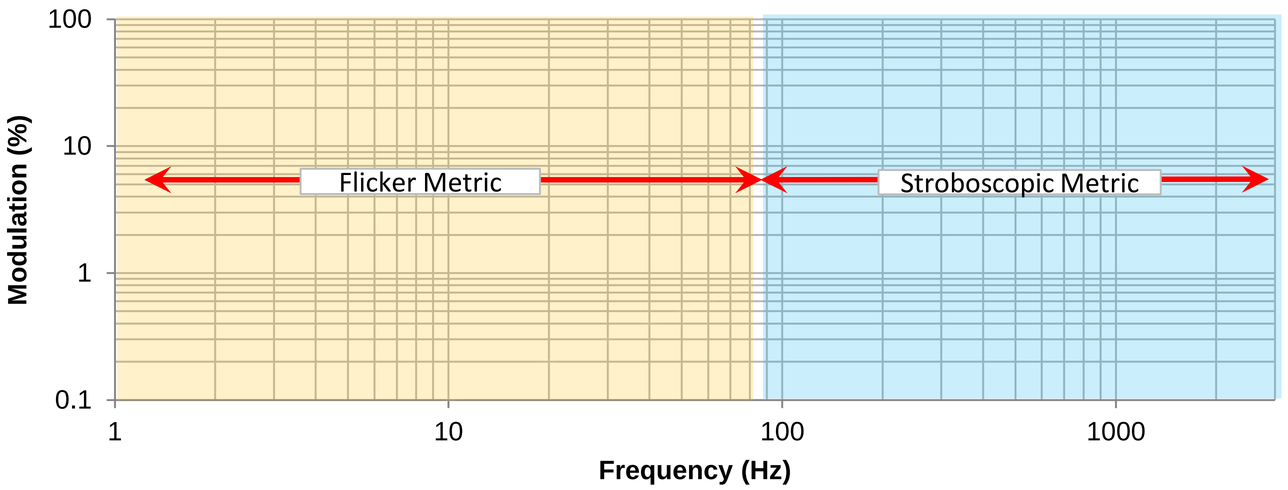
Round Robin: Detailed look at one dimmer/lamp (P_{st})



Each point measured 5 times.

NEMA TLA proposal (so far)

- A single value may not accurately capture all application-specific requirements
  - Some applications or users may be more sensitive to visible flicker (task-based work)
  - Some applications or users may require minimal stroboscopic flicker (video, motion-based work)
- A dual-value metric may be most suitable

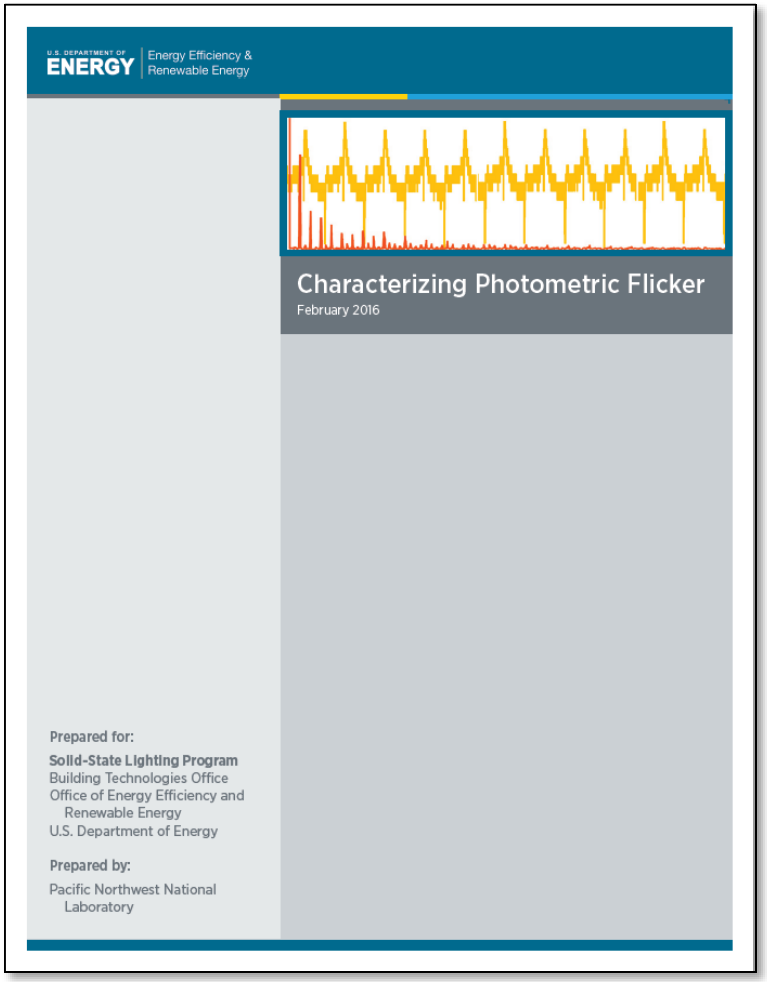


NEMA TLA next steps

- When completed,
  - Compare results
  - Select metrics for manufacturers to report
- Create suggested limits on the metrics for different applications
- Transfer methodology to IES for detail on applications and associated limits
- Immediate interest in using NEMA TLA metric as part of a consumer dimming logo

DoE Flicker Characterization Study

- Report on the performance of commercially available flicker meters against a benchmark
- Purpose of the study:
  - Help specifiers determine the flicker behavior of lighting products
  - Accelerate the development of standard test and measurement procedures
- Published in February 2016



Source: http://energy.gov/eere/ssl/downloads/characterizing-photometric-flicker

DoE Flicker Characterization Study: Conclusions

1. "Lighting manufacturers and testing laboratories should start characterizing lighting products for flicker"
2. "When characterizing flicker, take measurements at full as well as one or more dimmed light levels"
3. "Lighting designers and specifiers might consider purchasing a handheld meter and starting to characterize the flicker"

   "[But] watch out for ambient light and other conditions that might result in the handheld meter not yielding as accurate a result"

4. "Follow IES, CIE, and NIST developments for flicker…"

   "…especially those that consider aperiodic waveform content, or allow weighting factors to be applied to specific frequencies of interest…"

Other Industry Efforts

- CIE working group: *TC 1-83: Visual Aspects of Time-Modulated Lighting Systems*[1]

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

- Third-party flicker testing services[2]

Sources: [1] http://div1.cie.co.at/?i_ca_id=549&pubid=466
[2] https://ul.com/newsroom/pressreleases/ul-launches-verification-service-for-low-optical-flicker/

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Where do we go from here?

Recap: Characteristics of a good TLA metric

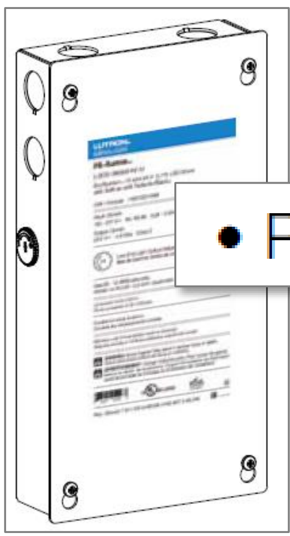
- Accounts for frequency
- Accounts for wave shape
- Covers visible and stroboscopic (non-visible) flicker
- Accounts for non-steady-state flicker
- Adaptable for different applications
- (Relatively) easy to measure, calculate, and understand
- Widely adopted

No one metric today meets all of these!

Standards adoption

- Some manufacturers are starting to cite IEEE-1789 in their product specifications:

- Meets IEEE1789 recommendations over its entire dimming range, eliminating negative health effects related to flicker



- PWM dimming meets IEEE1789.

- However, CA Title 24 is the only known US standard that <u>mandates</u> a flicker metric

Unintended consequences

- Adding stroboscopic measurements to flicker tests may cause otherwise "good" lamps to fail
  - *Most manufacturers' visual tests today don't account for stroboscopic flicker*
- Improper use of flicker metrics may mandate high-levels of performance, even when unnecessary

- Poor testing procedures may cause invalid results, or incorrectly attribute flicker to the control or driver
- Flicker tests may add to already-lengthy testing

Parting thoughts

- Should I be concerned about TLA?
  - Yes! It is a source of occupant discomfort and dissatisfaction
- Are there standards I should be citing for flicker?
  - Not yet! Current standards are either useless or overly stringent for most applications.
- How can I minimize chances of having flicker?
  - Work with quality manufacturers
  - Realize that low cost often correlates with less filtering (and more TLA)
  - Spec digital control schemes over analog ones
- Stay tuned for further developments!

Demonstration invitation

- Where do you see flicker?
- Where do you see stroboscopic effect?
- What's visible to your naked eye vs. a camera?
- Shows effects of frequency, wave shape, modulation depth, and duty cycle on TLA visibility

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Please remember to complete the course evaluations. Thank you.