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RENEWABLE ENERGY

Characterizing Photometric Flicker

Handheld Meters

November 2018

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Executive Summary

Temporal light modulation (TLM) is the variation of light output as a function of time, and its presence can have adverse effects on health and visual performance (e.g., increased occurrence of migraines, reduced visual-task performance). TLM has been the subject of recent articles primarily associated with flicker in LED lighting. Lighting system characteristics that can affect flicker vary by technology; examples include filament thickness for incandescent sources, phosphor persistence for fluorescent and coated metal halide sources, and circuit designs for electronically ballasted or driven sources. The characterization of flicker, especially in the field, is important to ensure adequate living and working conditions.

Today, various types of flicker meters are available, including high-speed and precise benchtop models for laboratory environments and portable handheld meters that can range from simple smartphone applications in an existing smart device to scientific grade meters that have capabilities beyond flicker measurements. In this report, the performance of eight handheld meters capable of measuring flicker in the field is compared to a reference benchtop meter chosen based on its performance in the initial round of meter comparisons performed by Pacific Northwest National Laboratory (PNNL).[1]

The two most commonly used metrics for quantifying flicker remain Percent Flicker and Flicker Index, though meters today also have the capability of measuring and reporting other flicker metrics. Fundamental Frequency is also reported by meters and refers to the dominant sinusoidal component – the one with the greatest amplitude – of the fast Fourier transform (FFT) of the flicker waveform. For many traditional lighting sources, the Fundamental Frequency is simply twice the input-line-voltage frequency (e.g., 120 Hz for 60 Hz AC in North America). While less commonly reported by handheld meters, the Stroboscopic Effect Visibility Measure (SVM) attempts to predict both the visibility and acceptability of the stroboscopic effect, a visual artifact resulting from a light source's TLM and motion in an environment. SVM differs from Percent Flicker and Flicker Index in that it uses Fourier analysis to convert the light-intensity waveform from its time-domain representation to a frequency-domain representation so that frequency dependencies for varying effects can be accounted for by means of a weighting function. SVM does not address non-visible flicker, however, and may not be suitable for predicting some neurological issues. Various meters were capable of reporting SVM.   Thus, it is a metric studied in this report.

Based on the previous testing of benchtop meters, the Admesy Asteria SC-ASTR-01 High-Speed Illuminance Photometer was selected for permanent installation in an integrating sphere in PNNL's Lighting Metrology Laboratory. This meter served as the reference meter to which the handheld meters were compared. The handheld meters were set up in the integrating sphere just adjacent to the reference meter. A set of 12 light sources was selected for this study based on their being typical of a specific architectural lighting product, exhibiting a specific waveform characteristic (e.g., amplitude modulation, shape, and frequency), and/or because they had previously been tested and were available for re-use in this study. In order to characterize the performance of each handheld meter, testing was completed using an integration time of as close to 2 seconds as possible to allow for capturing metrics that require much time for their reporting. In some cases, however, the integration time was not configurable or even known, for some meters.

Table ES. 1 and Table ES. 2present meter performance as it relates to Percent Flicker and Flicker Index, respectively, as well as the performance at maximum and dimmed light output levels across all light sources tested. Two meters in particular are worth mentioning to qualify the results presented, as well as the smartphone application (i.e., Viso [App]). For the Viso meter, the results of this table include only a portion of all light sources and dimmed levels tested, since it deemed light levels inadequate on many occasions and would have required positioning the meter closer to the light source. The Everfine meter had limitations during testing related to the highest frequency it could measure, which affected percent flicker, and a software bug in

[1] Pacific Northwest National Laboratory for U.S. Department of Energy, *Characterizing Photometric Flicker*, February 2016. https://www.energy.gov/sites/prod/files/2016/02/f29/characterizing-photometric-flicker.pdf.

data transfer that affected flicker index. The latter issue was resolved, and limited follow-on testing confirmed this. Lastly, the Viso Application for smartphones does not use a dedicated sensor, but rather a smartphone's camera, to determine flicker performance of a light source. Although the performance is not great compared to the dedicated meters, it can be a handy tool to help identify that a problem may exist and lead to follow-up testing with a more adequate device.

Table ES. 1. Deviation of Percent Flicker for handheld meters relative to reference meter measurement.

Percent Flicker	Viso (App)	Viso	AsenseTek	Fauser	UPRtek	Everfine	GL Optic	Gigahertz-Optik
Mean Deviation (all measurements)	17.31	0.20	1.27	3.14	2.34	19.10	0.75	0.68
Mean Deviation (max levels)	10.69	0.25	1.76	4.06	2.53	10.31	0.54	0.72
Mean Deviation (dimmed levels)	33.20	0.00	0.61	1.91	2.08	30.82	1.03	0.64

Table ES. 2. Deviation of Flicker Index for handheld meters relative to reference meter measurement.

Flicker Index	Viso (App)	Viso	AsenseTek	Fauser	UPRtek	Everfine	GL Optic	Gigahertz-Optik
Mean Deviation (all measurements)	0.100	0.017	0.024	N/A	0.016	0.163	0.023	0.008
Mean Deviation (max levels)	0.038	0.005	0.010	N/A	0.009	0.111	0.006	0.002
Mean Deviation (dimmed levels)	0.250	0.066	0.042	N/A	0.026	0.232	0.047	0.016

The meters tested hold qualities that vary in utility depending on the intended use of the meter. This report presents each meter in a way that informs the reader regarding its design and utility (e.g., detachable sensor head allowing measurements to be performed or observed remotely). It is necessary, though, to also be aware of meter limitations that prohibit certain measurements from being reliable (e.g., some of the meters began to fail to detect flicker at much lower frequencies compared to other meters) when selecting a meter. As flicker continues to be an important factor in the selection and use of lighting products, future flicker meters will enable users in the field to adequately characterize lighting in a space and determine whether the level of flicker is acceptable for the given application.

Table of Contents

List of Figures

List of Tables

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1 Introduction

1.1 Background

Temporal light modulation (TLM) is the variation of light output as a function of time. TLM can have adverse effects on health and visual performance and has been the subject of recent articles primarily associated with flicker in LED lighting.[1,2] Visible flicker is a type of temporal light artifact (TLA) that refers to variations in light intensity perceived by an observer where the observer and environment are not moving.[3] Lighting system characteristics that can affect flicker vary by technology; examples include filament thickness for incandescent sources, phosphor persistence for fluorescent and coated metal halide sources, and circuit designs for electronically ballasted or driven sources. In this report, the colloquial term "flicker" is used in lieu of TLM to describe repetitive variations in light output, over a large frequency range, irrespective of the relative eye or object movement. It is acknowledged that the measured TLM may result in other perceptual effects beyond visible flicker, such as the stroboscopic effect or the phantom array effect.

Work in this area by the U.S. Department of Energy has focused on methods of measuring TLM, which is necessary to evaluate the range of characteristics for LED lamps and luminaires. A previous report, *Characterizing Photometric Flicker*, compared three benchtop laboratory meters against a reference system built by Pacific Northwest National Laboratory (PNNL).[4] The meters all measured light-intensity waveforms and calculated essential flicker-performance characteristics and metrics similarly, both to each other and to the reference system, which was custom-built based on the available guidance at the time and found to produce consistent results to other flicker-testing apparatus in use at the time. Some differences in performance were found when the light-intensity waveforms had significant high-frequency content and when the meters were not properly configured (or configuration was not possible).

Today, more flicker meters are available, including more handheld meters that range from simple smartphone applications to scientific-grade meters. This report compares the performance of eight meters capable of measuring flicker in the field to a reference benchtop meter chosen based on its performance in the initial round of meter comparisons. Flicker-related research efforts have received significant attention of late and there is growing momentum to establish specific measurement procedures, agree on application-dependent metrics, and recommend performance criteria. Once these are in place, the use of handheld flicker meters will likely increase substantially, making the present a good time to investigate the performance of such meters and provide guidelines for field measurements of flicker.

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[1] Zielinska-Dabkowska, Karolina M., Make lighting healthier (Comment), *Nature*, Issue 553, p. 274-276, January 16, 2018. https://www.nature.com/articles/d41586-018-00568-7.

[2] Wilkins, Arnold J., *The scientific reason you don't like LED bulbs — and the simple way to fix them*, The Conversation, July 27, 2017. https://theconversation.com/the-scientific-reason-you-dont-like-led-bulbs-and-the-simple-way-to-fix-them-81639.

[3] Officially, Commission Internationale de l'Eclairage (CIE) Technical Note (TN) 006:2016, *Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models*, defines visible flicker as the "perception of visual unsteadiness induced by a light stimulus, the luminance or spectral distribution fluctuates with time, for a static observer in a static environment." http://files.cie.co.at/883_CIE_TN_006-2016.pdf.

[4] Pacific Northwest National Laboratory for U.S. Department of Energy, *Characterizing Photometric Flicker*, February 2016. https://www.energy.gov/sites/prod/files/2016/02/f29/characterizing-photometric-flicker.pdf.

1.2 Test and Measurement Practices

Flicker is garnering increased attention from lighting designers and specifiers, the standards and specification community, and, consequently, lighting manufacturers. Figure 1 shows the various standards bodies with a specific interest in TLM on national, regional, and global levels.

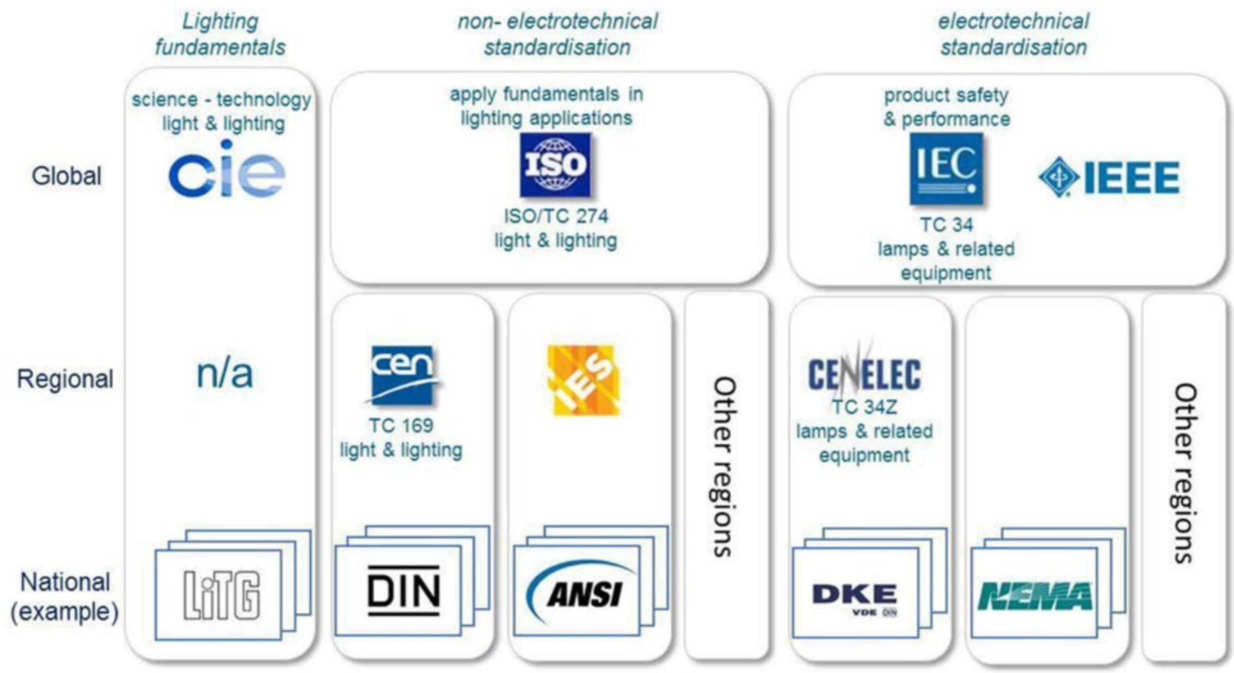

Figure 1. A graphic of the various standard bodies interested in TLM.

(Source: CIE Stakeholder Workshop for Temporal Light Modulation Standards for Lighting Systems.)

Following is a list of published flicker-related activities:

- The Institute of Electrical and Electronics Engineers (IEEE) published *P1789-2015, IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers* in June 2015. [5] The recommended practice sets thresholds for TLM, specifically the concept of modulation frequencies, for LEDs used in various applications at three risk levels. This was the first industry recommendation that specified how to limit TLM to reduce user risk. The document also discusses various LED dimming methods that alter the frequency of drive currents and voltage, specifically identifying their effects on TLM.

- CIE Technical Committee (TC) 1-83 published *Technical Note (TN) 006:2016, Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models* in 2016.[6] The TN provides definitions and a literature review. It also describes two methods to predict TLA, one in the time domain

[5] IEEE Std 1789-2015 – IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers. Available at http://standards.ieee.org/findstds/standard/1789-2015.html.

[6] CIE TN 006:2016, Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models. Available at http://files.cie.co.at/883_CIE_TN_006-2016.pdf.

(for predicting visible flicker) and another in the frequency domain (for predicting stroboscopic and phantom array effects).

- The National Electrical Manufacturers Association (NEMA) published *NEMA 77-2017: Temporal Light Artifacts: Test Methods and Guidance for Acceptance Criteria* in 2017.[7] This document describes various methods for quantifying the visibility of TLA, identifies specific metrics to quantify visible flicker and stroboscopic effect, provides a measurement method, and sets initial application-dependent limits.

- A CIE International Stakeholder Workshop for Temporal Light Modulation Standards for Lighting Systems was held in February 2017. The aim of the meeting was to establish a roadmap of research, recommendations, and standards activities. The discussions from the meeting are documented in the *CIE TN 008:2017 Final Report: CIE Stakeholder Workshop for Temporal Light Modulation Standards for Lighting Systems*.[8]

There are also various activities related to flicker currently being undertaken, including the following:

- CIE TC 1-83, *Visual Aspects of Time-Modulated Lighting Systems*, is tasked with using the data collected according to the measurement models identified in TN 006:2016 to verify the metrics used to predict TLA. Based on this verification, the TC will then develop a system to predict the issues of visibility of TLA, as opposed to neurological response, which may or may not lead to seeing the flicker.

- CIE TC 2-89, *Measurement of Temporal Light Modulation of Light Sources and Lighting Systems*, is tasked with establishing a standardized measurement procedure so that TLM can be consistently captured and the corresponding metrics can be calculated.

- The IES Testing Procedures Committee is currently drafting a lighting measurement guide, titled *Method of Measuring Optical Waveforms for Use in Temporal Light Artifact (TLA) Calculations*, focused on the measurement and quantification of TLM.

The information produced by the standards organizations is used by various programs. The ENERGY STAR® V2.0 *Lamps Specification* includes a requirement to report periodic frequency, Percent Flicker, and Flicker Index for lamps marketed as dimmable. A proposed revision, *Product Specification for Lamps (Light Bulbs)* Version 2.1, replaced the previous version on October 1, 2017. This version added the Short Term Flicker Indicator (P_{st}), Stroboscopic Visibility Measure (SVM), and the Flicker Perception Metric (M_P), also for all lamps marketed as dimmable. The *ENERGY STAR Method of Measurement for Light Source Flicker* outlines the measurement process, calculations, and test report (i.e., the ENERGY STAR® Dimming Data Sheet). ENERGY STAR is also implementing the measurement method and recommended performance limits stipulated in NEMA 77-2017.

The California Building Standards Code (Title 24 of the California Code of Regulations) includes energy efficiency requirements that apply to the construction of new and renovated buildings, both residential and commercial. The 2016 version has “reduced flicker operation” requirements for dimmable products to limit

[7] NEMA 77-2017, *Temporal Light Artifacts: Test Methods and Guidance for Acceptance Criteria*. Available at https://www.nema.org/Standards/Pages/Temporal-Light-Artifacts-Test-Methods-and-Guidance-for-Acceptance-Criteria.aspx.
[8] CIE TN 008:2017, *Final Report CIE Stakeholder Workshop for Temporal Light Modulation Standards for Lighting Systems*. Available at http://www.cie.co.at/publications/final-report-cie-stakeholder-workshop-temporal-light-modulation-standards-lighting.

TLM. These requirements are expressed as a limit on modulation depth as a function of frequency. There is an accompanying test method JA10 that is unique to California.[9]

As of July 2018, the DesignLights Consortium®, which is a group of utilities incentivizing most products outside the scope of ENERGY STAR®, does not have a flicker requirement, but they are considering adding one once there is an agreed-upon specification. They currently maintain a webpage dedicated to flicker and a document with key technical questions and requests for input.[10,11]

1.3 Metrics

The two most commonly used metrics for quantifying flicker remain Percent Flicker and Flicker Index. Percent Flicker (with a range from 0% to 100%) is perhaps better-known (albeit sometimes referred to by other monikers, such as modulation depth or percent modulation) and easier to calculate, but Flicker Index (with range from 0 to 1) has the advantage of being able to account for variation in waveform shape or duty cycle. Both metrics account for amplitude variation and DC offset, but since both only require analysis of a single waveform period, neither is able to account for variation in periodic frequency. Thus, both metrics are best used for comparing light sources with the same frequency. Two other metrics were reported by some meters tested; Stroboscopic Effect Visibility Measure (SVM) and the Lighting Research Center's Flicker Perception Metric (M_P).

Flicker sensitivity is generally accepted to be dependent on waveform frequency; the higher the frequency, the lower the sensitivity to most potential effects of flicker. While the periodic light-intensity waveforms created by traditional lighting sources may be purely sinusoidal (e.g., incandescent-source performance), often they contain multiple frequency components. That is, the light-intensity waveform appears to be composed of multiple, superimposed sinusoids. The dominant sinusoidal component – the one with the greatest amplitude – is referred to here as the Fundamental Frequency. For many traditional lighting sources, the Fundamental Frequency is simply twice the input-line-voltage frequency (e.g., 120 Hz for 60 Hz AC in North America). Electronically ballasted fluorescent light sources represent the predominant exception; the low-amplitude modulation found in such lighting systems is typically in the 20 to 60 kHz range. Given this lack of variation in Fundamental Frequency (in particular, for a given lighting technology), frequency has not historically been a key specification factor when considering flicker. With the advent of LED technology, however, this is no longer the case. The Fundamental Frequency found in LED source flicker can vary significantly. As a result, the guidance provided in IEEE Standard 1789-2015 consists of limits on Percent Flicker, as a function of the operating frequency generated by the driver or ballast for the light source.

SVM attempts to predict both the visibility and acceptability of the stroboscopic effect. The SVM differs from Percent Flicker and Flicker Index in a few significant ways. First, it can account for variations in waveform frequency – even for waveforms that have multiple frequency components. It uses Fourier analysis to convert the light-intensity waveform from its time-domain representation to a frequency-domain representation, so that frequency dependencies for varying effects (in this case, visibility) can be accounted for by a weighting function, which is a second key differentiator between the SVM and other metrics. Fourier analysis allows a complex, not just sinusoidal, waveform to be analyzed as a sum of individual frequency components. Notably, the weighting function is application-specific; as a result, the SVM does not address non-visible flicker, for example, and is likely not suitable for predicting some neurological issues. Other weighting functions, addressing other potential effects of flicker (e.g., increased occurrence of migraines, reduced visual-task performance) could be developed and applied using a similar approach. The SVM applies such a weighting, or sensitivity function, to frequencies between 80 and 2,000 Hz. Calculating the SVM from a light-intensity

[9] California Energy Commission, 2016 Reference Appendices for the 2016 Building Energy Efficiency Standards – Title 24, Part 6, and Associated Administrative Regulations in Part 1. See Reference Appendix JA10. Available at http://www.energy.ca.gov/2015publications/CEC-400-2015-038/CEC-400-2015-038-CMF.pdf.
[10] DesignLights Consortium Flicker webpage. Available at https://www.designlights.org/workplan/flicker/ (accessed August 2018).
[11] DesignLights Consortium, Flicker: Key Questions. Available at https://www.designlights.org/default/assets/File/Workplan/DLC-Workplan_Flicker_Key-Questions.pdf (accessed August 2018).

waveform requires at least 1 second of data with a minimum sampling frequency of 4,000 samples per second (with at least 5,000 preferred) to generate enough frequency resolution to accurately apply the sensitivity function. Finally, while the SVM is necessarily greater than zero, it is not otherwise limited in range; for reference, the SVM of a typical incandescent lamp is less than 0.5, at both full output and all dimmed levels, and the threshold of visibility (i.e., just visible by 50% of subjects) for SVM is defined as 1.0.

A metric less commonly reported (only one meter in this testing), the M_P metric was developed by the Lighting Research Center at Rensselaer Polytechnic Institute. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) program published the Flicker Perception Metric (M_P) for evaluating flicker, in the range of 5 to 65 Hz, using a weighted Fourier transform approach. For a single-frequency sinewave with 30% modulation depth, the M_P value is 1 at 54 Hz. Similar to both SVM and P_{st}^{LM}, a value of 1 is the threshold at which 50% of observers would indicate perception of visible flicker.[12]

Two other flicker metrics worth mentioning are the International Electrotechnical Commission's (IEC's) Flicker meter Short-Term Flicker Severity (P_{st}^{LM}) and the Compact Flicker Degree (CFD). The flicker meter method was developed by IEC to predict the visibility of light modulation from voltage fluctuations in electrical power systems. One of the included metrics is P_{st}^{LM}, which quantifies visible flicker up to 80 Hz based on a 180-second sample length. CIE TN 006:2016 and NEMA 77-2017 recommend the use of P_{st}^{LM} to quantify the visibility of TLA. ASSIST's M_P also supports the findings (specifically the response threshold) of P_{st}^{LM}. CFD is a Fourier-based metric that is designed to predict TLA. CFD is similar in approach to ASSIST's M_P, but includes a greater range of frequencies (up to 2,000 Hz). CFD is presented as a percentage, with higher percentages indicating potential issues with TLA; the values can exceed 100% with artificially created waveforms. One meter in this testing was capable of reporting values for P_{st}^{LM}, but the waveform data required to calculate that metric could not be obtained. For that reason, and because each measurement requires a 180-second sample length, this metric is not presented or evaluated in this report.

Table 1 includes the required measurement parameters needed to calculate different metrics. The measurement requirements were first recorded from the original documentation of the metrics; if there were no specific requirements, then they were taken from the various measurement methods (e.g., ENERGY STAR®, National Electrical Manufacturers Association). Any discrepancies between the measurement requirements in the metrics documentation and the various measurement methods are noted in the table footnotes.

Table 1. Measurement parameters for various different flicker metrics.

	Percent Flicker	Flicker Index	ASSIST's M_P	Philips SVM	IEC P_{st}^{LM}	CFD
Target frequency range (Hz)	--	--	5-65	80-2000	0-80	0-250,000
Sampling frequency (Hz)	--	--	2,000[a]	4,000[b]	4,000[c]	20,000[d]
Sample length (s)	1	1	2	1	180	1
Cut-off filter (Hz)	--	--	100	3,000[e]	1,000[f]	--[g]

(a) ENERGY STAR® requires at least 10,000 Hz.
(b) 10,000 Hz is more ideal (according to Philips).
(c) Although 4,000 Hz is the minimum required sampling frequency, for a cut-off filter at 1,000 Hz, an increased sampling frequency of 10,000 Hz is recommended.
(d) 20,000 Hz is the minimum necessary for sufficient presentation and calculation (according to Der Lichtpeter's CFD website, https://www.derlichtpeter.de/en/light-flicker/cfd/).
(e) NEMA 77-2017 requirement.
(f) NEMA 77-2017 requires 2,000 Hz.
(g) Depends on the sampling rate.

[12] The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) Program. https://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-FlickerMetric.pdf.

1.4 Scope

This report documents the performance of eight handheld flicker meters that were available in 2017 when the study was initiated. Each meter was used to measure 12 test light sources according to an internal procedure following laboratory best practices. The resulting waveforms and flicker metrics (Percent Flicker, Flicker Index, Fundamental Frequency, SVM, and M_P) were evaluated and, where possible, compared to those from a previously evaluated benchtop meter, which was considered the reference.

2 Test and Measurement

2.1 Test Light Sources

Because no standard light source(s) were available for evaluating flicker measurement capability, a set of 12 light sources was established for this study. The lighting devices were selected based on their being typical of a specific architectural lighting product, exhibiting a specific waveform characteristic (e.g., amplitude modulation, shape, and frequency), and/or because they had previously been tested and were available for re-use in this study. Table 2 provides further details for these light sources.

Table 2. Test light sources.

The following light sources were selected based on their exemplification of a familiar type of architectural lighting product, specific waveform characteristics, and/or because they had previously been tested.

ID	Type	Description	Reason for selection
A	LED	White-tunable linear LED cove luminaire.	NGL 2015[a] prototype with low-duty cycle but high-frequency (730 Hz) flicker. **Tested at four light-output levels.**
B	HAL	Halogen infrared (HIR) PAR38 halogen screw-base lamp.	Common halogen lamp used in retail applications included as a benchmark.
C	LED	High color rendering index (CRI) PAR38 LED replacement screw-base lamp.	10% flicker at full output.
D	LED	PAR38 LED replacement screw-base lamp.	100% flicker at full output.
E	LED	PAR38 LED replacement screw-base lamp.	0% flicker at full output.
F	CFL	Compact fluorescent lamp (CFL) self-ballasted screw-base A-lamp.	Integral high-frequency electronic ballast. Included as a benchmark.
G	LED	BR30 LED screw-base replacement lamp.	Uses AC LED technology.
H	LED	Recessed 2 x 2 LED troffer with a contoured diffuser.	0 – 10 V dimming driver that produces minimal flicker at full and dimmed output. **Tested at four light-output levels.**
I	FL	Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 – 10 V electronic dimming ballast.	Benchmark of 1990s-to-present 0 – 10 V dimmable fluorescent technology. **Tested at four light-output levels.**
J	FL	4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast.	Included as a benchmark product, as it represents flicker that was common before the 1990s widespread adoption of electronic ballasts.[b]
K	LED	Philips TLA demo unit waveform WF21.	Represents a typical LED with a fundamental frequency of 100 Hz.
L	LED	Philips TLA demo unit waveform WF22.	Represents a typical 60W incandescent bulb with a fundamental frequency of 100 Hz.

(a) Next Generation Luminaires™ (NGL) Solid-State Lighting (SSL) Design Competition: http://www.ngldc.org/.
(b) This flicker was accepted by most, tolerated by some, considered distracting or physiologically disturbing by others. The 4' fluorescent strip light with T12 or T8 lamps magnetic ballasts is a source widely believed to contribute to headaches and malaise in some populations, along with likely reduction in visual task performance.

2.2 Reference Flicker Meter

Based on the previous testing of benchtop meters, the Admesy Asteria SC-ASTR-01 High-Speed Illuminance Photometer was selected for permanent installation on the exterior of a 2-meter integrating sphere in the PNNL Lighting Metrology Laboratory. A porthole on the bottom section of the sphere was used, directly below the light source, ensuring maximum light collection during testing. The typical distance from light source to the reference meter was approximately 90 cm, with some slight variation possible due to the dimension of the test light source. In addition to flicker analysis, the Admesy Asteria can measure luminance, illuminance, and luminous intensity, although these capabilities are not the focus of this report. Figure 2 shows the reference flicker meter as placed permanently under the integrating sphere and the adjacent porthole opening with a custom flange used to attach the commercially-available handheld flicker meters.

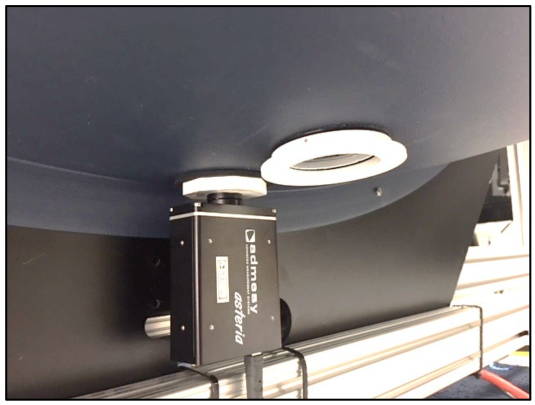

Figure 2. Positioning of reference and handheld flicker meters on integrating sphere.

The reference meter was placed permanently under the integrating sphere about 90 cm from the light source inside the sphere. A flange designed for easy attachment of handheld meters is also visible. When not used, this flange was covered.

2.3 Commercially-Available Handheld Flicker Meters

To identify commercially-available handheld meters, PNNL surveyed the instrument market, primarily through Internet searches and manufacturer trade shows, but also via inquiries to independent commercial laboratories currently characterizing or planning to characterize flicker. The focus was on handheld meters; meters designed for high-throughput production-line characterization were not considered. Once the appropriate handheld commercial meters were identified, PNNL requested manufacturer quotes and product information, along with availability. Eight products were selected and ordered for testing, with prices ranging from $2,000 to $5,000 and all available to ship within 8 weeks of ordering. A basic comparison of the selected products and the reference meter is shown in Table 3.

Table 3. Basic comparison of commercially-available handheld flicker meters and the reference meter.

The eight products selected are compared for the following performance characteristics: size, measurement time, sampling rate, and calculated outputs, based on manufacturer claims. In the Sampling Characteristics column, "S" refers to samples.

Meter	Dimension/ Weight	Measurement Time	Sampling Characteristics	Calculated Outputs
Viso Systems Flicker Tester app for iPhone[a]	Varies	-	-	Percent Flicker Flicker Index Fundamental Frequency SVM
Viso Systems LabFlicker	115 x 53 x 13 mm 155 g	1	50 kS 50 kS/s	Percent Flicker Flicker Index Fundamental Frequency SVM
AsenseTek Lighting Passport PRO	68.5 x17 x56mm 76.5 g	6 ms – 16 s	-	Percent Flicker Flicker Index Fundamental Frequency
Fauser Light meter LM10	120 x 79 x 28 mm	-	-	Percent Flicker Flicker Frequency (Highest)
UPRtek MK350N Premium	147.5 x 78 x 24 mm 225 g	0.1 ms – 64 s	Up to 100 kS/s	Percent Flicker Flicker Index Fundamental Frequency SVM
Everfine SFIM-300	180 x 70 x 30 mm 200 g	50 ms – 12 s	Up to 50 kS/s	Percent Flicker Flicker Index Fundamental Frequency FFT spectrum
JUST Normlicht Inc. GL Optic Spectis 1.0 T	74 x 146 x 24 mm 315 g	10 ms – 10 s	Up to 125 kS/s	Percent Flicker Flicker Index Dominant Frequencies SVM
Gigahertz-Optik BTS256-EF BiTec Sensor Light meter[b]	159 x 85 x 45 mm 500 g	5 ms – 180 s	Up to 50 kS/s	Percent Flicker Flicker Index Fundamental Frequency SVM M_P P_{st}^{LM}
Admesy Asteria SC-ASTR-01 High-Speed Illuminance Photometer[c]	69 x 31 x 93 mm 320 g	1 ms – unknown[d]	Up to 250 kS; up to 187 kS/s	Percent Flicker Flicker Index Fundamental Frequency

(a) Flicker Tester: http://www.visosystems.com/products/flicker-tester/.
(b) Gigahertz-Optik BTS256-EF BiTec Sensor Light meter: https://www.gigahertz-optik.de/en-us/product/BTS256-EF
(c) Admesy Asteria SC-ASTR-01 High Speed Illuminance Photometer: http://www.admesy.nl/product/asteria/.
(d) The Asteria SC-ASTR-01 can take measurements for longer times using a DELAY function that averages a predefined number of samples to produce a measurement point. Admesy has advised that the DELAY function can currently be used to extend measurement time to 20 s, and that a forthcoming software update will enable measurement times of up to 200 s.

2.4 Test Setup and Procedure

The eight commercially-available handheld meters were set up in the integrating sphere just adjacent to the reference meter. To maintain consistent placement of meters and minimize stray light, a custom flange was developed for the integrating sphere porthole, as well as custom sleeves/holders for each meter that allowed easy and repeatable placement of each handheld meter onto the flange. Figure 3 demonstrates the placement of the handheld meter onto the flange.

Figure 3. Handheld meter slid into place on flange, next to the reference meter.

Each light source was connected to a laboratory power supply delivering 120 VAC and allowed to thermally stabilize for approximately 5 minutes before measurement. The ambient temperature was maintained at 25° C ± 1° C. Previous experiments have demonstrated that flicker performance is not a strong function of thermal stabilization; thus, in the interest of time, thermal stabilization of the light source was limited in time. Lamp temperatures and other operating characteristics (e.g., power and light output) were not monitored during this warmup. Light output, however, was captured throughout the testing of each test light source by the reference meter. To minimize testing time, dimmable test light sources were not required to establish a new thermal equilibrium at each dimmed level when testing occurred within the same day, but the typical 5-minute stabilization was performed when testing continued on a different day.

Each test light source was measured by all of the handheld meters in a continuous sequence. Light sources A, H, and I were chosen for evaluating different dimming scenarios (e.g., LED, fluorescent, 0-10V dimming, DMX dimming) and operated at varying light-output levels, as specified in Table 2. Light sources H and I light levels were set using a Lutron Nova T 0-10VDC dimmer. The light levels tested were maximum/100%, 50%, 20%, and minimum. For the 50% and 20% levels, this was done by measuring maximum lumen output with the reference meter, adjusting the dimmer, and iteratively measuring the lumen output with the reference meter until the target light output was reached. Once reached, throughout that dimmed level testing, values were maintained within 2% of the initial light output by adjusting the dimmer setting. Light source A was tested using a proprietary manufacturer provided DMX controller at the same percentages relative to the 100% setpoint value on the controller to achieve the dimmed light output levels (see Table 4 for settings). At the lowest DMX setting, the light output could not be reduced any further, causing a 4.06% increase in light output during testing, or 0.28 lumens. Table 4 shows the dimming level and voltage used during testing. Note that the minimum dimmed level was the lowest setting on the dimmer or controller possible without regard for the stability of the light source, as it was desirable to observe any flicker that may have been present at this setting.

Table 4. Dimming values and tolerances.

Light Source	Dimmer Type	Voltage/Setting	Actual Lumens	Actual Dimmed Level
A	DMX	100	1873	100%
		70	925	49%
		44	367	20%
		1	7	0.4%
H	0-10 VDC	9.58	2984	100%
		4.79	1503	50%
		1.84	597	20%
		0.84	262	9%
I	0-10 VDC	9.58	3207	100%
		3.67	1605	50%
		1.86	644	20%
		0.83	159	5%

Both prior to starting measurements for any test light source – or dimmed level of a test light source – and after completing all handheld meter measurements, a full set of measurements was performed using the reference meter, including the flicker characteristics and light-intensity waveform. For each handheld meter measurement performed, a nearly simultaneous measurement with the reference meter was also performed, with the photometric and flicker metrics recorded for both. For the reference meter, the light-intensity waveform was only recorded at the start and end of a series of measurements on a given test light source.

For both test and reference meters, five sequential measurements were obtained to evaluate repeatability. Since data acquisition was mostly a manual process, at times requiring transferring data from a handheld meter to a computer, the measurement time for, and lag time between, handheld meter measurements varied slightly, but the process remained consistent throughout the testing. With rare exceptions, repeatability of the reported flicker metrics across five consecutive readings was deemed adequate. Percent Flicker values of handheld flicker meters showed an average deviation of 0.066 percentage point with a maximum average deviation of 0.59 percentage point. Similarly, Flicker Index values of handheld flicker meters showed an average deviation of 0.00053 with a maximum average deviation of 0.022. In the maximum cases for these metrics, the readings were for a light source dimmed at its lowest level and with high-frequency content. SVM repeatability showed an average deviation of 0.009 with a maximum average deviation of 0.32, with the maximum reading occurring for the same light source dimmed at its lowest level.

2.4.1 Flicker Measurement

To characterize the performance of each commercial handheld meter, testing was completed using an integration time of as close to 2 seconds as possible. The integration time was not configurable or even known, for some meters.

Table 5 shows the actual conditions used for meters that allowed integration times to be set, or that were known, including the reference meter. The Viso app, Viso Systems meter, and Fauser meter, in particular, did not provide an option to specify an integration time for flicker measurements. As such, their performance in this report is evaluated based on the meter’s own established integration time.

Table 5. Test and measurement conditions.

For each meter, the measurement time, sampling rate, and the number of samples are specified, if configurable or known. Additionally, the fast Fourier transform (FFT) resolution (defined as the inverse of the sample duration) and maximum FFT frequency (the number of FFT bins – equal to half the number of samples multiplied by the FFT resolution) are calculated.

Meter	Measurement Time (ms)	Sampling Rate (samples/s)	Number of Samples	FFT Resolution (Hz)	Max FFT Frequency (Hz)
Viso Systems Flicker Tester app for iPhone[a]	–	–	–	–	–
Viso Systems LabFlicker[b]	–	60,000	–	–	30,000
AsenseTek Lighting Passport PRO Spectrometer[c]	–	–	–	–	–
Fauser Light meter LM10[d]	–	–	–	–	–
UPRtek MK350N	2,000	32,768	65,536	0.5	16,384
Everfine SFIM-300[e]	3,000	781	2,343	0.33	387
JUST Normlicht Inc. GL Optic Spectis 1.0 T	2,000	7,813	15,626	0.5	3,907
Gigahertz-Optik BTS256-EF BiTec Sensor Light meter	2,000	50,000	100,000	0.5	25,000
Asteria SC-ASTR-01	2,000	186,567	373,137	0.5	93,284

(a) Viso Systems Flicker Tester app does not have a manual or provide any user-adjustable settings, and does not specify/provide sampling information. It is possible that these may vary depending on the smartphone on which the app is installed, and thus specifications could vary from device to device. Although a "Shutterspeed" is provided for the iOS app and "Exposure Time" for the Android app, it is unclear if there is a correlation between those values and the sampling rate or a number of samples being analyzed.
(b) Viso Systems LabFlicker does not allow users to select an integration time or sampling rate. The default sampling rate is 60,000 samples per second. During testing, export of light intensity waveform data was not available. The newest update allows exported data at 50,000 samples per second.
(c) AsenseTek Lighting Passport allows users to set integration time for exposure purposes; for this reason, the automatic exposure integration was selected.
(d) Fauser Lightmeter LM10 does not allow users to select an integration time or sampling rate. Settings for the Fauser only allow setting the sampling interval time as 0.25 s, 1 s, 10 s, and 1 minute.
(e) Everfine SFIM-300 displays an on-screen message momentarily informing the user that frequencies below 125 Hz would not measure properly when integration time is set to 3 seconds. However, since a measurement is provided and the user would be unaware of the high frequency content in a light source, the data was used and analyzed.

2.5 Meter-Specific Testing Methodology

The following descriptions provide meter-specific details relevant to the testing performed, as well as deviations from the standard test setup and/or measurement protocol that may have been necessary.

Viso Systems Flicker Tester Application

The Flicker Tester app from Viso Systems is unique in that it is an application installed on a smartphone, and leverages the camera to provide flicker measurements. The results provided in this report are specific to the version of the application used and the device on which it was installed.[13] The Apple version of the app provides Percent Flicker, Flicker Index, Fundamental Frequency,[14] and a visual representation of the flicker

[13] Version 1.0 of the Flicker Tester app was installed on an iPod Touch 5th Generation.
[14] On the iPod device used, the app actually displays "Frequency [calibrate]", and it is not clear what calibration is required or whether the frequency provided is representative of the Fundamental Frequency. During this testing, that reading was assumed to represent Fundamental Frequency.

waveform. The Google Play version of the app provides the same metrics as the Apple app plus SVM. Furthermore, the Frequency measurement is not qualified with "[calibrate]" on the Google Play version.[15]

Figure 4. Screenshots showing the Apple iOS (left) and Google Play Android (right) versions of the Viso Flicker Tester App.

Source: Viso Systems Apple App and Google Play stores.

Since the Flicker Tester app uses the device's camera to take a measurement, a means to diffuse the image entering the camera is recommended to ensure accurate results. The manufacturer's website recommends the use of either frosted film or paper in front of the lens. Testing was conducted with plain white paper as the diffusing mechanism, as it is assumed that most users of this app would find paper more easily accessible than frosted film. The app has no user-configurable settings for measurements. During testing, measurements were saved to the "Photos" app and were later retrieved to a computer by connecting the device via USB and using Windows Explorer.

During testing, the typical test setup did not allow the device to obtain sufficient light to take a measurement for various test light sources. When this occurred, a deviation from the standard testing methodology was made to obtain a measurement: The integrating sphere was opened and the iPod Touch was placed near the test light source. A video on the vendor's website demonstrates the proximity required for measurements, and the app shows "Hold the camera as close as possible to the light source" on the display when there is insufficient light. Although there is a potential for ambient light to influence the measurements when the integrating sphere is opened, the proximity of the device to the test light source and the room/lighting configuration is such that any impact is expected to be minimal, at best, and something that would likely be unavoidable in real-world use of this app.

Viso Systems LabFlicker

The Viso Systems LabFlicker (Figure 5) is a portable meter that requires a connection to a computer to function. The Viso Systems Light Inspector software is required to begin collecting samples.[16] With the software active, the LabFlicker can measure Percent Flicker, Flicker Index, Fundamental Frequency, and SVM.

Data collected during flicker testing was exported from the Viso Light Inspector software by saving a screenshot as a JPEG. Measurement results are continuously updated in the software interface and have a fixed integration time and sample rate. During testing, these settings were unable to be changed. In the time since

[15] Android Google Play version characteristics obtained from the Google Play Store (https://play.google.com/store/apps/details?id=com.visosystems.viso.flickertester&hl=en) on June 27, 2018.
[16] Testing was conducted using software version 5.35 and firmware version 1.12.

testing was conducted, a software update was released that allows the meter to export the light-intensity waveform data to a CSV or PDF file and the resolution changed to 50,000 samples per second.[17]

Figure 5. Viso Systems LabFlicker handheld meter.

Source: Viso Systems.

Although the LabFlicker meter provides measurements and a waveform each time, the meter screen and software may indicate that the light levels are too low for an accurate measurement, and this is also indicated by a large “X” across the meter screen and the waveform section on the software (Figure 6). Dimmed levels, in particular, resulted in such warnings, but even some full/max light output levels were also noted as having insufficient light levels for the meter to obtain a valid measurement. Given that this is a standalone meter that should be capable of providing a measurement at the distance tested, no accommodation was given to enable a measurement to be made (e.g., to open the integrating sphere and place the sensor closer to the light source, as was done for the Viso Flicker app).

In comparing the LabFlicker meter against the reference meter, the flicker metrics for all test light sources regardless of the meter/program indicating light levels as being too low, are presented. In later sections of this report analyzing flicker metric performance (e.g., deviation or matching to the reference meter), the flagged measurements were not considered in the calculations, as it was assumed the user would have understood that the measurement accuracy could not be trusted and attempted to move closer to the light source.

[17] New software version 5.52 and firmware version 1.19. During testing for functionality, the data could be downloaded, but it was observed that the comma-separated value was actually separated by semicolons. In most cases, this is a mere inconvenience that may be overcome by selecting the appropriate data delimiter when importing the data into a program (e.g., Excel or MATLAB).

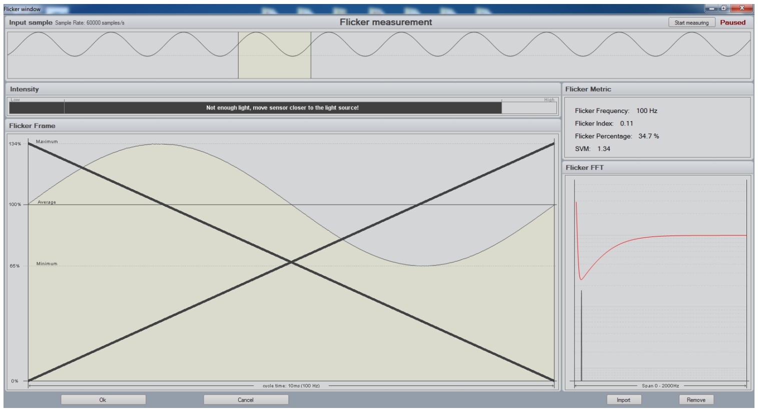

Figure 6. Viso Systems LabFlicker invalid reading.

The Viso Systems LabFlicker software showing light levels as inadequate for an accurate measurement.

AsenseTek Lighting Passport Pro

AsenseTek's Lighting Passport Pro (Figure 7) is composed of two parts: a measuring head that contains the light sensor and a control unit that was used to remotely initiate measurements using Bluetooth. The Lighting Passport testing deviated slightly from the standard testing methodology by placing the sensor head inside the integrating sphere and covering the porthole on which it was seated with a cover plate. Sampling was completed using the Spectrum Genius Mobile app.[18]

Percent Flicker, Flicker Index, and Fundamental Frequency are among the metrics collected during each scan. Measurement data is stored as a text document and can be accessed from any program capable of opening a text file. Measurements can be taken and saved as either single scans or multiscan files. After measuring, iTunes was used to export the text data file from the iPod Touch to a computer.

Figure 7. AsenseTek Lighting Passport Pro Spectrometer. Source: AsenseTek.

[18] https://www.lightingpassport.com/.

Fauser Lightmeter LM10

The Fauser Lightmeter LM10 (Figure 8) is a portable meter, including both a display unit and a sensor head. The sensor head connects to the meter, directly or with a cable extension. Measurements can only be taken using the handheld unit. After measurements were completed, the meter was connected to a computer. This was required to make changes to sampling characteristics.[19]

Figure 8. Fauser Light meter LM10.

Source: Fauser.

The LM10 provides Percent Flicker and also specifies and records "Ripple Content," noted as W = ((ϕ_{max} – ϕ_{min}) / ϕ_{max}) * 100%, where ϕ refers to the luminous flux in lumen, and "Flicker Frequency," noted as between 50 Hz and 400 kHz with a resolution of 5 Hz.

Abnormal Flicker Frequency values were encountered that were significantly different from what was observed on the corresponding reference meter measurements. The manual indicates that the Flicker Frequency measurement refers to "the highest frequency for flickering." Since no correlation for Flicker Frequency to Fundamental Frequency was identified, these results are not provided for the LM10.

UPRtek MK350N Premium

UPRtek's MK350N Premium (Figure 9) is a single unit with an integrated display and sensor. For this study, measurements were taken using a USB connection along with UPRtek's uFlicker control software. The software allows users to select metrics to report from measured data as well as set sample frequency, number of samples, and filter cutoff frequency.

Figure 9. UPRtek MK350N Premium.

Source: UPRtek.

[19] Software version: 2.2.0.0, firmware version: 1.11e.

Everfine SFIM-300

The Everfine SFIM-300 Spectral Flickering Irradiance Meter (Figure 10) includes a meter with an integrated display as well as a detachable sensor head. A USB extension was used to link the sensor head with the meter. Data collection for this study was performed via computer using the SFIM-300 software. Settings for sample time, sample frequency, and integration time were accessible from both the meter and the software interface.

Figure 10. Everfine SFIM-300 Spectral Flickering Irradiance Meter.

Source: Everfine.

During testing, the software encountered an issue when presenting and storing Flicker Index data. Flicker Index data reported using the software was off by a factor of 100. This issue persisted when using the software to review data taken with the handheld and recalled later for review. Data taken by the handheld and then reviewed on the device screen was displayed without issue. Since completion of testing, a new software version was released that corrected the error.[20]

GL Optic Spectis 1.0 touch

GL Optic's Spectis 1.0 touch Spectral Light Meter (Figure 11) is a single-unit handheld meter. The onboard settings menu allows users to change integration time, repeat time, and sampling rate. Samples taken during testing were transferred to the computer via the micro-SD card.

Figure 11. GL Optic Spectis 1.0 touch Spectral Light Meter.

Source: GL Optic.

[20] Corrected software version: V2.00.118, September 28, 2017. Previous version: V2.00.114, November 22, 2016.

Gigahertz-Optik BTS256-EF

An integrated sensor head and display allow the Gigahertz-Optik BTS256-EF (Figure 12) to be used as a handheld unit. When tethered to a computer, the meter can take high-resolution data. For this study, measurements were initiated via computer.

Figure 12. Gigahertz-Optik BTS256-EF handheld flicker meter.

The S-BTS256 software was used to control the meter. Once initialized, the software generated a database file on the computer to store data.[21] This is part of the hardware initialization step and removes the file size constraints that are present when using the meter as a handheld unit. Additionally, the software allows users to take "TLA measurements." This measurement mode was specifically created to measure TLA and will output values for P_{ST}, SVM, and M_P.[22] Settings for this measurement mode are frequency and duration. The software provides a table to indicate if the user-provided settings are sufficient to calculate each TLA value. A color coding scheme is used for user feedback, with green being good, yellow for values that can be calculated but will need to be extrapolated, and red for conditions that will not meet the meter's needs to calculate a given value. After completing the scan, flicker metrics were provided in the "numerical" values window and a plot of the waveform was displayed in the graphical window. The scan was then added to the database data subset using the subset toggle buttons. The subset was used to generate flicker and other lighting data via a report that was exported as a Word document.

Scans taken with high sample rates and longer collection times produced large file sizes. For computer systems with lower performance capabilities, it is possible for the file sizes produced by TLA scans to lead to crashes. Crashes were generally experienced when testing at the maximum sampling rate with sampling times exceeding 2 minutes.

2.6 Data Analysis

As in the predecessor report on benchtop meters, there were two components in analyzing the performance of each meter: (1) measuring the waveform and (2) calculating metrics. To assess waveform measurement only, measured light intensity waveform data was exported for analysis in MATLAB. For those meters that were capable of such data export, the raw data was compared with raw data from the reference meter. Fast Fourier Transform (FFT) analysis was used to convert each raw-data waveform from its time-domain representation to a frequency-domain representation, and the top four frequency components were reported for each test condition, along with their corresponding signal amplitudes. For the testing condition established, Percent

[21] Software version V2018.1.3.
[22] The software update enabling TLA measurements was provided after testing began. As a result, the first group of tests did not include values for SVM and Assist MP.

Flicker, Flicker Index, Fundamental Frequency, and SVM (if the sampling rate was sufficient) were calculated. For the test light sources that were evaluated at various light-output levels, the full-output waveforms were analyzed together with the full-output waveforms for the remaining test light sources; the remaining three dimmed-output waveforms were analyzed separately. For some meters, a visual representation of the measured light intensity waveform was provided but was not available for export. For these meters, screen captures of the waveforms were used for visual comparisons.

Most handheld meters reported Percent Flicker, Flicker Index, and Fundamental Frequency; about half reported SVM, and one meter (Gigahertz-Optik) reported the M_P metric.

Table 5 summarizes the output available from each meter in the configuration used for testing. All reported metrics from each handheld meter were compared to the same metrics reported by the reference meter. In all cases, the reported data was the median of the five individual measurements of each test light source and light level, if applicable.

Finally, the calculations performed by each meter were examined by comparing the reported values to those calculated by PNNL using the raw light intensity waveform.

3 Results and Analysis

3.1 Reported Values: Test vs. Reference

Figure 13 through Figure 20 graphically compare the median values for Percent Flicker, Flicker Index, and Fundamental Frequency reported directly by each handheld meter to the same value reported by the reference meter. Table 6 provides data obtained for SVM and M_P for all meters reporting such because the reference meter did not provide that metric directly for comparison.

If available, the light intensity waveform data of the handheld meter is presented side-by-side to the reference meter waveform data in Appendix A.

3.1.1 Viso Systems Flicker Tester App for iPhone

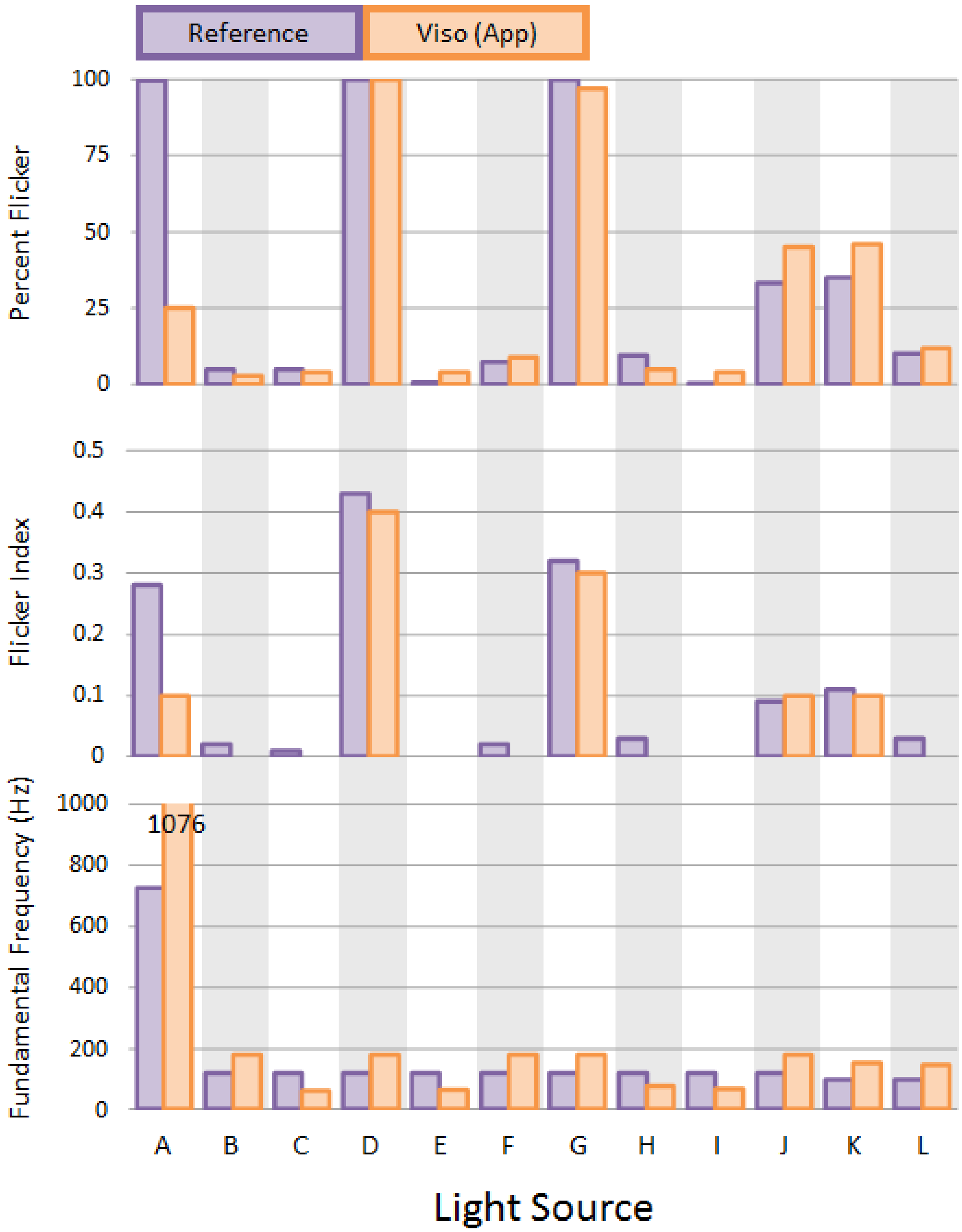

Figure 13. Viso (App) and reference meter flicker metrics for the various light sources tested.

3.1.2 Viso Systems LabFlicker

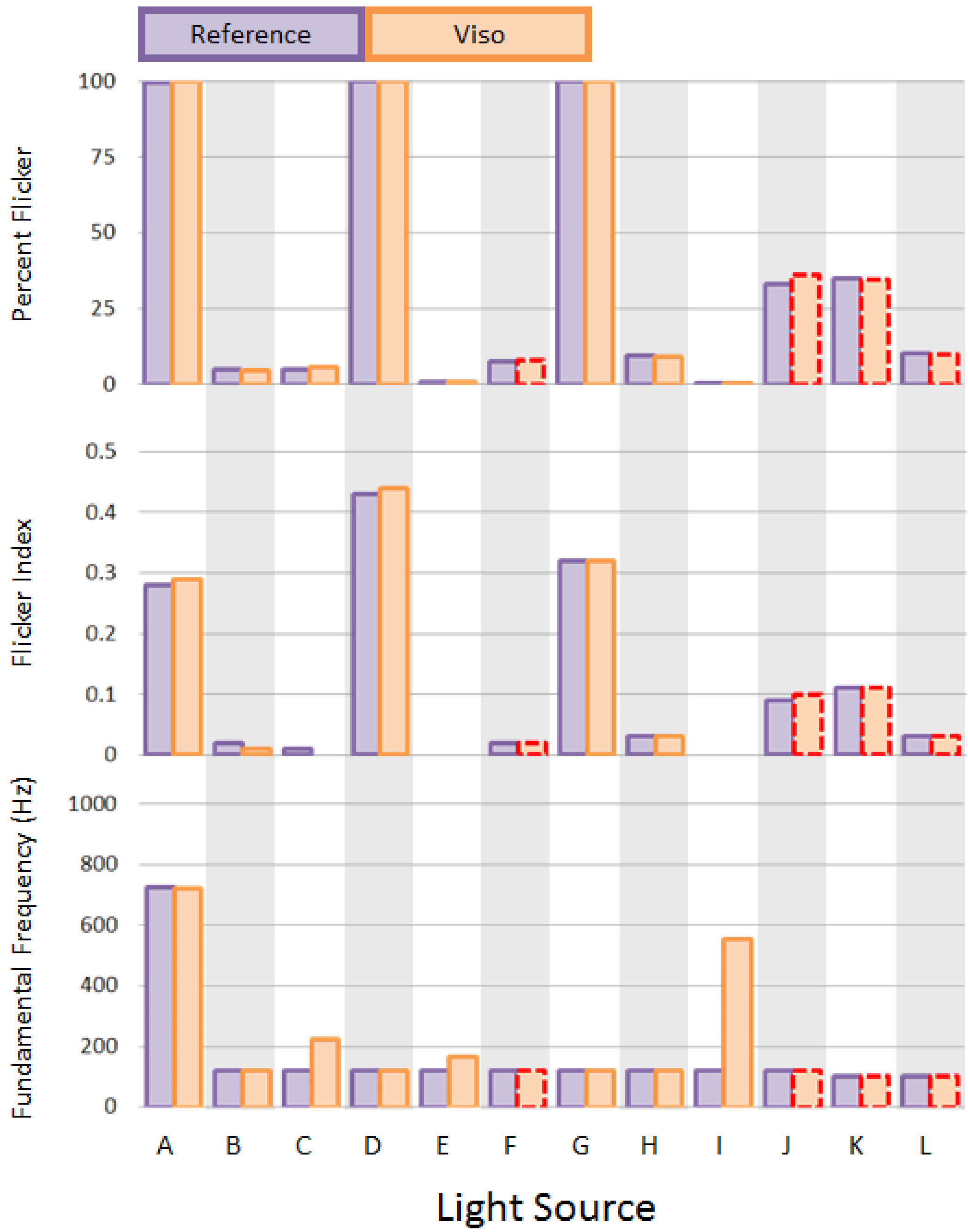

Figure 14. Viso and reference meter flicker metrics for the various light sources tested.

Red dashed blocks represent readings where the meter indicated light levels were too low for an accurate measurement.

3.1.3 AsenseTek Lighting Passport Pro

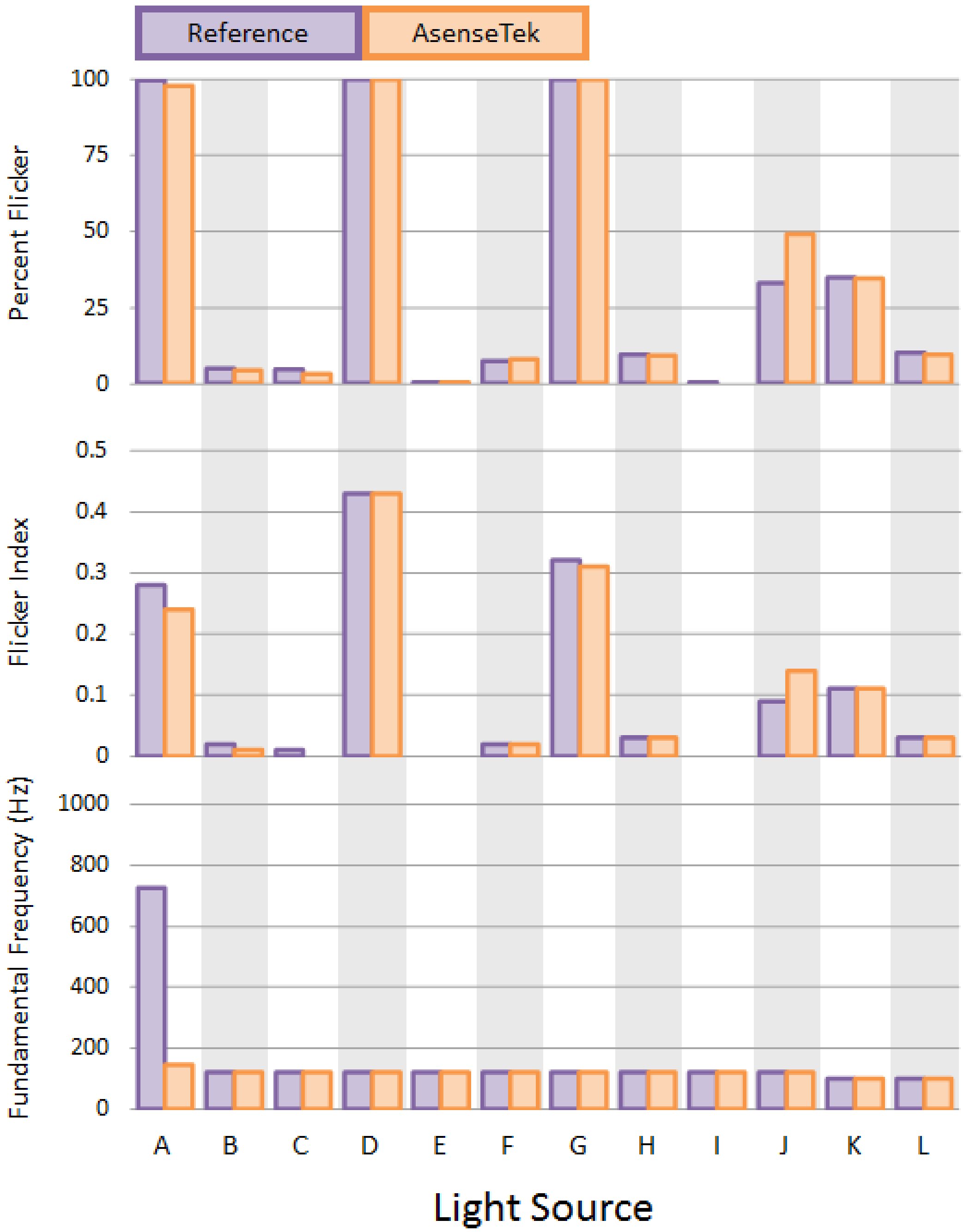

Figure 15. AsenseTek and reference meter flicker metrics for the various light sources tested.

3.1.4 Fauser Lightmeter LM10

Figure 16. Fauser and reference meter flicker metrics for the various light sources tested.

3.1.5 UPRtek MK350N Premium

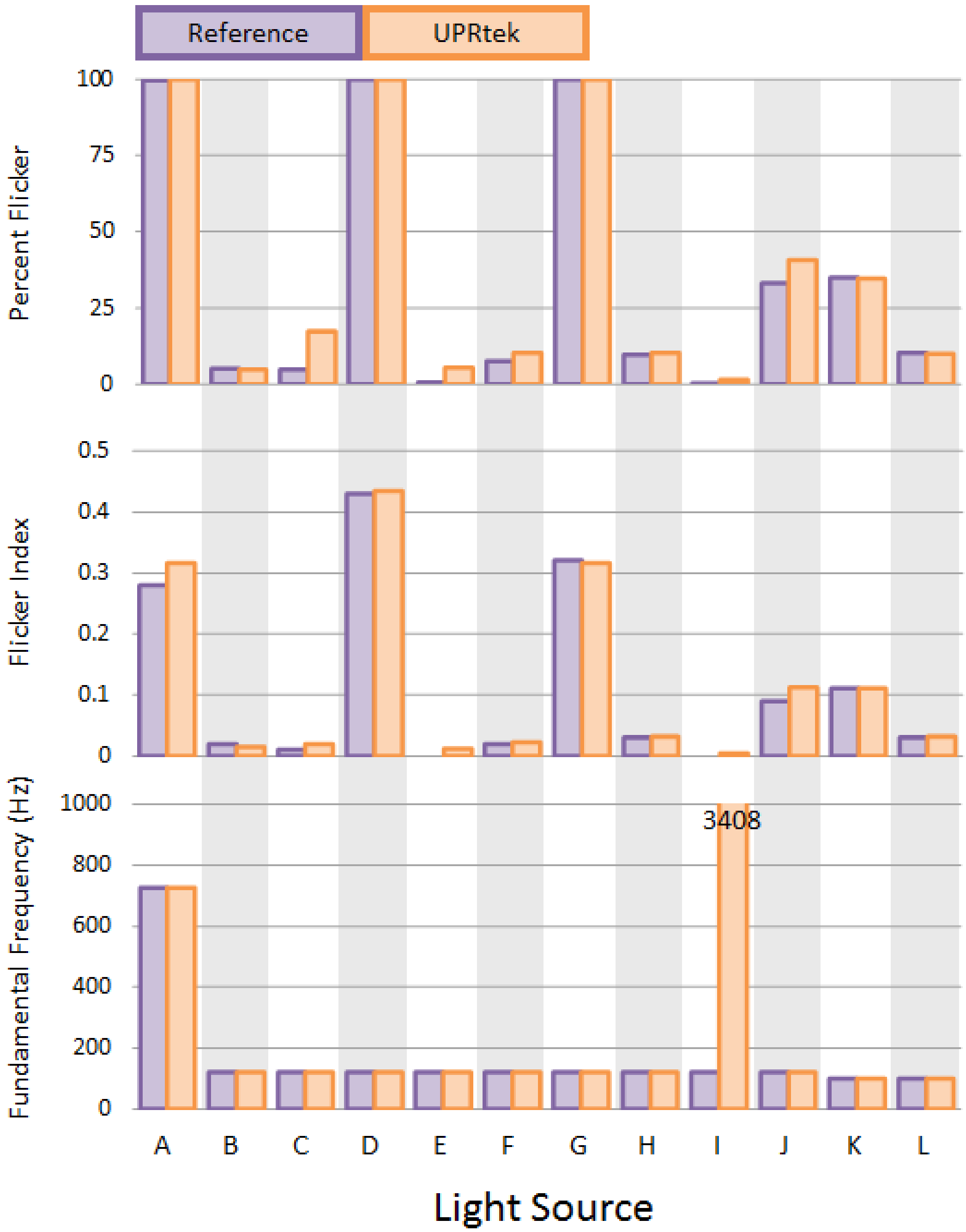

Figure 17. UPRtek and reference meter flicker metrics for the various light sources tested.

3.1.6 Everfine SFIM-300

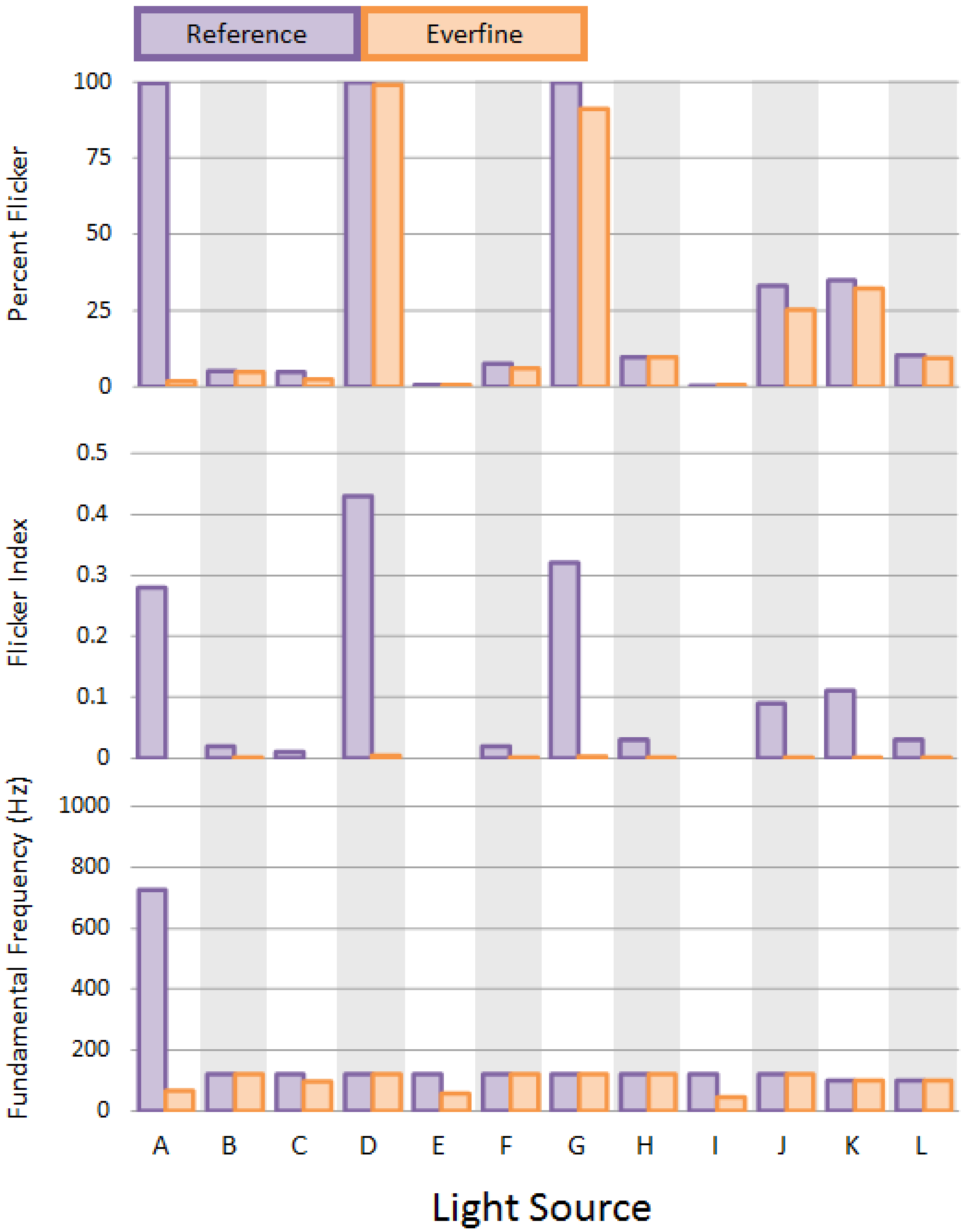

Figure 18. Everfine and reference meter flicker metrics for the various light sources tested.

3.1.7 GL Optic Spectis 1.0 touch

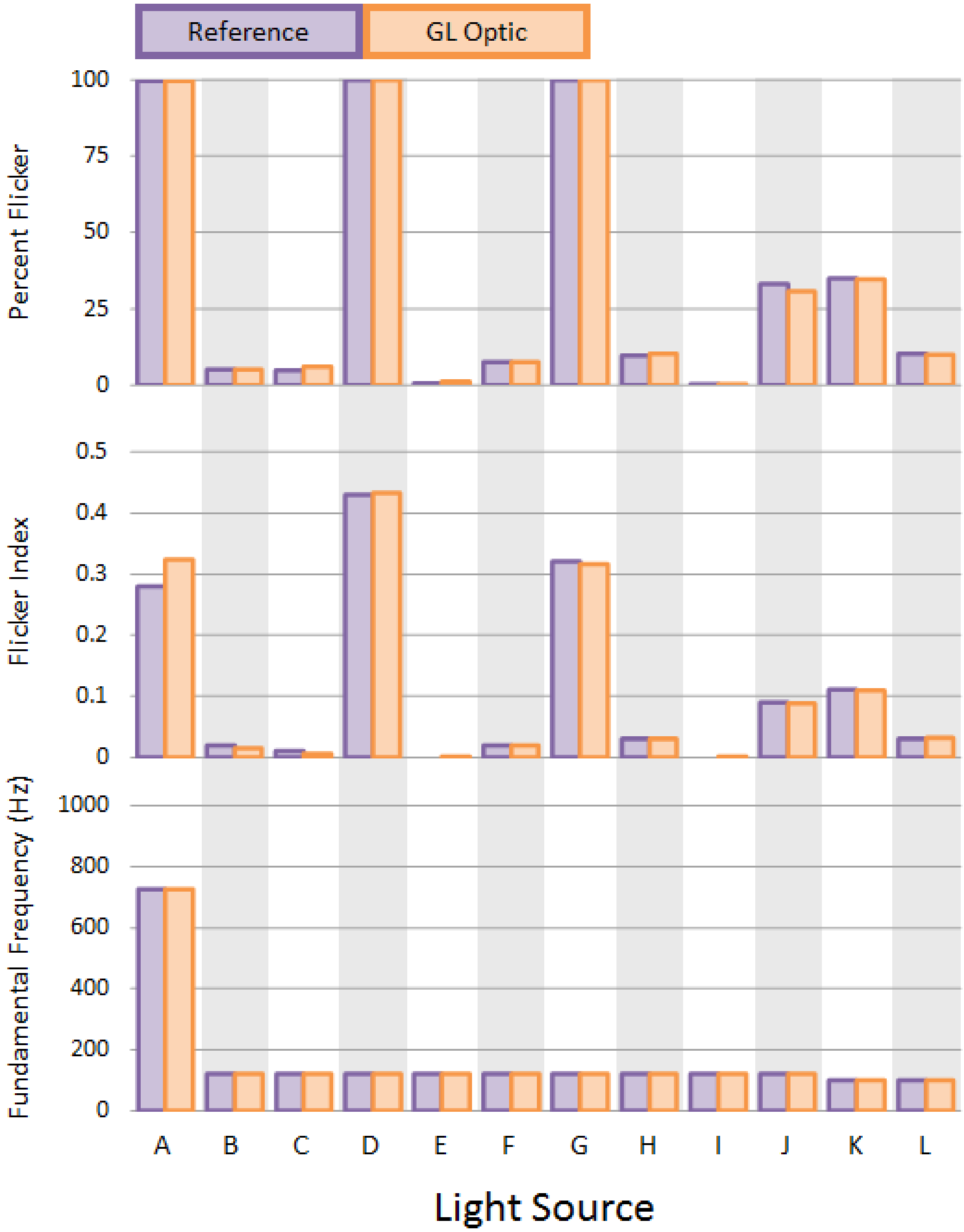

Figure 19. GL Optic and reference meter flicker metrics for the various light sources tested.

3.1.8 Gigahertz-Optik BTS256-EF

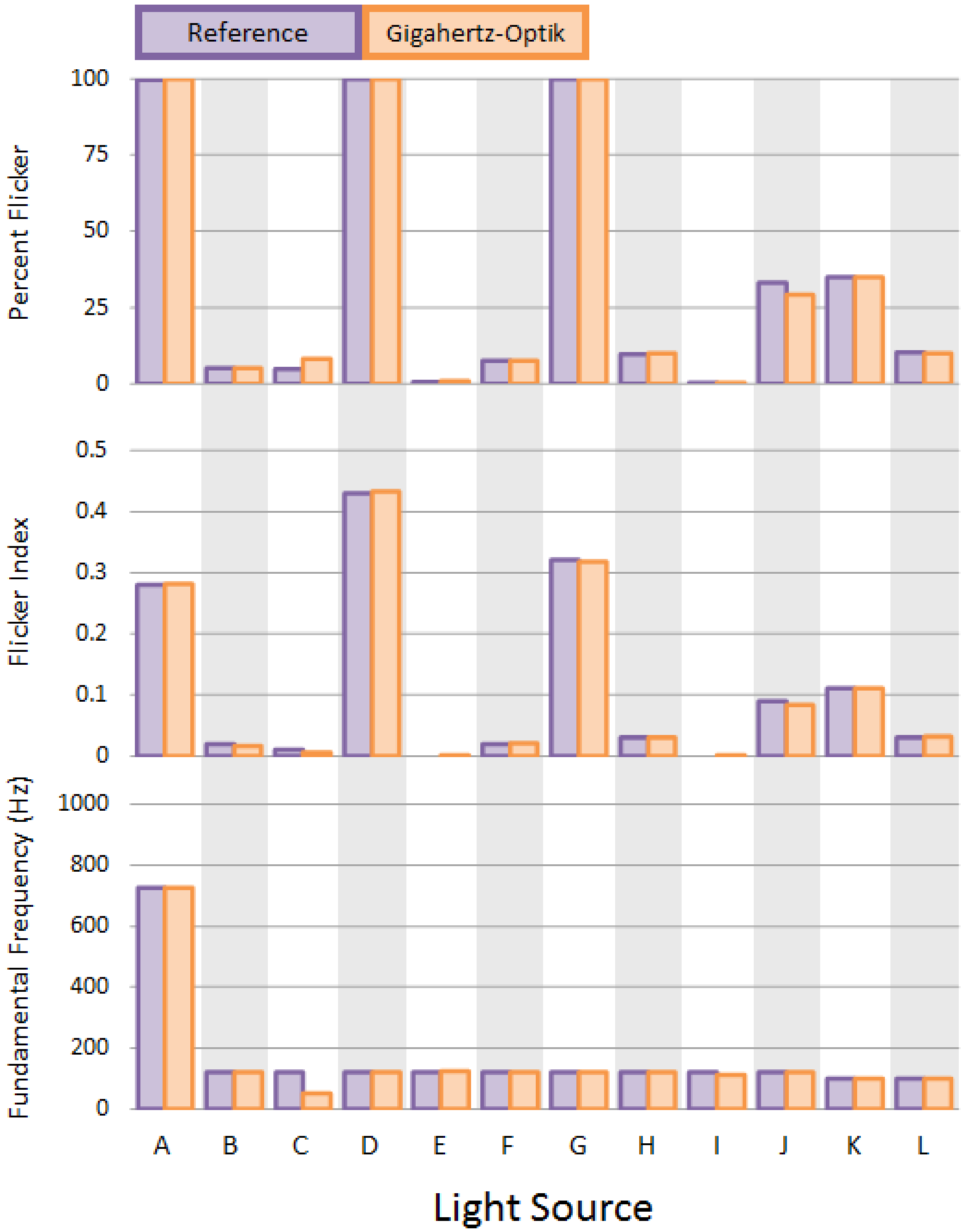

Figure 20. Gigahertz-Optik and reference meter flicker metrics for the various light sources tested.

Table 6. SVM and M_P data (median) for the Viso Flicker meter (VISO), UPRtek MK350N Premium (UPRT), GL Optic Spectis 1.0 touch (GL-O), and Gigahertz-Optik BTS256-EF (G-O) meters.

	Light Source											
	A	B	C	D	E	F	G	H	I	J	K	L
VISO SVM	0.95	0.17	0.02	4.71	0.01	0.24	3.4	0.33	0.03	1.16	1.34	0.38
UPRT SVM	0.93	0.17	0.04	4.71	0.01	0.24	3.39	0.36	0	1.29	1.34	0.38
GL-O SVM	0.99	0.17	0.03	4.53	0.01	0.22	3.26	0.33	0	0.96	1.29	0.37
G-O SVM	0.94	0.18	0.04	4.70	0.01	0.23	3.4	0.35	0	0.95	1.38	0.39
G-O M_P	0.079	0.024	0.221	0.494	0.026	0.026	0.303	0.341	0.007	0.097	0.016	0.007

The meter-specific results in each meter's section correspond only to the maximum light output of the test light source. Table 7 and Table 8 provide a representation of overall meter performance as it relates to Percent Flicker and Flicker Index, respectively, as well as the performance at maximum and dimmed light output levels. For the Viso Systems LabFlicker, measurements that were flagged as not having sufficient light for an accurate measurement were not included in this analysis.

Table 7. Deviation of Percent Flicker for handheld meters relative to reference meter measurement.

Percent Flicker	Viso (App)	Viso	AsenseTek	Fauser	UPRtek	Everfine	GL Optic	Gigahertz-Optik
Mean Deviation (all measurements)	17.31	0.20	1.27	3.14	2.34	19.10	0.75	0.68
Mean Deviation (max levels)	10.69	0.25	1.76	4.06	2.53	10.31	0.54	0.72
Mean Deviation (dimmed levels)	33.20	0.00	0.61	1.91	2.08	30.82	1.03	0.64

Table 8. Deviation of Flicker Index for handheld meters relative to reference meter measurement.

Flicker Index	Viso (App)	Viso	AsenseTek	Fauser	UPRtek	Everfine	GL Optic	Gigahertz-Optik
Mean Deviation (all measurements)	0.100	0.017	0.024	N/A	0.016	0.163	0.023	0.008
Mean Deviation (max levels)	0.038	0.005	0.010	N/A	0.009	0.111	0.006	0.002
Mean Deviation (dimmed levels)	0.250	0.066	0.042	N/A	0.026	0.232	0.047	0.016

3.2 Comparisons Using Calculated Values

To independently examine each meter's ability to measure the light intensity waveform and calculate metrics, comparisons were made between the meter-calculated and PNNL-calculated values for the handheld meters only (Figure 21 and Figure 22), and between PNNL-calculated values from both the handheld and reference meter waveforms (Figure 23 and Figure 24). These summary comparisons were made by averaging the deviations between the compared values across all test light sources at the maximum and dimmed output levels.

For the PNNL calculations, FFT analysis was used to convert each raw-data waveform from its time-domain representation to a frequency-domain representation, and the top four frequency components are reported for each test condition, along with their corresponding signal amplitudes. Since the duration of measurements performed for all meters was 2 seconds or more, Percent Flicker, Flicker Index, Fundamental Frequency, and SVM (if the sampling rate was sufficient) were calculated. For the test light sources that were evaluated at various light-output levels, only the full-output waveforms were included in the summary comparisons.

The Percent Flicker and Flicker Index analyses depict maximum, median (50%), mean, and minimum deviations (absolute differences) of the calculations from the test and reference waveforms as well as the 75% (3rd quartile) and 25% (1st quartile) histogram bins. The Fundamental Frequency analysis simply shows the percentage of handheld meter values that matched (defined as within 10 Hz) those produced by the reference-meter analysis. For the majority of the test light sources and dimmed conditions, the difference between the Fundamental Frequency reported by the commercial-meter and reference-meter calculation was either small (e.g., within 10 Hz) or large (e.g., hundreds or thousands of Hz). The significant deviations mainly occurred when measurements were taken of light-intensity waveforms with significant high-frequency content – greater than the dominant 120 Hz found in many products at full output. The determination of Fundamental Frequency is highly dependent on the meter's ability to accurately capture waveform characteristics. Given that sampling conditions could not be defined for some meters, a match (defined as within 10 Hz) was deemed to be a more appropriate metric than absolute difference.

Figure 21 provides box plots for Percent Flicker and Flicker Index showing the distribution of deviation data (i.e., minimum, first quartile, median, third quartile, and maximum, as well as the mean) and a bar chart for Fundamental Frequency showing the percent matching, as defined. These plots compare the value reported by the meter for the given metric to the MATLAB calculated value for that metric using the meter's waveform. As noted earlier, the Everfine meter had a data transfer issue in the software, which did not impact the waveform output, and thus it showed significant deviations. Overall, with the exception of Everfine and fundamental frequency matching of the Gigahertz-Optik, the metrics reported by the handheld meters were a good match to the MATLAB calculated metrics, and handheld meter performance in this regard was similar or better than the reference meter.

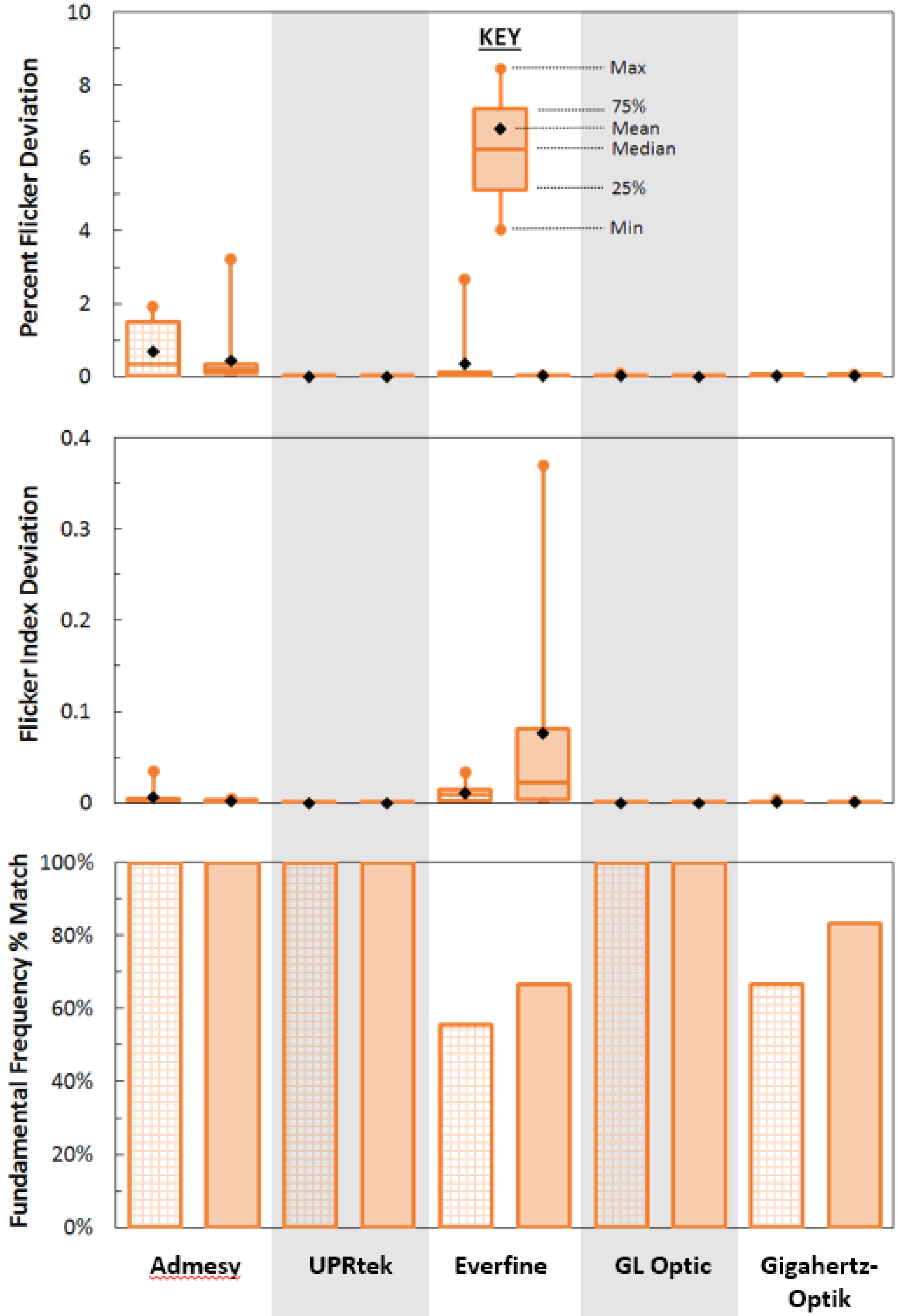

Figure 21. Comparison of the metrics reported by the meter and metrics derived from MATLAB calculations from the same meter's waveform.

Left-side bars (patterned) represent dimmed-output results, right-side bar (solid) represent full-output results.

Figure 22 shows the absolute SVM deviation between meter-reported and PNNL-calculated values for the three meters that could meet the requisite measurement requirements.

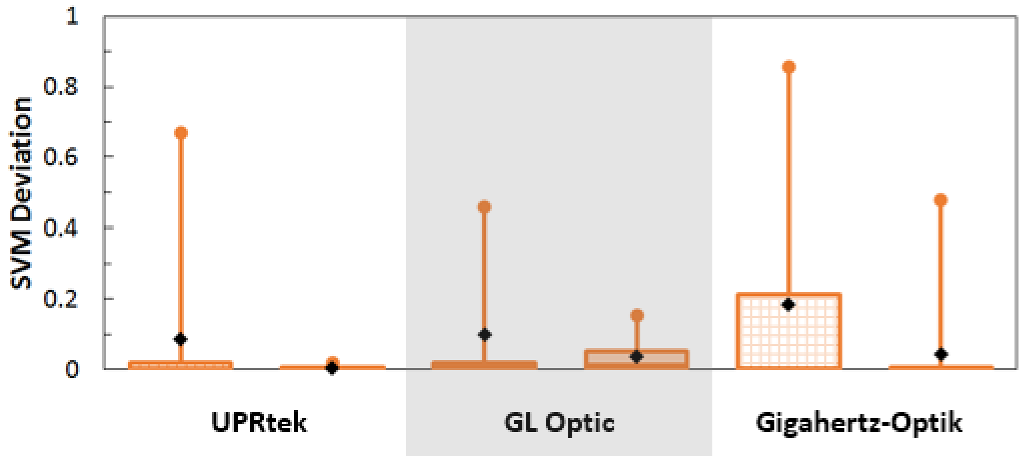

Figure 22. Comparison of SVM as reported by the meter and SVM as derived from MATLAB calculations from the same meter's waveform.

Left-side bars (patterned) represent dimmed-output results, right-side bars (solid) represent full-output results.

Whereas the previous analysis compared the value reported by the meter for the given metric to the MATLAB calculated value for that metric using the handheld meter's waveform, in this section the ability of each handheld meter to measure light-intensity waveforms was evaluated and compared to the reference meter waveforms; Percent Flicker, Flicker Index, and Fundamental Frequency were calculated by PNNL using the raw light intensity waveforms output by the handheld and reference meters. In this section, it is important to note that the reference meter is not a standard for flicker measurements, and it too showed its own deviations from the then reference meter during the first round of benchtop meter tests. As a result, while the data is presented here for comparative purposes, no general conclusions are drawn regarding the deviations observed in relation to the reference meter.

Figure 23 provides box plots for Percent Flicker and Flicker Index showing the distribution of deviation data and a bar chart for Fundamental Frequency showing the percent matching, as defined. These plots compare the MATLAB calculated values from the handheld meter waveform to the MATLAB calculated values from the reference meter waveform. As noted earlier, the Everfine meter had a data transfer issue present in the software, which does not impact the waveform output, and so that would not manifest itself in these plots. However, the Everfine does have much lower sampling capability at the integration time selected and the significant deviations here are reflective of that. Otherwise, the calculations made from the handheld meter waveforms do show a small amount of deviation when compared to the calculations made from the reference meter waveforms.

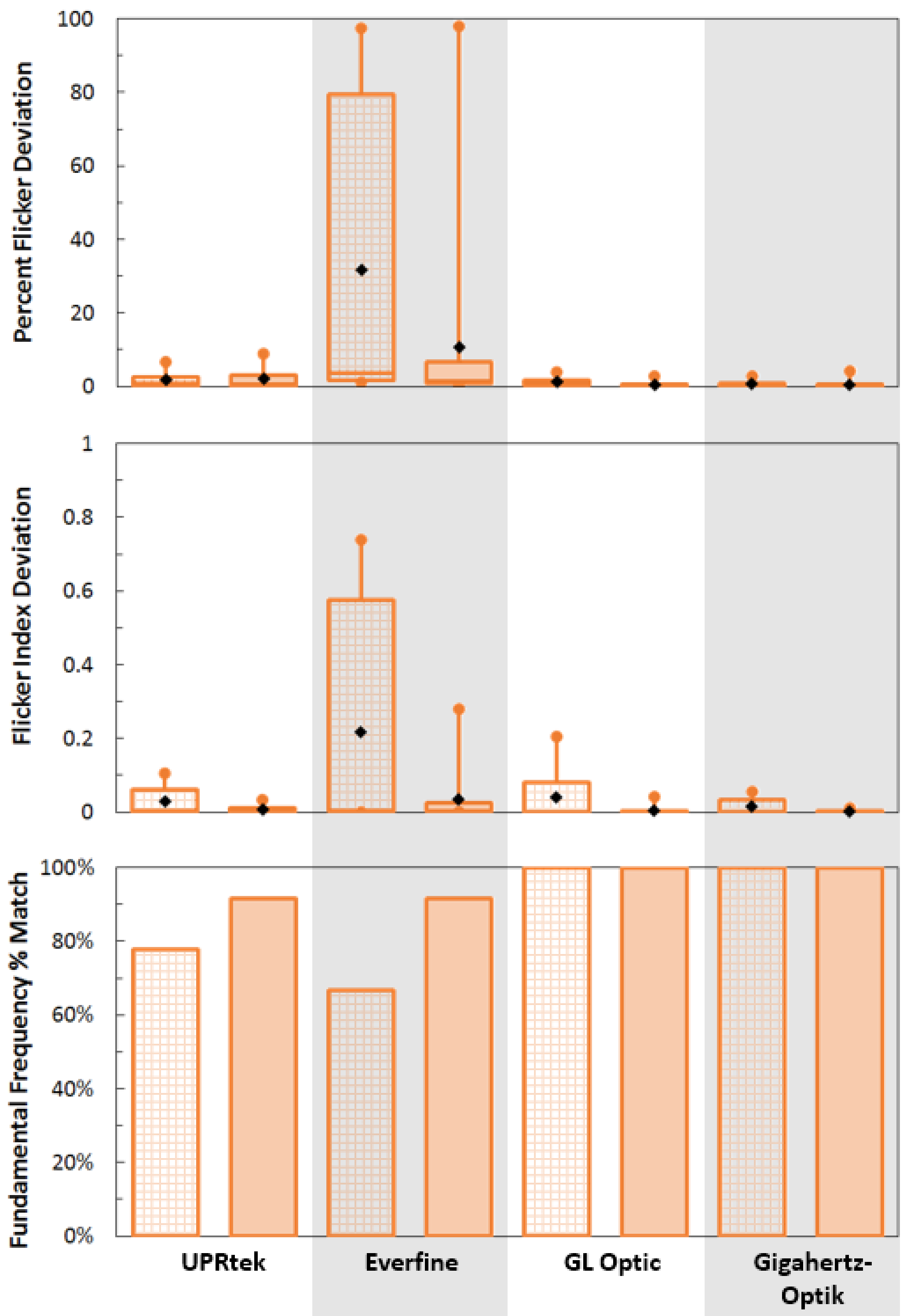

Figure 23. Comparison of handheld meter metrics calculated from waveform measurements using MATLAB and measurements from the reference meter metrics derived from the reference meter waveform using MATLAB.

Left-side bars (patterned) represent dimmed-output results, right-side bars (solid) represent full-output results.

Figure 24 shows the absolute SVM deviation for the three meters that could meet the requisite measurement requirements.

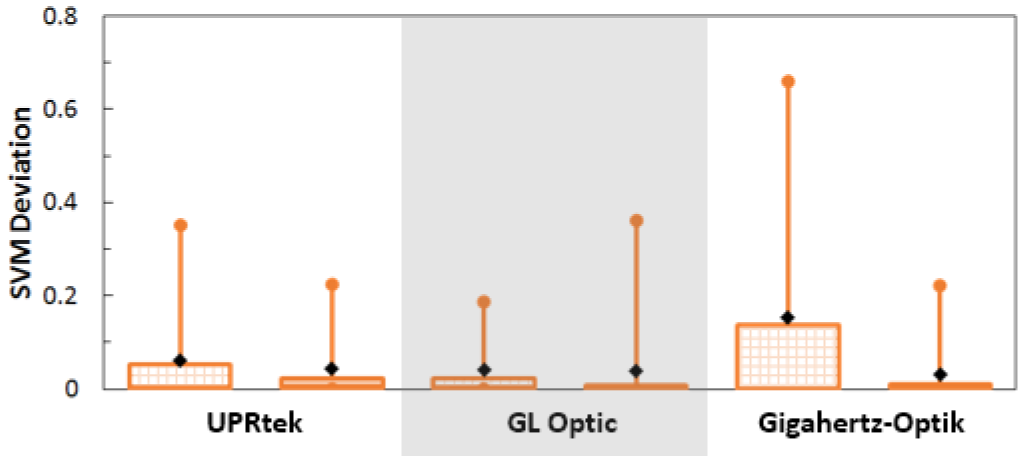

Figure 24. Comparison of handheld meter SVM calculated from waveform measurements using MATLAB and measurements from the reference meter SVM derived from the reference meter waveform using MATLAB.

Left-side bars (patterned) represent dimmed-output results, right-side bars (solid) represent full-output results.

4 Conclusions

Handheld flicker meters today are capable of providing performance nearing that of a benchtop meter in a controlled environment. Even free applications available for smart devices can provide a measurement that could be used as an indicator that a flicker problem may exist (accurate within about 10% for Percent Flicker and 0.04 points for Flicker Index across all maximum light output measurements). However, the accuracy of these devices needs to be followed up by more precise flicker measuring equipment, handheld or benchtop. Although this study uncovered some limitations and anomalies, these have been addressed either in product literature, on the device/software itself, or through firmware/software updates. As flicker continues to be an important factor in the selection and use of lighting products, future flicker meters will enable users in the field to adequately characterize lighting in a space and determine whether the level of flicker is acceptable for the given application.

5 Considerations

The test meters hold qualities that vary in utility depending on the intended use of the meter. It is necessary to be aware of meter limitations that prohibit certain measurements from being reliable: Some of the meters began to fail to detect flicker at much lower frequencies compared to other meters. Other aspects to consider for meter selection include the following:

- Is there a need for other types of field measurements (light levels, color/spectrum, etc.)? Various meters tested have capabilities beyond the measurement of flicker, which makes them useful for other field measurements and evaluations.
- How will the meter be physically used? Some meters, for example, had sensors on the same side as the screen, others on top, and others had sensors on detachable heads that would allow measurements to occur remotely from the controller/body. One meter needed to be tethered to a computer in order to function. Knowing how testing will be done in the field is helpful in identifying whether a given meter would be a better option for the intended tasks.

- How will the data be used after the measurement is taken? And will light intensity waveform data be useful or necessary? The waveform data, for example, may be used for calculating metrics that the meter does not automatically report, or for calculating metrics that will be developed in the future.
- Are formal reports needed? Some meters generate reports that may be used for recordkeeping or delivering to clients.

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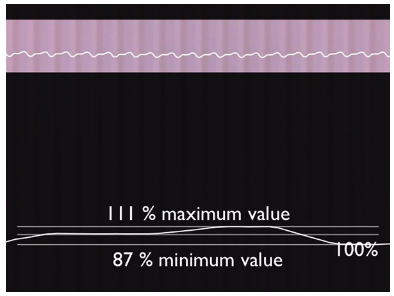
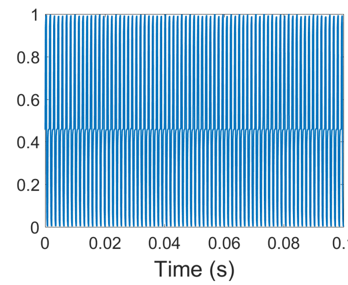
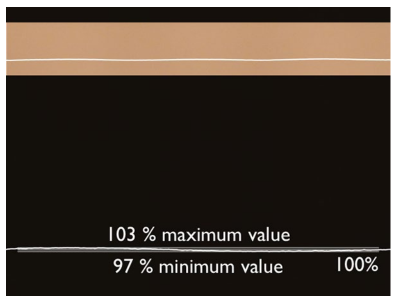
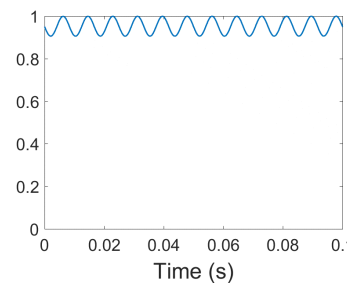
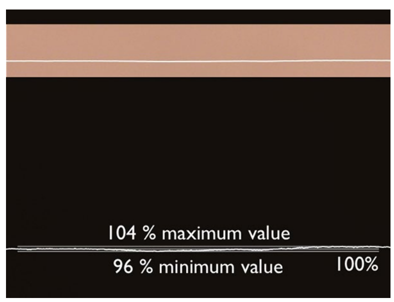
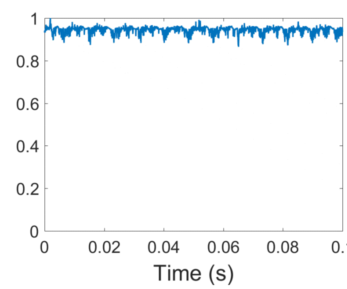
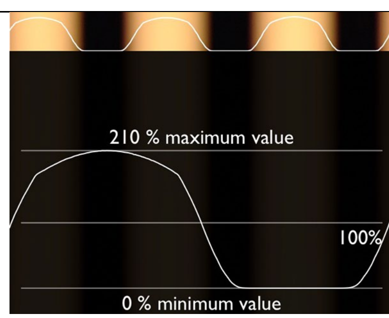
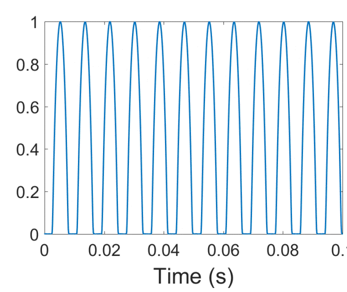
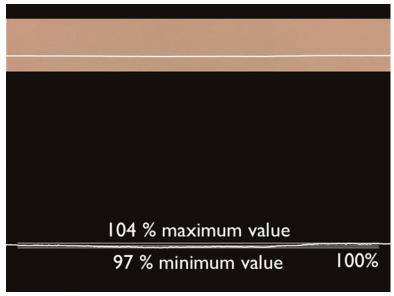
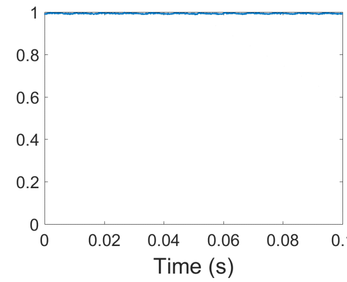
Appendix A

This appendix presents light output waveforms for the maximum light output for each test light source, comparing the handheld meter to the reference meter waveform. For visibility and comparative purposes, only a 0.1-second snippet is shown of the full waveform collected (2 to 3 seconds depending on the meter, with the exception of the Viso App and the Viso Flicker meter, which were only graphically captured).

		Light Output Waveform	
Luminaire #	**Luminaire Type**	**Viso (App) (as presented)**	**Reference (normalized)**
A	White-tunable linear LED cove luminaire		
B	Halogen Infrared (HIR) PAR38 halogen screw-base lamp		
C	High CRI PAR38 LED replacement screw-base lamp		
D	PAR38 LED replacement screw-base lamp		

<table>
<tr><th></th><th></th><th colspan="2">Light Output Waveform</th></tr>
<tr><th>Luminaire #</th><th>Luminaire Type</th><th>Viso (App) (as presented)</th><th>Reference (normalized)</th></tr>
<tr><td>E</td><td>PAR38 LED replacement screw-base lamp</td><td>
</td><td>
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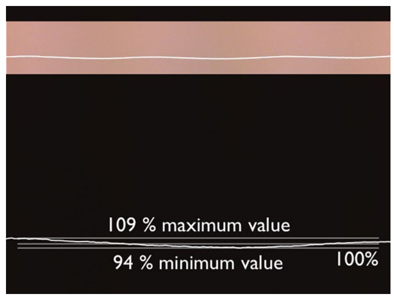
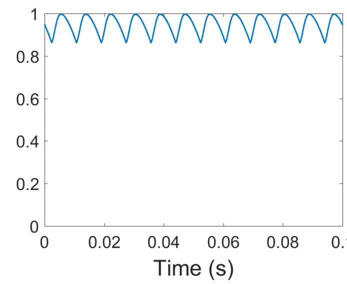
<tr><td>F</td><td>CFL self-ballasted screw-base A-lamp</td><td>
</td><td>
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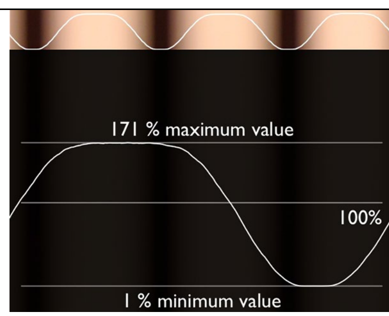
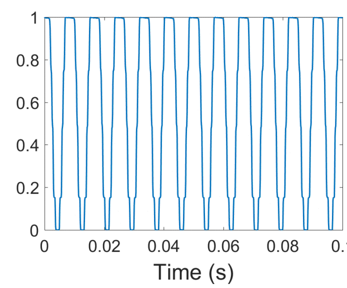
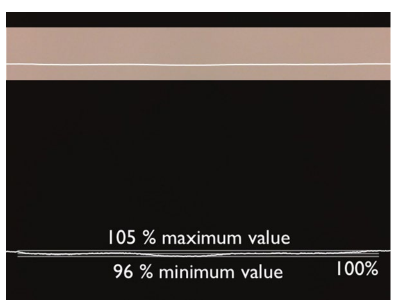
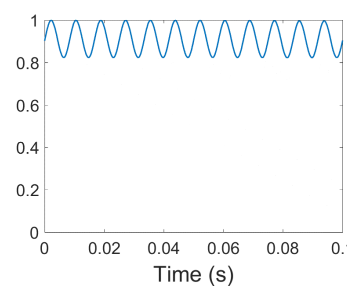
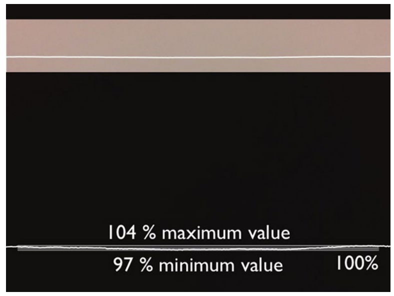
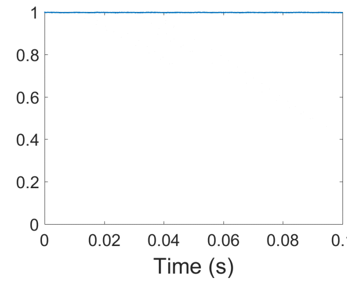
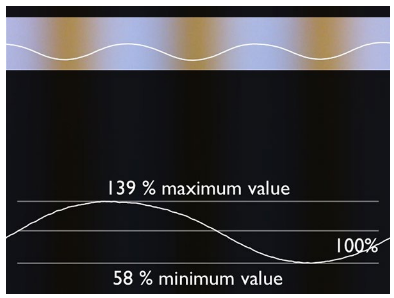
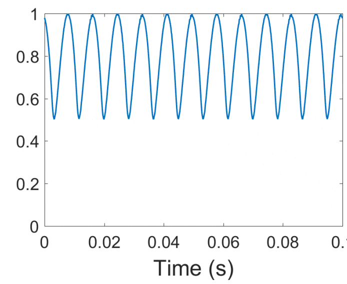
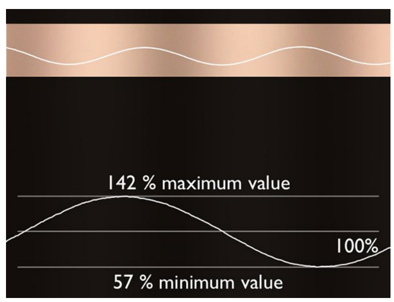
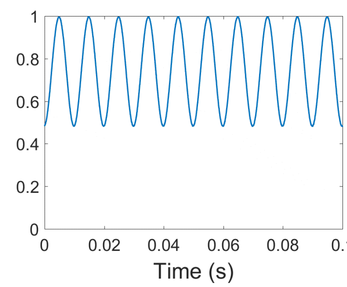
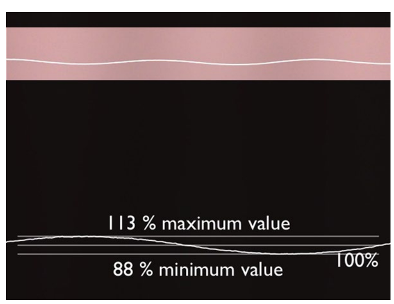
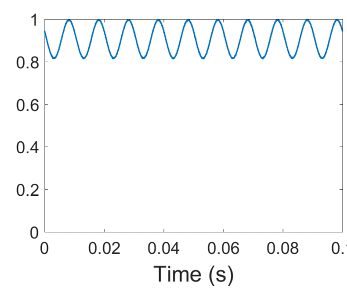
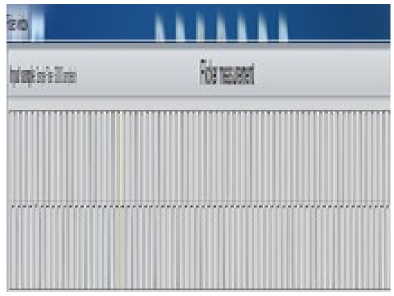
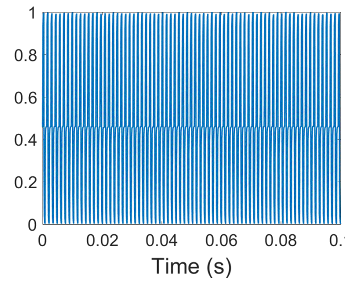
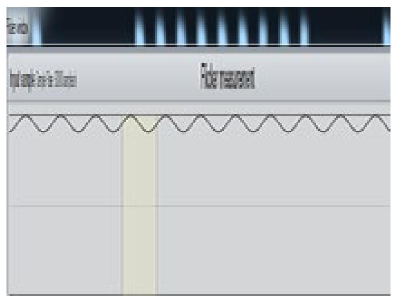
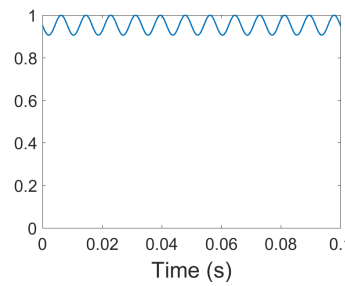
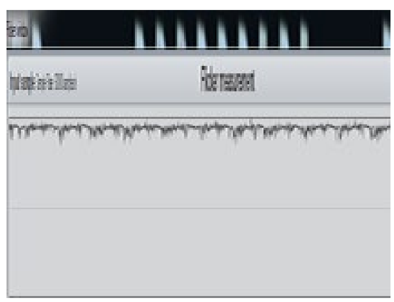
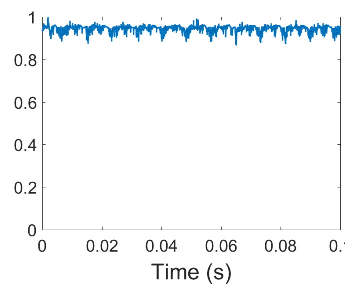
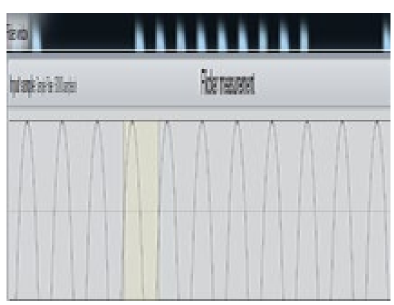
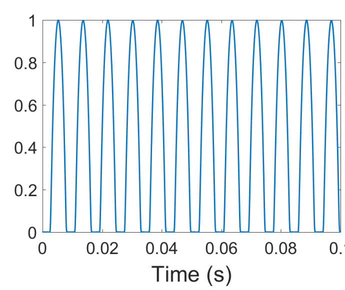
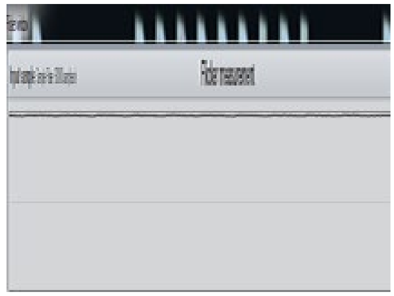
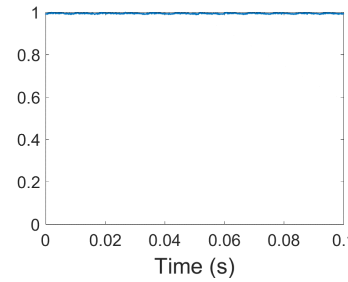
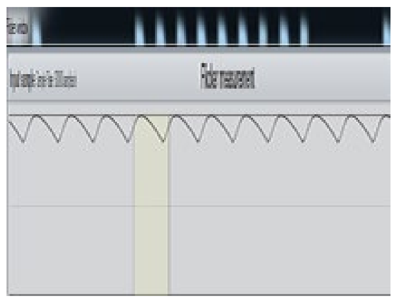
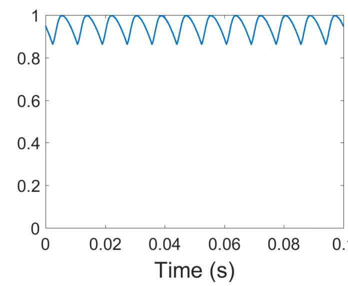
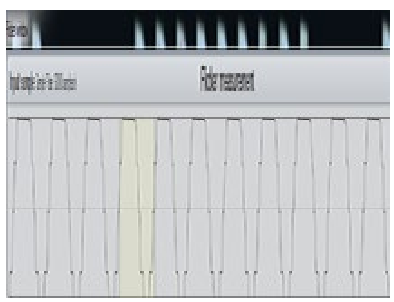
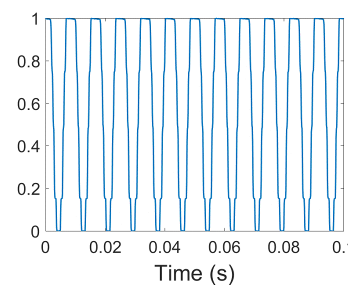
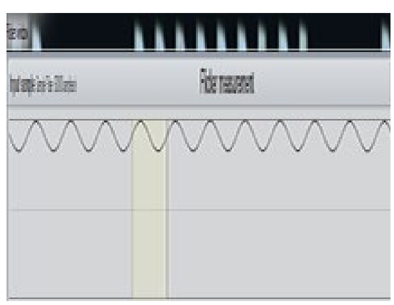
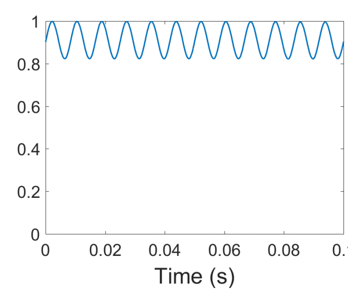
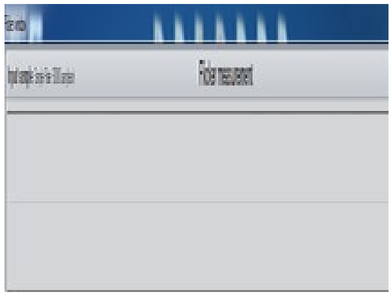
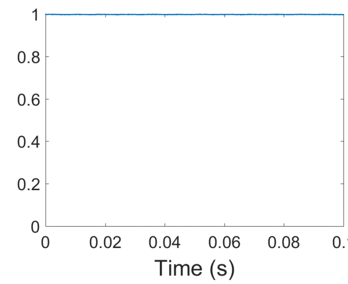
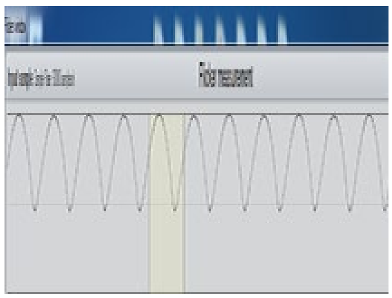
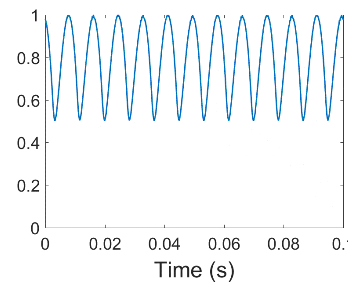
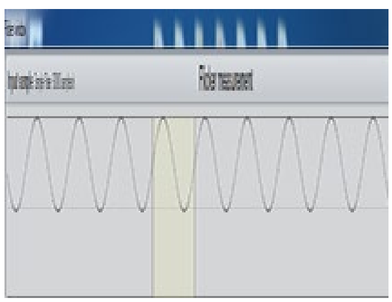
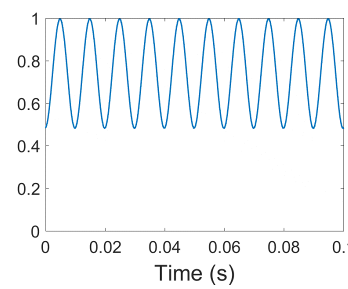
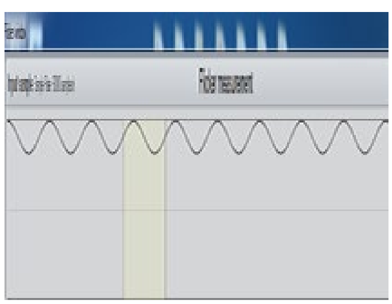
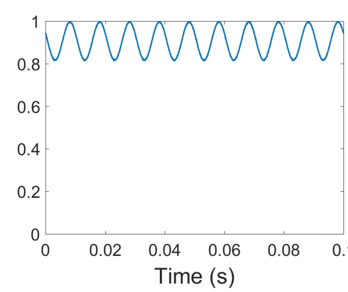
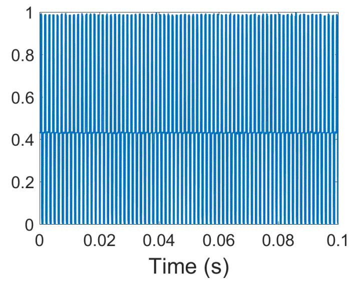
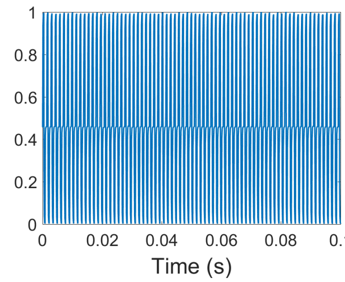
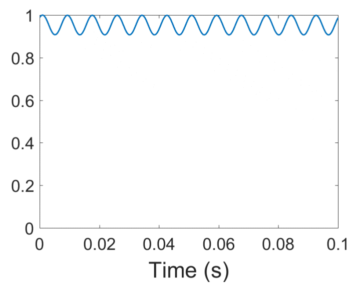
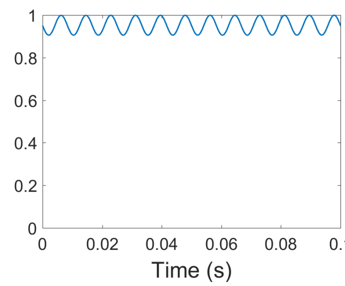
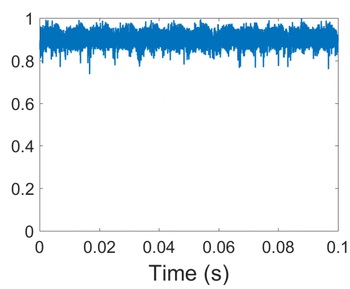
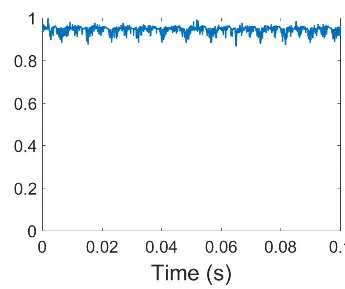
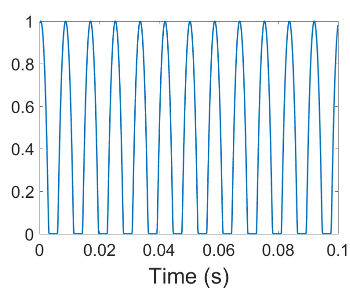
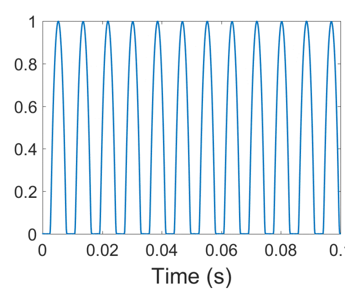
<tr><td>G</td><td>BR30 LED screw-base replacement lamp</td><td>
</td><td>
</td></tr>
<tr><td>H</td><td>Recessed 2 x 2 LED troffer with a contoured diffuser, producing a batwing distribution</td><td>
</td><td>
</td></tr>
</table>

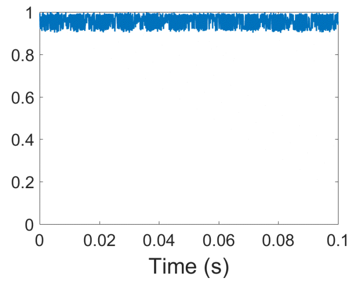
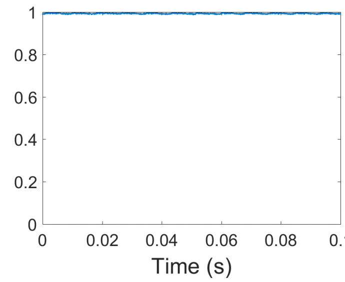
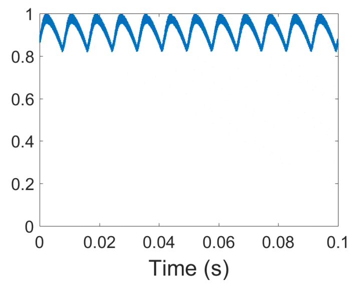
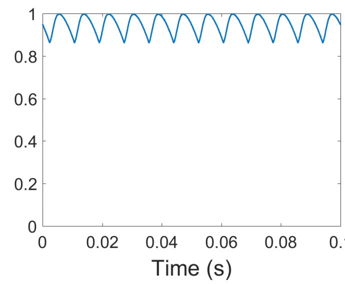
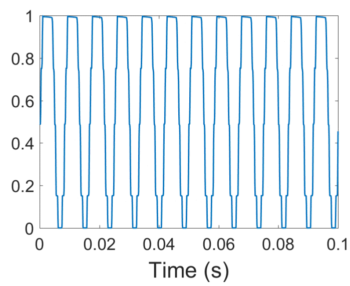
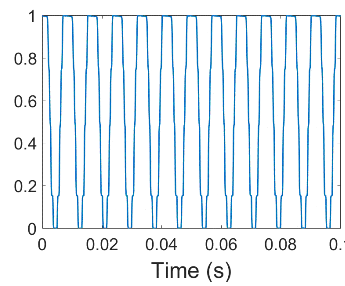
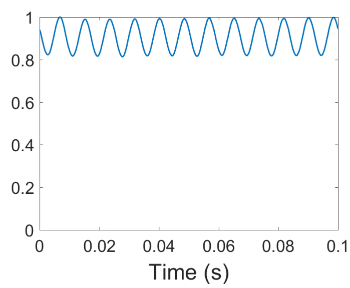
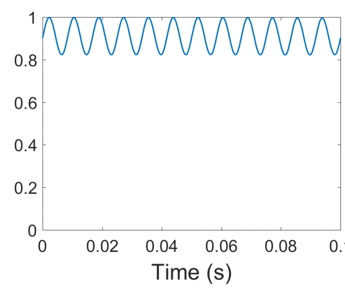
		Light Output Waveform	
Luminaire #	**Luminaire Type**	**Viso (App) (as presented)**	**Reference (normalized)**
I	Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 - 10 V electronic dimming ballast		
J	4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast		
K	Philips TLA Demo Unit - Typical LED		
L	Philips TLA Demo Unit - Typical 60W incandescent lamp		

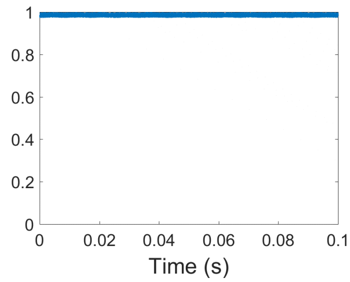
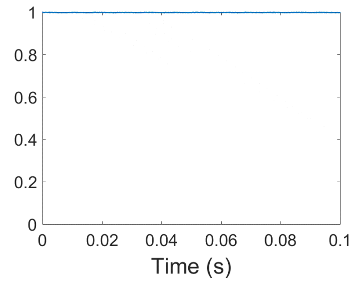
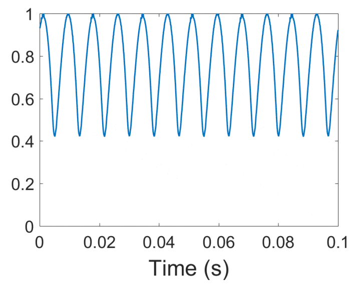
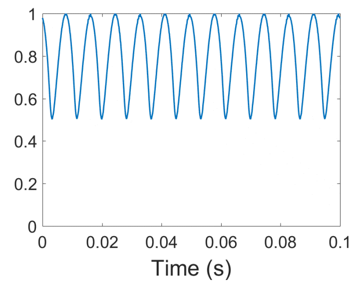
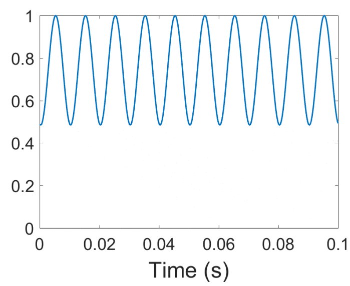
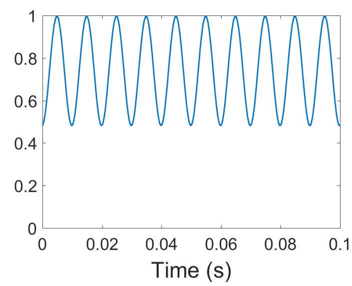
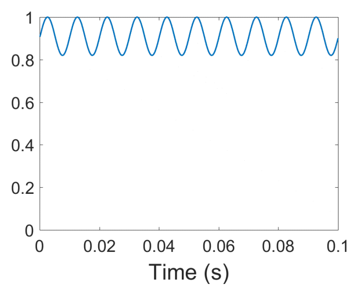
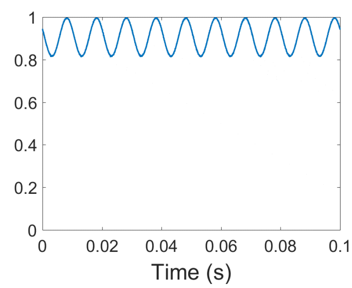
		Light Output Waveform	
Luminaire #	**Luminaire Type**	**Viso (as presented)**	**Reference (normalized)**
A	White-tunable linear LED cove luminaire		
B	Halogen Infrared (HIR) PAR38 halogen screw-base lamp		
C	High CRI PAR38 LED replacement screw-base lamp		
D	PAR38 LED replacement screw-base lamp		

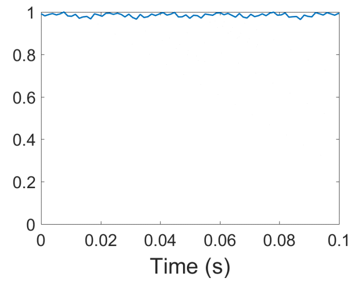
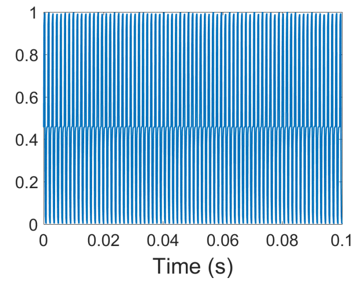
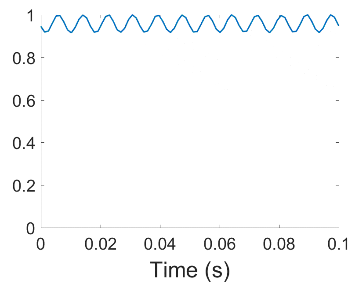
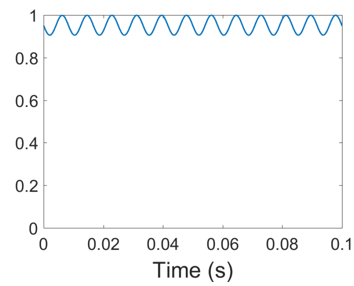
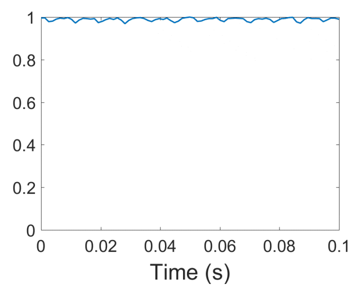
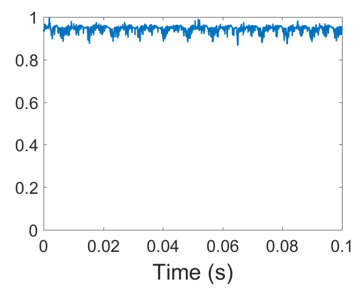
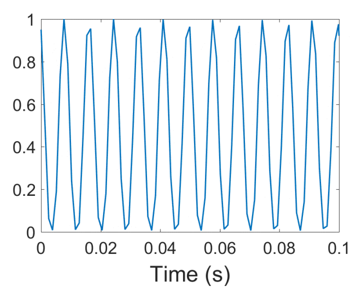
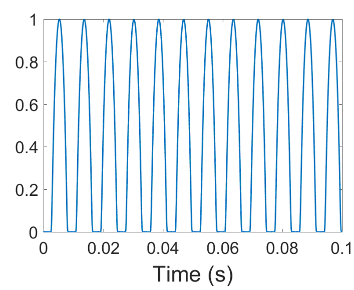
		Light Output Waveform	
Luminaire #	**Luminaire Type**	**Viso (as presented)**	**Reference (normalized)**
E	PAR38 LED replacement screw-base lamp		
F	CFL self-ballasted screw-base A-lamp		
G	BR30 LED screw-base replacement lamp		
H	Recessed 2 x 2 LED troffer with a contoured diffuser, producing a batwing distribution		

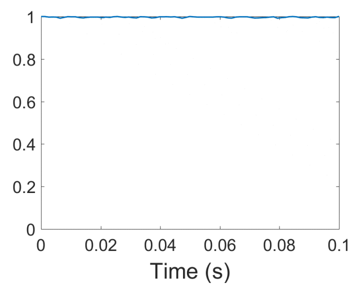
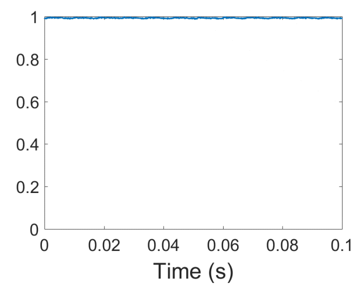
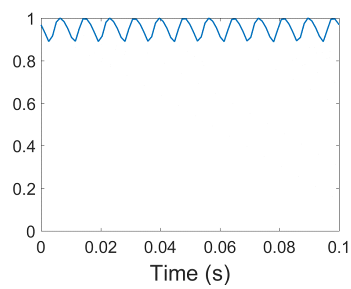
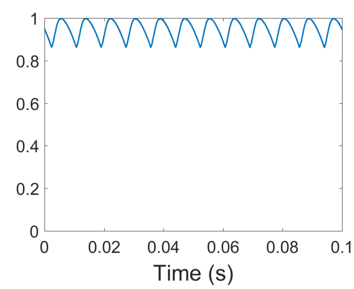
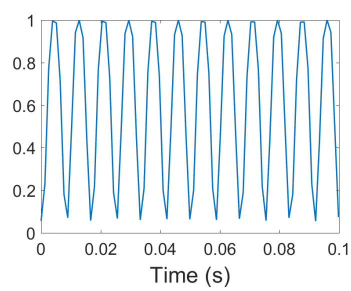
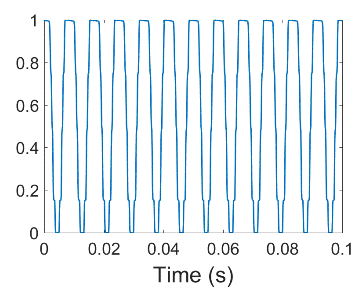
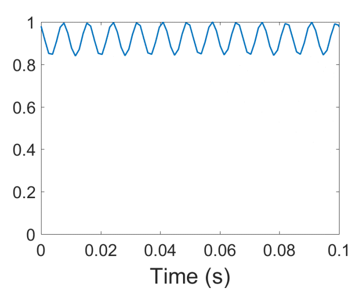
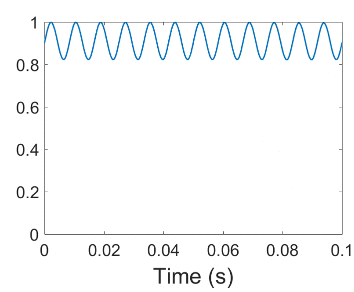
		Light Output Waveform	
Luminaire #	**Luminaire Type**	**Viso (as presented)**	**Reference (normalized)**
I	Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 - 10 V electronic dimming ballast		
J	4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast		
K	Philips TLA Demo Unit - Typical LED		
L	Philips TLA Demo Unit - Typical 60W incandescent lamp		

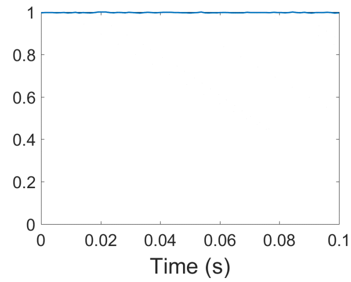
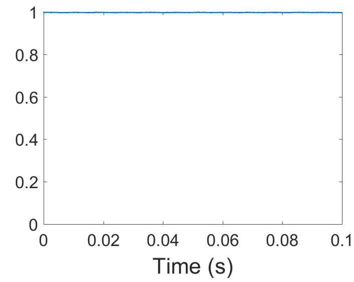
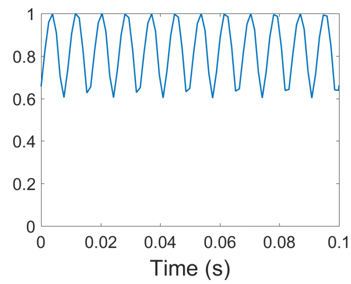
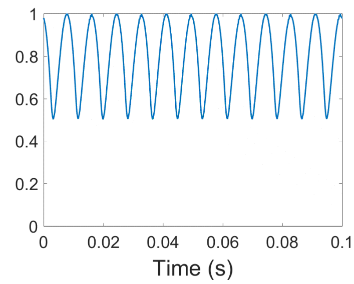
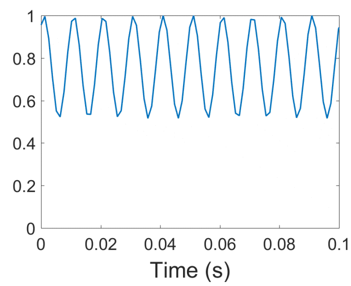
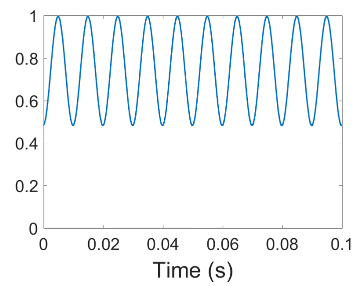
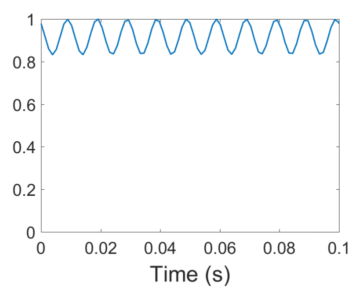
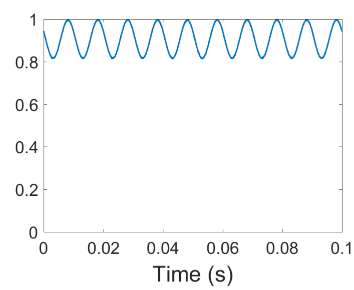
		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**UPRtek**	**Reference**
A	White-tunable linear LED cove luminaire		
B	Halogen Infrared (HIR) PAR38 halogen screw-base lamp		
C	High CRI PAR38 LED replacement screw-base lamp		
D	PAR38 LED replacement screw-base lamp		

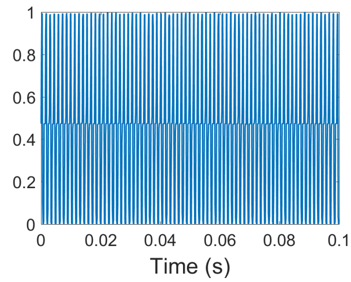
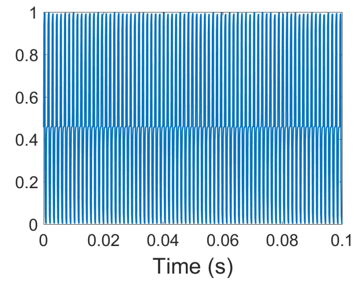
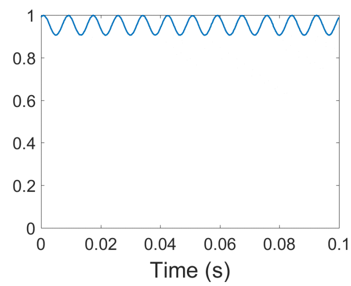
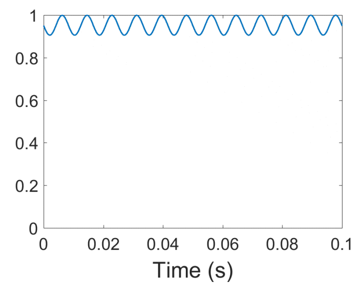
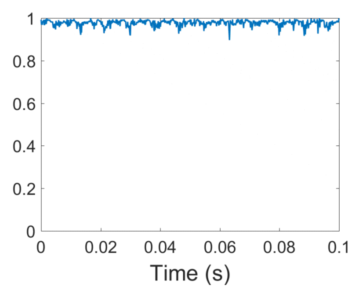
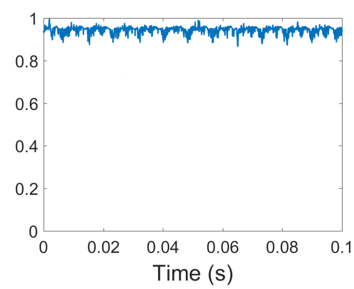
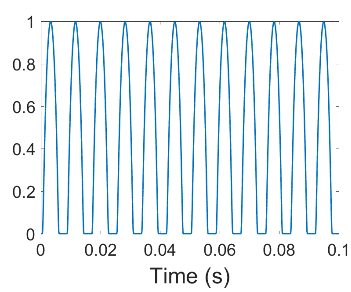
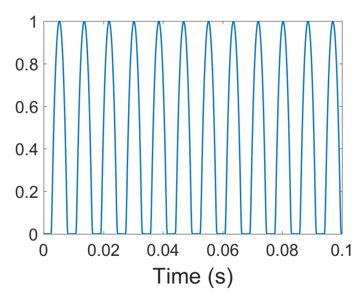
		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**UPRtek**	**Reference**
E	PAR38 LED replacement screw-base lamp		
F	CFL self-ballasted screw-base A-lamp		
G	BR30 LED screw-base replacement lamp		
H	Recessed 2 x 2 LED troffer with a contoured diffuser, producing a batwing distribution		

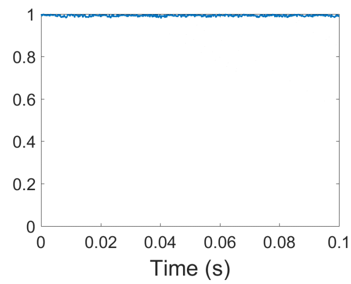
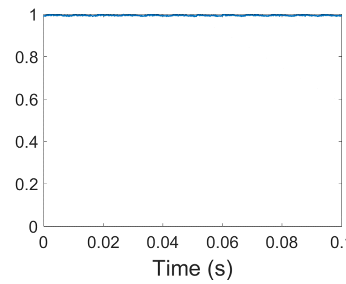
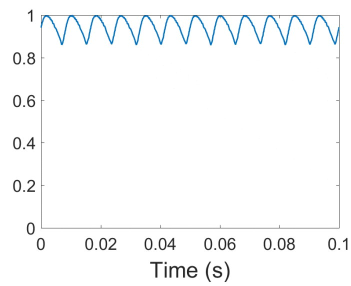
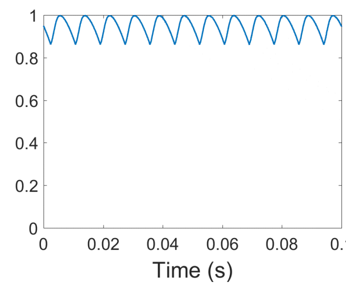
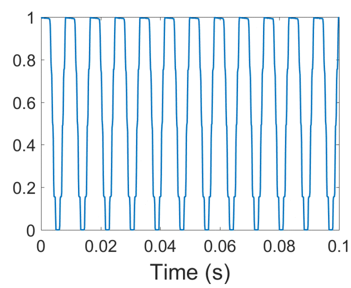
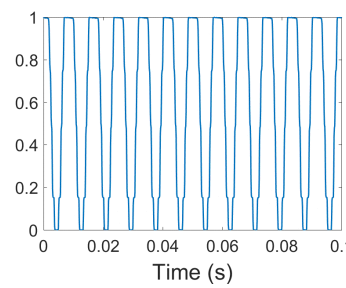
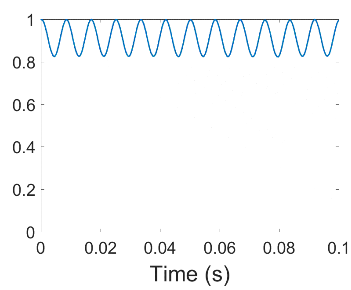
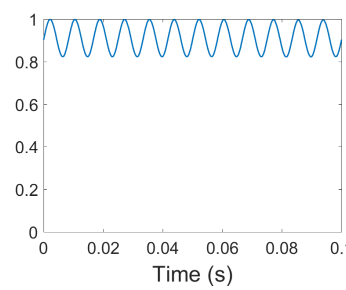
Luminaire #	Luminaire Type	Normalized Light Output Waveform	
		UPRtek	**Reference**
I	Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 - 10 V electronic dimming ballast		
J	4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast		
K	Philips TLA Demo Unit - Typical LED		
L	Philips TLA Demo Unit - Typical 60W incandescent lamp		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**Everfine**	**Reference**
A	White-tunable linear LED cove luminaire		
B	Halogen Infrared (HIR) PAR38 halogen screw-base lamp		
C	High CRI PAR38 LED replacement screw-base lamp		
D	PAR38 LED replacement screw-base lamp		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**Everfine**	**Reference**
E	PAR38 LED replacement screw-base lamp		
F	CFL self-ballasted screw-base A-lamp		
G	BR30 LED screw-base replacement lamp		
H	Recessed 2 x 2 LED troffer with a contoured diffuser, producing a batwing distribution		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**Everfine**	**Reference**
I	Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 - 10 V electronic dimming ballast		
J	4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast		
K	Philips TLA Demo Unit - Typical LED		
L	Philips TLA Demo Unit - Typical 60W incandescent lamp		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**GL Optic**	**Reference**
A	White-tunable linear LED cove luminaire		
B	Halogen infrared (HIR) PAR38 halogen screw-base lamp		
C	High CRI PAR38 LED replacement screw-base lamp		
D	PAR38 LED replacement screw-base lamp		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**GL Optic**	**Reference**
E	PAR38 LED replacement screw-base lamp		
F	CFL self-ballasted screw-base A-lamp		
G	BR30 LED screw-base replacement lamp		
H	Recessed 2 x 2 LED troffer with a contoured diffuser, producing a batwing distribution		

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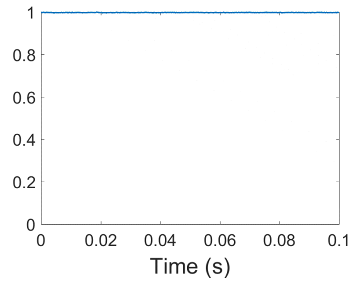
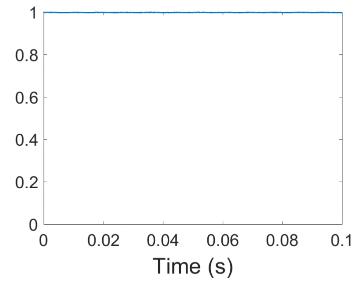
<tr><th>Luminaire #</th><th>Luminaire Type</th><th>GL Optic</th><th>Reference</th></tr>
<tr><td>I</td><td>Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 - 10 V electronic dimming ballast</td><td>
</td><td>
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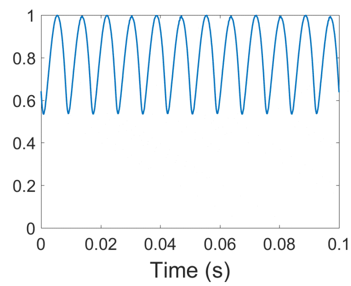
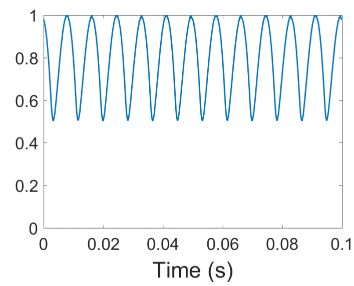
<tr><td>J</td><td>4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast</td><td>
</td><td>
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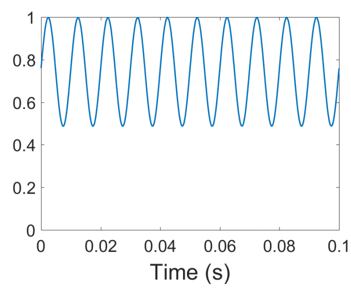
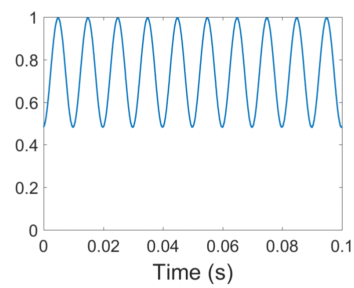
<tr><td>K</td><td>Philips TLA Demo Unit - Typical LED</td><td>
</td><td>
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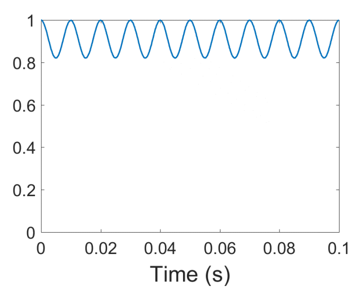
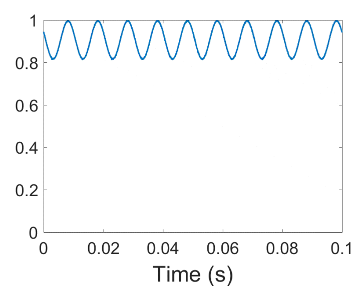
<tr><td>L</td><td>Philips TLA Demo Unit - Typical 60W incandescent lamp</td><td>
</td><td>
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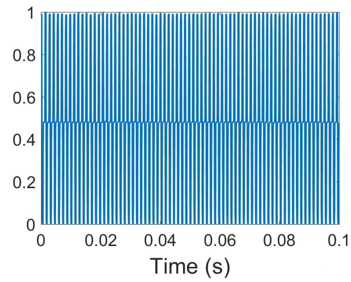
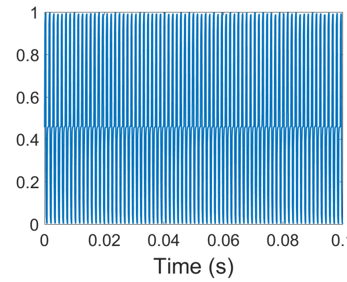
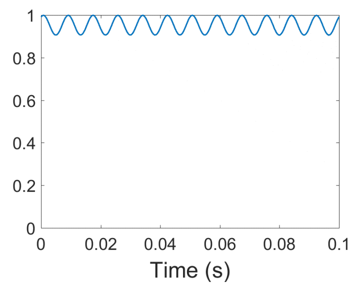
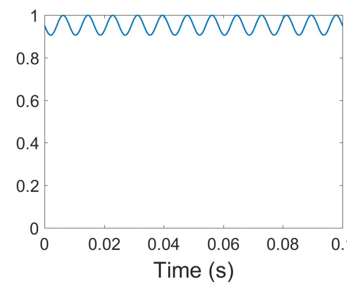
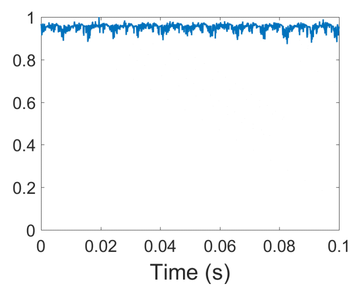
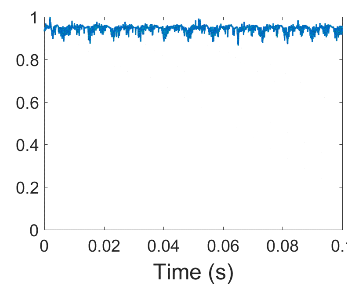
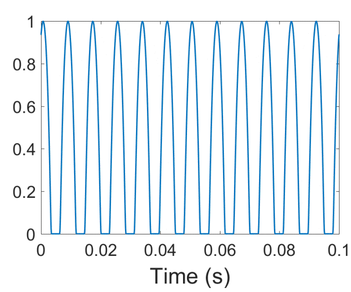
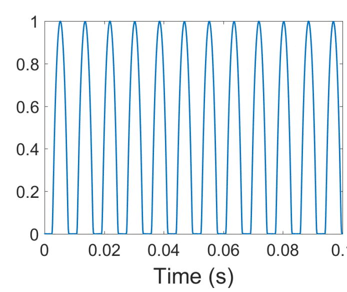
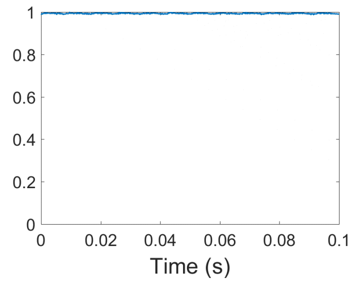
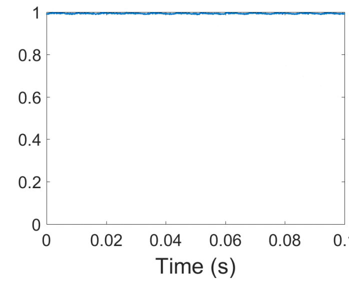
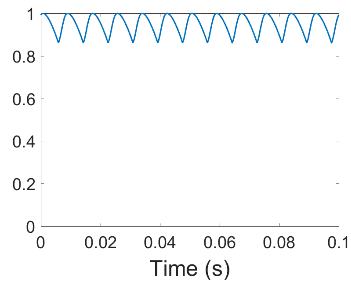
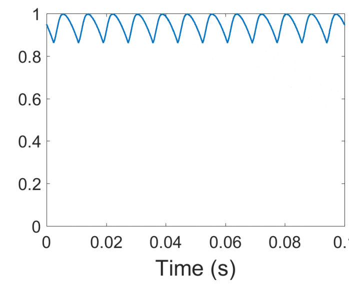
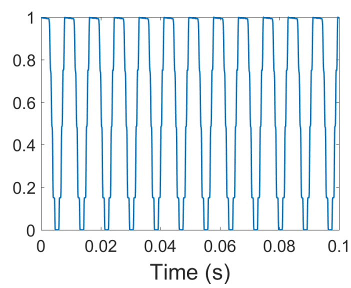
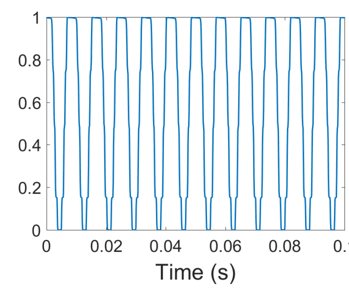
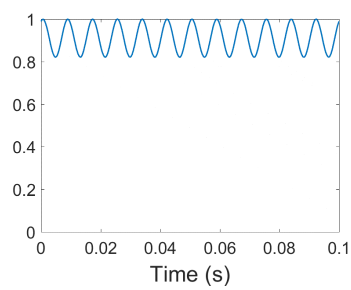
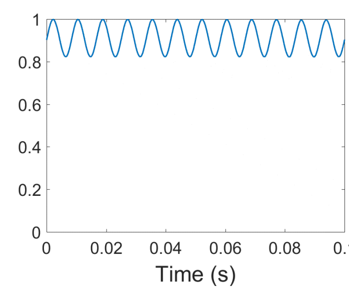
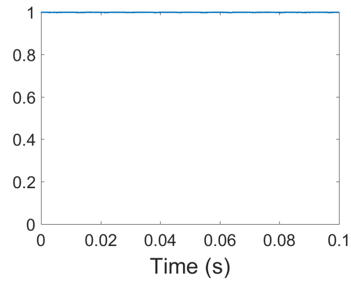
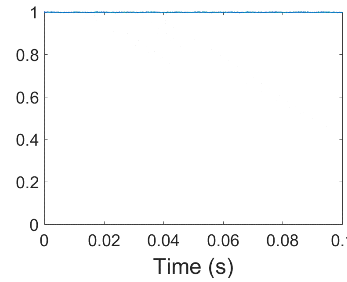
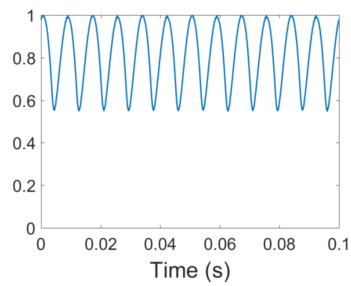
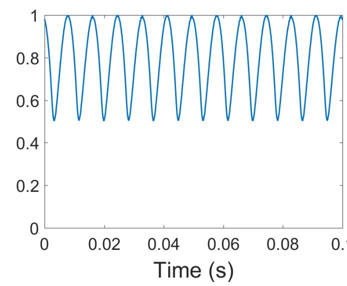
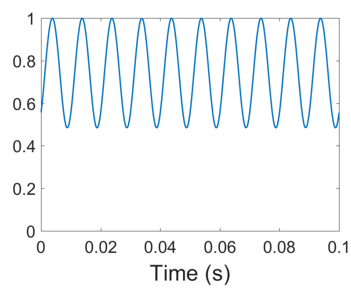
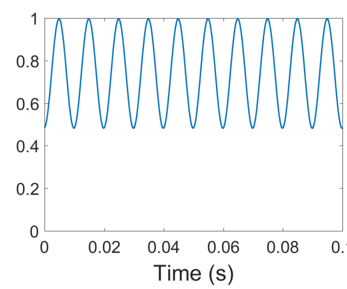
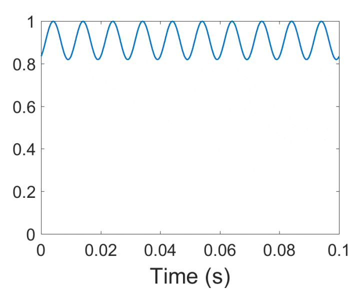
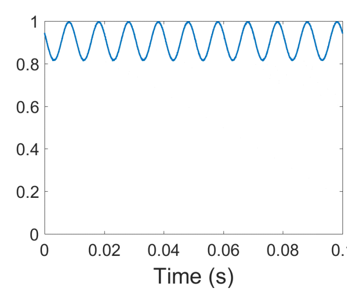
		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**Gigahertz-Optik**	**Reference**
A	White-tunable linear LED cove luminaire		
B	Halogen Infrared (HIR) PAR38 halogen screw-base lamp		
C	High CRI PAR38 LED replacement screw-base lamp		
D	PAR38 LED replacement screw-base lamp		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**Gigahertz-Optik**	**Reference**
E	PAR38 LED replacement screw-base lamp		
F	CFL self-ballasted screw-base A-lamp		
G	BR30 LED screw-base replacement lamp		
H	Recessed 2 x 2 LED troffer with a contoured diffuser, producing a batwing distribution		

		Normalized Light Output Waveform	
Luminaire #	**Luminaire Type**	**Gigahertz-Optik**	**Reference**
I	Recessed T8 2 x 2 lensed (prismatic) troffer with two 32W T8 fluorescent U-lamps and 0 - 10 V electronic dimming ballast		
J	4' fluorescent strip light with one T12 lamp and magnetic rapid-start ballast		
K	Philips TLA Demo Unit - Typical LED		
L	Philips TLA Demo Unit - Typical 60W incandescent lamp		

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