Pacific Northwest
NATIONAL LABORATORY

A new metric for visibility of the phantom array effect

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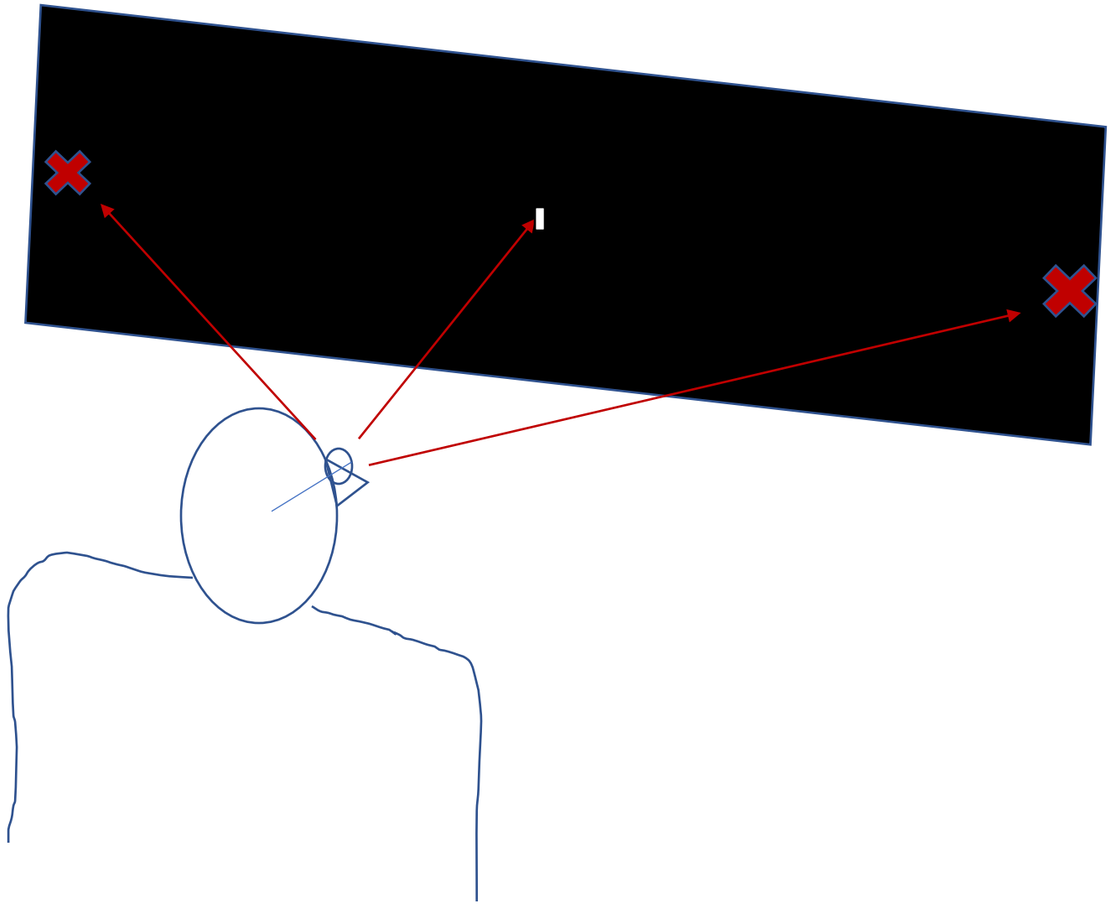
Phantom Array Effect

Phantom array effect (PAE) occurs when your eyes move. The effect can turn a flickering light source or the object it is illuminating into a series of dots, parallel lines or repeated images across your visual field, akin to rabbit tracks in the snow. You may have noticed this from some automobile taillights when driving at night.
It's also called ghosting.

Image source: IES

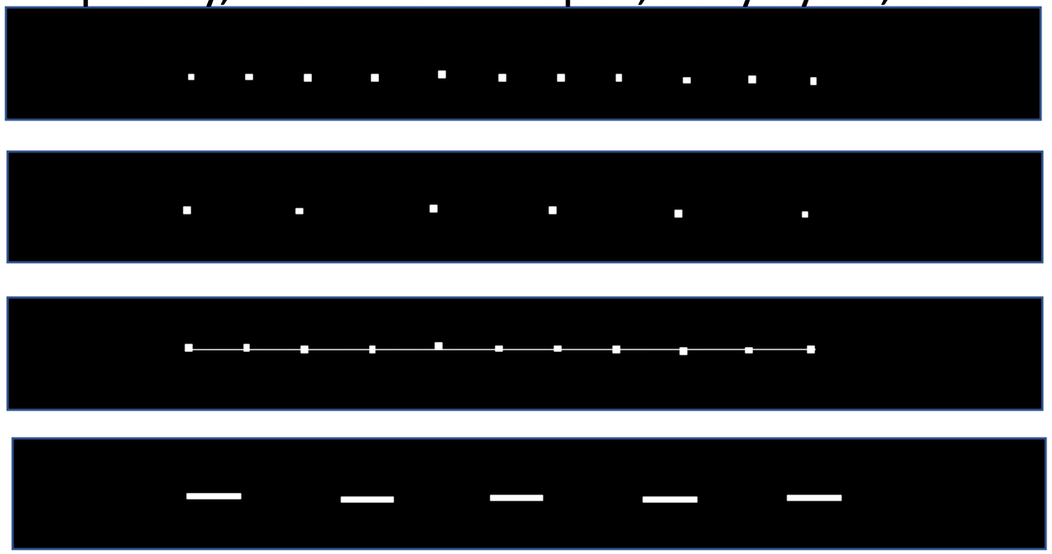
Phantom array effect – Visual patterns



Fixed view on-axis view

Scanning view of continuous (DC) source

Scanning view of TLM source, depending on frequency, modulation depth, duty cycle, etc.



Scope of Study

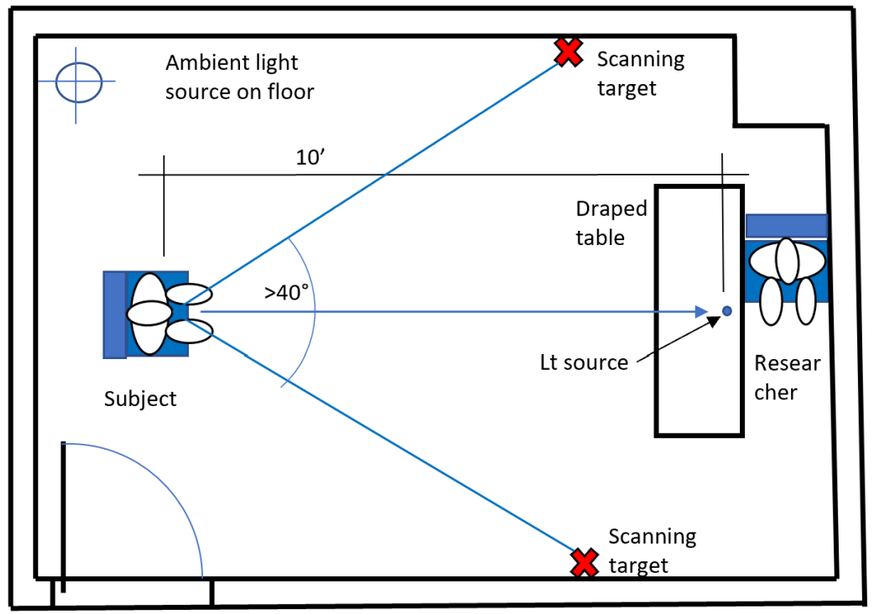
- Background
  - PAE may cause danger in traffic and transportation.
  - So far, reliable and generic metrics are still under development.

- Goals of this study
  - Investigate human's visual sensitivity to PAE
  - Develop a metric to quantify PAE
  - Verify this metric in terms of viability and robustness with sampling rate
  - Provide recommendations for this metric, such as recommended metric value, sampling rate, sampling duration, etc.

Subjects, Test Setup and Rating Scales

- Subjects
  - 36 people – 17 of them have high sensitivity to PAE (determined by their responses to test light signals)

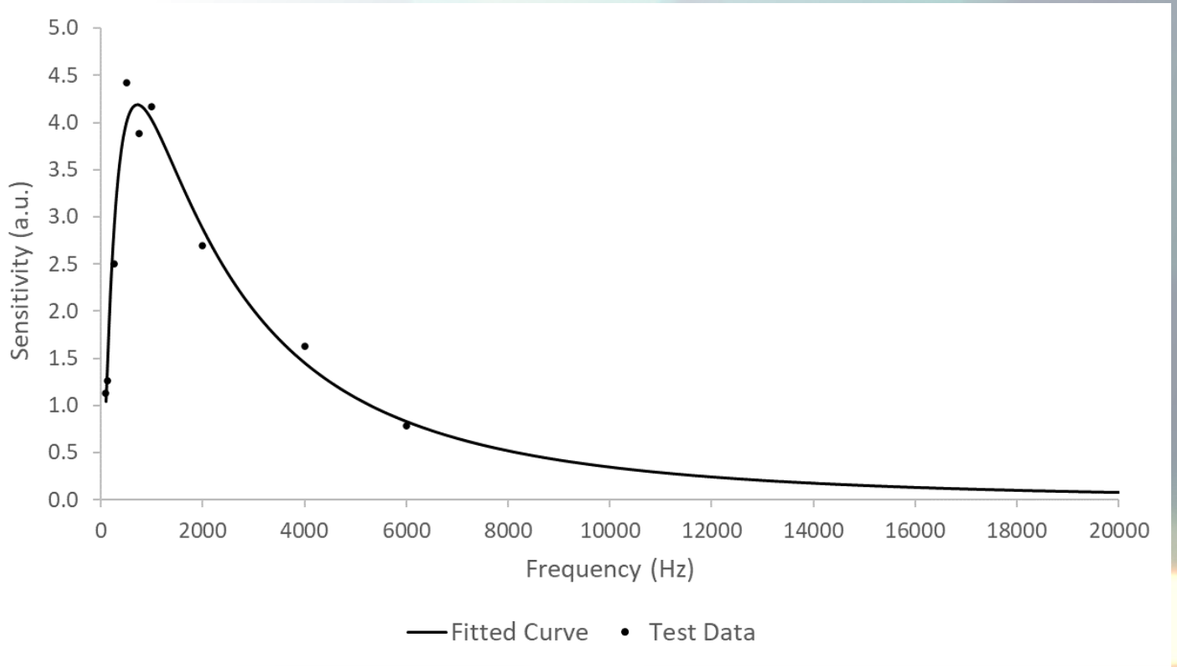
- Scale of ratings for Phantom Arrays
  - 6 – Highly visible repeating pattern
  - 5
  - 4
  - 3
  - 2
  - 1 – *Assumed threshold for "just-noticeable"*
  - 0 – No repeating pattern visible



Floor Plan of Experiment Room, not to scale

Test Results and Analysis

- We tested and calculated the threshold modulation depth of sine waves for frequencies at 90, 120, 250, 500, 750, 1000, 2000, 4000, and 6000 Hz.
- Sensitivity data points were found by calculating the reciprocals of the threshold modulation depths.
- A log-normal function was used for curve fitting to derive a sensitivity curve for average people.
- This sensitivity curve drops close to 0 slowly as frequency increases.



$$Sensitivity = \frac{6023.4}{f} e^{-\frac{(\ln f - 7.97)^2}{2.79}}$$

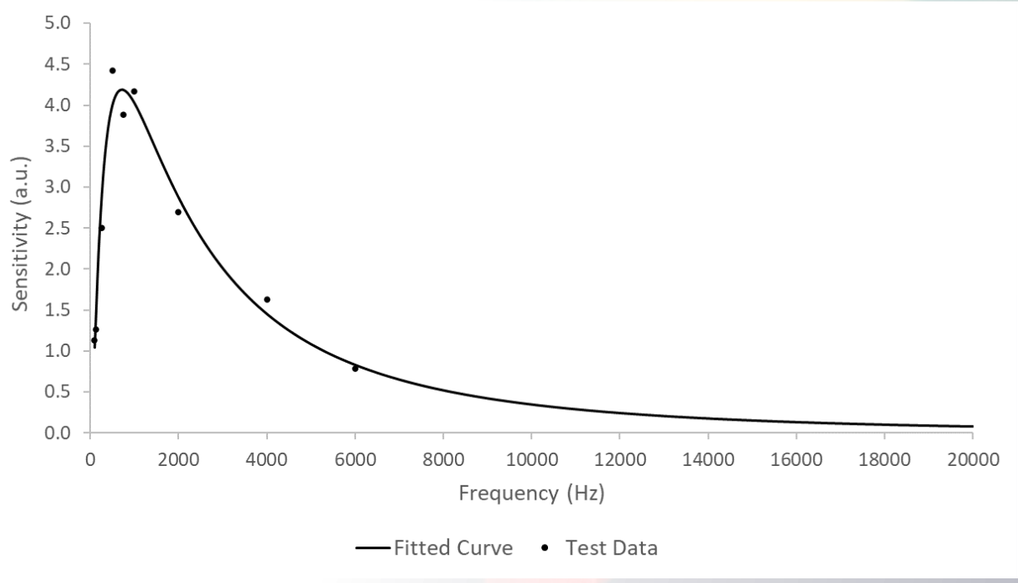
$$\mathrm{f} = \mathrm{frequency}$$

Form of the new metric

- We use Minkowski Norm as a mathematical model to develop Phantom Array Visibility Measure (PAVM)

$$PAVM = \sqrt[n]{\sum_{m=1}^{\infty}(C_m * S_m)^n} \quad \begin{cases} < 1, & not\ visible \\ = 1, & just\ visible \\ > 1, & visible \end{cases}$$

where C_m is the amplitude of the m^{th} Fourier component of a Temporal Light Modulation (TLM) waveform divided by the direct current (DC) value of the waveform, and S_m is the sensitivity value of visibility for a sinusoidal wave at the frequency of the m^{th} Fourier component, calculated from a time-domain threshold visibility function.



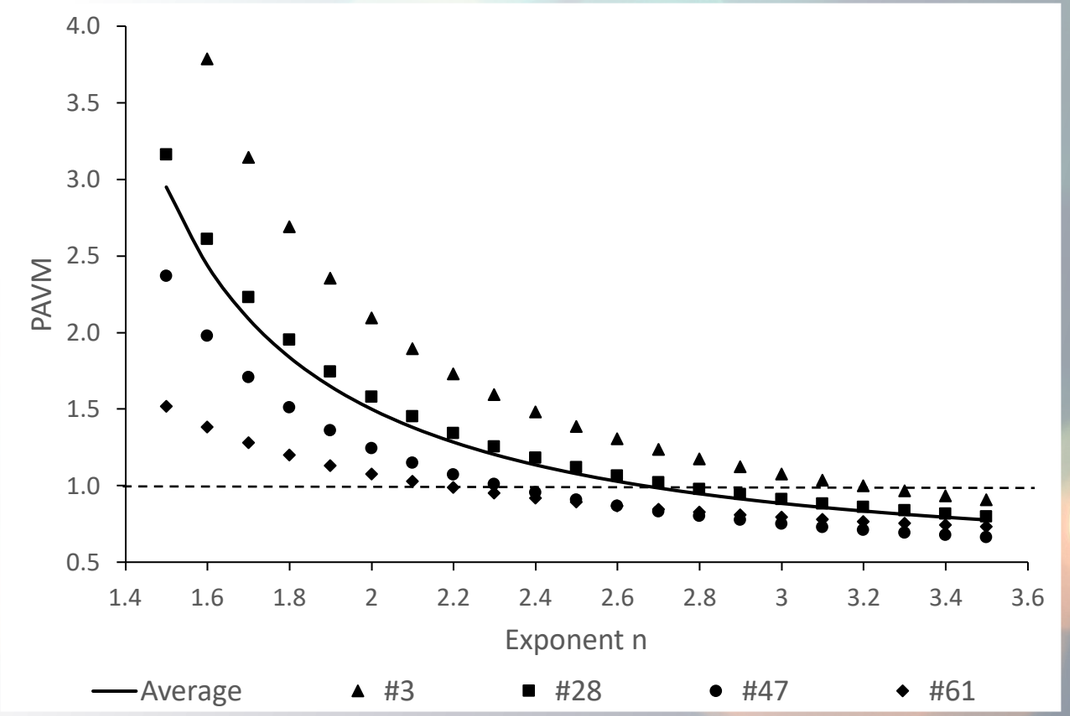
Determine Minkowski Exponent

$$PAVM = \sqrt[n]{\sum_{m=1}^{\infty}(C_m * S_m)^n} \quad \begin{cases} < 1, & not\ visible \\ = 1, & just\ visible \\ > 1, & visible \end{cases}$$

Waveform	#3	#28	#47	#61
Frequency (Hz)	90	90	120	6,000
Modulation (%)	50	50	50	100
Duty cycle (%)	10	30	50	50
Mean rating, all subjects*	1.056	1.028	0.972	1.111
Probability of being visible, all subjects	50%	56%	58%	50%

*Note: here, Rating ≠ PAVM

The Minkowski exponent n was determined to be 2.7 for the 4 just noticeable waveforms to yield the average PAVM = 1.

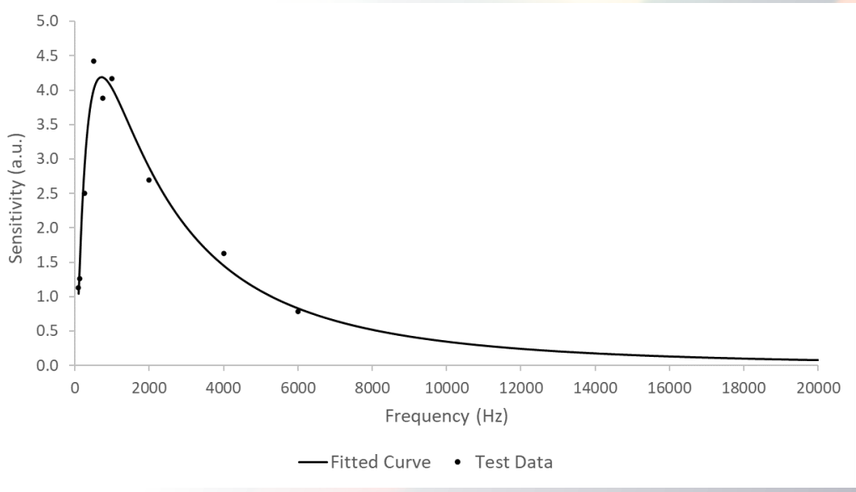


Phantom Array Visibility Measure (PAVM)

- Therefore, the PAVM measure was developed as

$$PAVM = \sqrt[2.7]{\sum_{m=1}^{\infty} (C_m * S_m)^{2.7}} \begin{cases} < 1, & not\ visible \\ = 1, & just\ visible \\ > 1, & visible \end{cases}$$

where C_m is the amplitude of the m^{th} Fourier component of a TLM waveform divided by the direct current (DC) value of the waveform, and S_m is the sensitivity value of visibility for a sinusoidal wave at the frequency of the m^{th} Fourier component, calculated from a time-domain threshold visibility function.

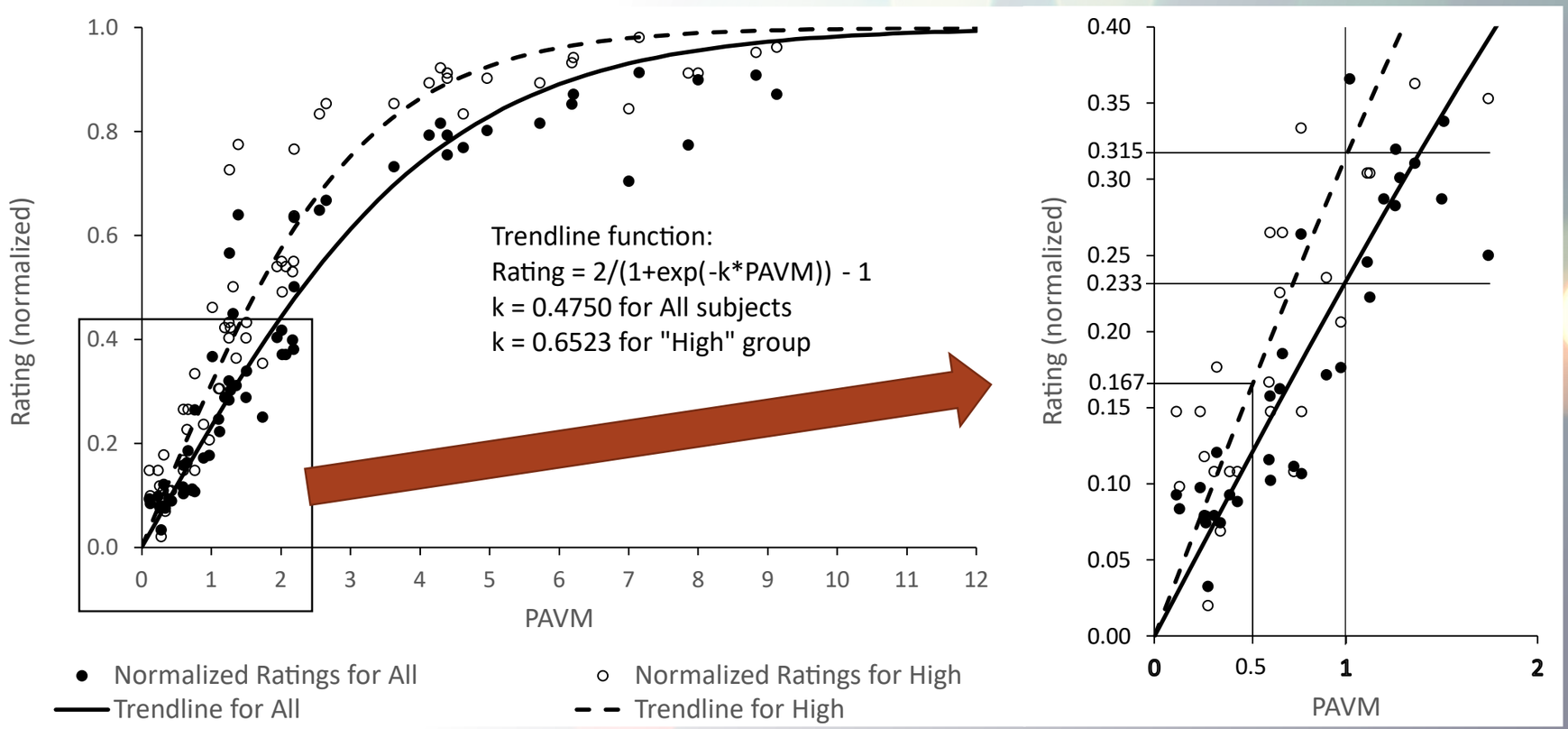


Ratings vs. PAVM values

- For each waveform, rating scores from *All* and *Higher-sensitivity* subjects were averaged and normalized to compare with the calculated PAVM values.
- To make this PAVM metric a better one, we recommend PAVM ≤ 0.5, where the normalized average rating ~ 0.167 for high-sensitivity people, thus, the original rating (in our study) ~ 1.0 as an intuitive threshold.

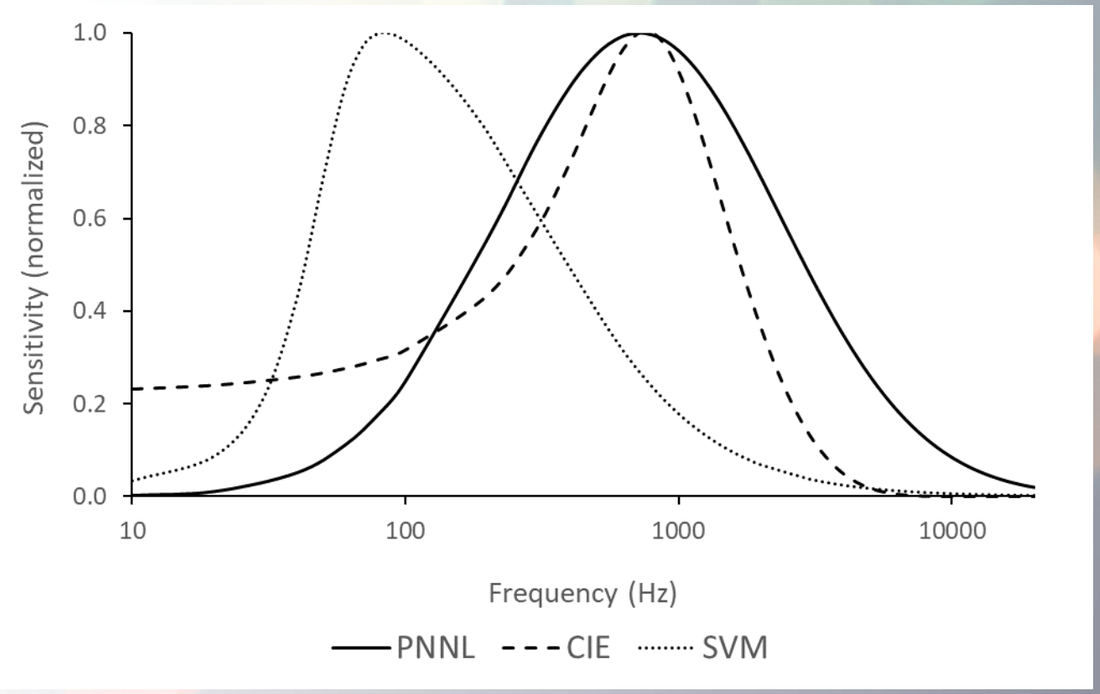
Rating Scores

Normalized	Original
0.167	1.00
0.233	1.40
0.315	1.89



Discussion and Summary

- The sensitivity of PAE reaches peak at around 715 Hz based on PNNL experimental conditions.
- This sensitivity curve has a less steep decline than provisional PAVM function described in CIE 249:2022. The PNNL curve better explains why some observers can still see PAE at 20,000 Hz.
- We recommend a sampling rate of 200 kSa/s or higher to obtain a stable PAVM value. And 2 second sampling duration.
- Sensitivity curves for PAE have different peak than Stroboscopic Effect. This is why we need a specific measure for PAE.



Acknowledgments

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Thank You!
Questions?

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