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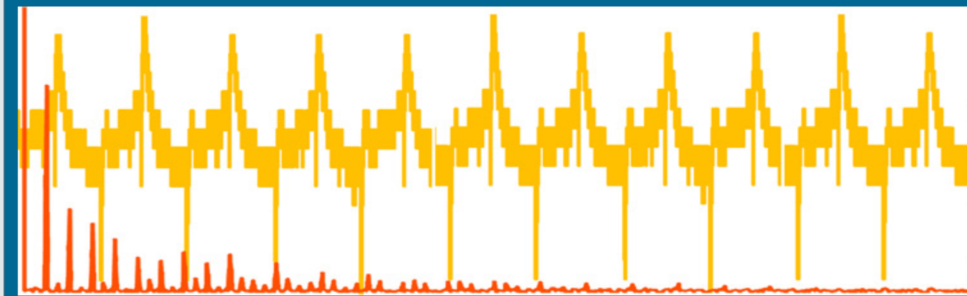

Characterizing Photometric Flicker

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Prepared by:

Pacific Northwest National Laboratory

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Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy

TE Perrin
CC Brown
ME Poplawski
NJ Miller

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Pacific Northwest National Laboratory
Richland, Washington 99352

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Characterizing Photometric Flicker

Summary

The focus of this study is simply to report on the commercial availability and performance of emerging flicker meters. Commercial-meter measurements and calculations were compared against those generated by a photoelectric characterization system developed by the Pacific Northwest National Laboratory (PNNL). The results and analysis show that the three commercially available flicker meters evaluated for this study measured light-intensity waveforms and calculated essential flicker-performance characteristics and metrics similarly, both to each other and to the reference meter chosen as an accuracy benchmark. Some differences in performance were found, however, 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. Such conditions may be found in light sources that employ pulse-width modulation to achieve their target light output (e.g., intensity or color). If the meter was not appropriately configured (e.g., sampling frequency was too low), or if proper configuration was not possible given meter constraints (e.g., maximum number of available data points), then the waveform characteristics were not accurately captured, often resulting in the calculation of flicker metrics that deviated significantly from the reference.

While the results of this report may be of interest to many lighting-industry stakeholders, the intended audience includes lighting and meter manufacturers, test laboratories, and standards and specification bodies. It is hoped that this report will further interest in measuring and reporting flicker, thereby enabling the use of flicker characteristics to mitigate the potential effects of flicker in lighting installations and accelerating the development of standard test and measurement procedures. The commercial availability of flicker meters should make it easier for designers and specifiers to minimize the risk of flicker-induced problems for their clients in the near future.

Introduction

Background

Flicker is garnering increased attention from lighting designers and specifiers, the standards and specification community, and, consequently, lighting manufacturers. An IEEE group[1] has developed a recommended practice[2] for evaluating flicker risks, and the U.S. Environmental Protection Agency ENERGY STAR® and California Title 20 programs are requiring the reporting of flicker performance and/or considering the adoption of flicker criteria. Some manufacturers appear to be giving flicker increased design priority, as evidenced by the improved performance of new product generations. An understanding of why flicker matters and how much it varies across commercially available products is increasingly becoming essential for proper lighting design. Specifying the right product for a given application and risk sensitivity further requires the ability to quantitatively characterize flicker.

All conventional light sources—including incandescent, high-intensity discharge (HID), and fluorescent—modulate luminous flux and intensity to some degree, usually as a consequence of drawing power from AC mains sources (i.e., 60 Hz AC in North America). Many terms are used when referring to this time variation, including “flicker,” “flutter,” and “shimmer.” The Illuminating Engineering Society of North America (IES) Lighting

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[1] IEEE PAR1789: http://grouper.ieee.org/groups/1789/.

[2] IEEE Std 1789™-2015, *IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*: http://standards.ieee.org/findstds/standard/1789-2015.html.

Handbook defines flicker as "the rapid variation in light source intensity."[3] The periodic waveform that usually characterizes flicker can be principally described by four parameters: its amplitude modulation (i.e., the difference between its maximum and minimum levels over a periodic cycle), its average value over a periodic cycle (also called the DC component), its shape or duty cycle (the ratio between the pulse duration and the period of a rectangular waveform), and its periodic frequency (the number of recurring cycles per second).

Photometric flicker – in which the flicker is a characteristic of the light source, as opposed to electrical flicker, which is caused by AC mains noise – was an issue when magnetically ballasted fluorescent and HID luminaires were common (before the mid-1990s). Research at that time identified light-source flicker to be related to migraines, headaches, autistic behaviours, reduced visual-task performance and comfort, along with other neurological issues.[4] When high-frequency electronic ballasts were introduced for energy efficiency, the negative effects of flicker were reported less frequently and largely disappeared from public discourse. With the introduction of LED lighting products to the marketplace, flicker has re-emerged as a concern, partly because the time-modulation of LED light output can be greater than the modulation possible with fluorescent or HID sources. For LED sources, the amount of flicker present is generally determined by the LED driver or by the dimmer and driver pairing, if applicable.

Researchers have known that light sources with low-frequency flicker, such as 3 to 70 Hz, can have serious neurological consequences, including triggering photosensitive epilepsy, for some populations. Frequencies of 100 Hz, which occur with 50 Hz power in Europe, are recognized as contributing to headaches and migraines.[5] Frequencies of 120 Hz are annoying and distracting at the very least for some populations, especially when there is large amplitude modulation. Flicker at 120 Hz from magnetically ballasted fluorescent lighting, and 100 to 300 Hz flicker from 100%-modulation LED products, have also been shown to reduce visual-task performance.[6,7]

Flicker is often detected indirectly, when a flickering light or an object lighted with flickering light is moving relative to the observer's gaze (stroboscopic effect), or when the observer's gaze is moving relative to the light or object (phantom-array effect). Both effects can be hazardous. Stroboscopic effects, for example, may result in the apparent slowing or stopping of moving machinery in an industrial setting, and phantom-array effects can be distracting to some individuals when driving at night. It is important to note that when the optical and neurological systems sense the modulation of light output over time, that flicker may have a physiological effect on the human observer, whether the light modulation or its indirect effects are perceived or not.

Flicker may not be problematic in many applications. The flicker from a task light in a brightly daylighted room may not be noticeable because the variation in light output is small compared to the ambient light level. Flicker in an industrial application may be mitigated by arranging adjacent luminaires on alternate phases of a three-

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3 Rea, M.S. (2000) *The IESNA Lighting Handbook: Reference and Application*. New York, NY: Illuminating Engineering Society of North America.

4 Wilkins, A.J., Veitch, J.A., Lehman, B. (2010) *LED Lighting Flicker and Potential Health Concerns: IEEE Standard PAR1789 Update*. Energy Conversion Congress and Exposition (ECCE), 2010 IEE, 171-178: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5606065.

5 Wilkins, A.J., Nimmo-Smith, I.M., Slater, A. and Bedocs, L. (1989) *Fluorescent lighting, headaches and eye-strain*. Lighting Research and Technology, 21(1), 11-18: http://lrt.sagepub.com/content/21/1/11.abstract.

6 Veitch, J.A., McColl, S.L. (1995) *Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort*. Lighting Research and Technology, 27(4), 243-256: http://web.mit.edu/parmstr/Public/NRCan/nrcc38944.pdf.

7 Alliance for Solid-State Illumination Systems and Technologies (2012) *ASSIST recommends… Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems*. 11(1), Troy, NY: Lighting Research Center: http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-Flicker.pdf.

phase electrical service and ensuring that the light from adjacent zones overlaps. Mild flicker from luminaires in spaces where users spend only a few minutes of time may not cause any complaints.

Some people are more sensitive to flicker than others. Populations that are more likely to be affected by flicker include autistic individuals; people who suffer from headaches or migraines and are sensitive to patterns and stripes; individuals with photosensitive epilepsy; and people performing reading tasks, since the presence of flicker can result in larger eye saccades, reducing comprehension. Flicker is a serious concern when video equipment is used, since the interaction between flicker and the frame-capture rates can result in distracting images. More information on flicker can be found in a U.S. Department of Energy (DOE) Fact Sheet on the topic.[8]

Test and Measurement Practices

At this time, there is no standardized test procedure for measuring photometric flicker from light sources, and manufacturers rarely report flicker characteristics. Ideally, a test and measurement procedure would facilitate the capture of light-source intensity or luminance over time, potentially describe how to characterize periodic waveform characteristics (e.g., amplitude modulation, shape or duty cycle, frequency) using one or more metrics, and identify aperiodic characteristics. Both the IES Testing Procedures Committee and CIE Technical Committee 1-83: Visual Aspects of Time-Modulated Lighting Systems are considering the development of standardized test and measurement procedures for flicker.

Metrics

The two most commonly used metrics for quantifying flicker are Percent Flicker and Flicker Index. Despite the lack of any standardized test and measurement procedures, both have been described and defined by the IES. Percent Flicker (with a limited 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 (also with a limited range, from 0 to 1) has the advantage of being able to account for variation in waveform shape or duty cycle, for rectangular waveforms. 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 periodic light sources with the same frequency.

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 comprised 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 sources represent the predominant exception; the low-amplitude modulation found in such lighting systems is typically in the 20 - 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 has been shown in

[8] DOE SSL Program (2013) *Flicker*. Building Technologies Office Solid-State Lighting Technology Fact Sheet: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/flicker_fact-sheet.pdf.

numerous previous CALiPER reports.[9] As a result, the guidance provided in IEEE Standard 1789™-2015 consists of limits on Percent Flicker, as a function of frequency.

The Stroboscopic Effect Visibility Measure (SVM), developed at Philips Research, attempts to predict both the visibility and acceptability of the stroboscopic effect.[10] 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 means of a weighting function. Fourier analysis allows a complex, not just periodic, waveform to be analyzed as a sum of individual frequency components. The use of a weighting function is the second key differentiator between the SVM and other metrics. Notably, the weighting function is application-specific; as a result, the SVM does not address invisible 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 – derived from Philips in-house experiments, and expressed in terms of modulation depth (as a function of frequency) – to frequencies between 80 and 2,000 Hz. Calculating the SVM from a light-intensity waveform requires at least one second of data with a minimum sampling frequency of 4,000 samples/second (with at least 5,000 preferred), in order 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.

Scope

The focus of this study is to simply report on the commercial availability and performance of emerging flicker meters. While the components for building a flicker characterization system have long been available, only recently have integrated meters that are focused on characterizing flicker become available. These devices hold the promise of enabling lighting stakeholders to view and approach measuring flicker in the same way that they perceive and approach measuring illuminance, for example. Characterizing the performance of flicker meters is a somewhat subjective task, at present. The lighting industry has not yet produced a standard test and measurement procedure or reference characterization system for flicker. Further, the National Institute of Standards and Technology (NIST) does not yet provide a reference source with a defined amount and/or type of flicker. As a result, a number of experimental and analysis choices were made in order to proceed; these are described below and depicted graphically in Table 1.

First, a variety of light sources with a wide range of light-intensity waveform characteristics were evaluated by all flicker meters. Second, performance of the commercial flicker meters was described by comparing results to those obtained by a defined reference flicker meter. More specifically:

1) The ability of each commercial meter to characterize flicker was evaluated by comparing its calculations of Percent Flicker, Flicker Index, and Fundamental Frequency, made from a waveform that it collected, with reference-meter calculations made from a waveform that it collected.

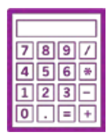
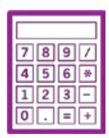
[9] CALiPER Testing: http://energy.gov/eere/ssl/caliper-testing.

[10] Perz, M. et al. (2015) *Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems*. Lighting Research and Technology, 47, 281-300: http://lrt.sagepub.com/content/47/3/281.

2) The ability of each commercial meter to (just) calculate flicker metrics was evaluated by comparing its calculations of Percent Flicker, Flicker Index, and Fundamental Frequency, made from a waveform that it collected, with reference-meter calculations made from the same commercial-meter waveform.
3) The ability of each commercial meter to (just) measure light-intensity waveforms was evaluated by comparing reference-meter calculations of Percent Flicker, Flicker Index, Fundamental Frequency, and SVM (if sampling characteristics were sufficient), made from a waveform collected by the commercial meter, with reference-meter calculations made from a waveform collected by the reference meter.

The three analysis scenarios are depicted graphically in Table 1.

Table 1 **Flicker meter performance analysis scenarios.** Purple icons represent the commercial meter; orange icons represent the reference meter; green icons represent an output derived from both the commercial and reference meter. The TEST outputs were compared to the REFERENCE outputs for each analysis scenario.

	TEST					REFERENCE				
	Measurement		**Calculation**		**Output**		**Output**		**Calculation**		**Measurement**
1		→		→	A / B 1 Percent Flicker 90 2 Flicker Index 0.1 3 Fundamental Frequency 120	vs.	A / B 1 Percent Flicker 90 2 Flicker Index 0.1 3 Fundamental Frequency 120	←		←	
2		→		→	A / B 1 Percent Flicker 90 2 Flicker Index 0.1 3 Fundamental Frequency 120	vs.	A / B 1 Percent Flicker 90 2 Flicker Index 0.1 3 Fundamental Frequency 120	←		←	
3		→		→	A / B 1 Percent Flicker 90 2 Flicker Index 0.1 3 Fundamental Frequency 120 4 SVM 1.3	vs.	A / B 1 Percent Flicker 90 2 Flicker Index 0.1 3 Fundamental Frequency 120 4 SVM 1.3	←		←	

Test and Measurement

Test Samples

Test samples 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 samples.** 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
LML-013A-15	LED	White-tunable linear LED cove luminaire.	NGL 2015[11] prototype with low-duty cycle but high-frequency (730 Hz) flicker. **Tested at five light-output levels.**
LML-018A-15	CMH	PAR38 ceramic metal halide screwbase lamp.	Integral high-frequency electronic ballast; included as a benchmark for retail lighting applications.
LML-019A-15	HAL	Halogen Infrared (HIR) PAR38 halogen screwbase lamp.	Common halogen lamp used in retail applications included as a benchmark.
LML-020A-15	LED	High CRI PAR38 LED replacement screwbase lamp.	10 percent flicker at full output.
LML-021A-15	LED	PAR38 LED replacement screwbase lamp.	100 percent flicker at full output.
LML-022A-15	LED	PAR38 LED replacement screwbase lamp.	0 percent flicker at full output.
LML-023A-15	CFL	CFL self-ballasted screwbase A-lamp.	Integral electronic ballast. Included as a benchmark.
LML-024-13	LED	BR30 LED screwbase replacement lamp.	Uses AC LED technology.
LML-024A-15	LED	Recessed 2 x 2 LED troffer with contoured diffuser, producing a batwing distribution.	0 – 10 V dimming driver that produces minimal flicker at full and dimmed output.
LML-025A-15	LED	Troffer retrofit kit with curved opal diffuser, installed in conventional fluorescent 2 x 2 recessed troffer.	Includes 0 – 10 V dimming driver that produces 100 percent flicker at 240 Hz when dimmed to 50% output. **Tested at five light-output levels.**
LML-027A-15	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 five light-output levels.**
LML-029A-15	FL	4' fluorescent striplight 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.[12]
LML-032A-14	LED	Violet-pump LED MR16 replacement lamp operated with magnetic transformer.	100% flicker at full or dimmed output.
LML-026A-15	CFL	Recessed CFL downlight with 18W quad-tube two-pin lamp and rapid-start magnetic ballast.	Benchmark product representing common technology from the 1980s and 1990s, expected to produce a sinusoidal light-intensity waveform similar to that of magnetically-ballasted linear fluorescent.

[11] Next Generation Luminaires™ (NGL) Solid-State Lighting (SSL) Design Competition: http://www.ngldc.org/.

[12] This flicker was accepted by most, tolerated by some, considered distracting or physiologically disturbing by others. The 4' fluorescent striplight with T12 or T8 lamps is a source widely believed to contribute to headaches and malaise in some populations, along with likely reduction in visual task performance.

Reference Meter

A photoelectric characterization system developed by PNNL was used to capture reference flicker measurements for this study. This system and an accompanying test and measurement procedure have been previously documented and used to characterize flicker performance for numerous CALiPER reports.[13] To date, manufacturers or other testing bodies have not called into question the test and measurement procedure or the results obtained by this system. In the interests of simplicity, this system will be referred to as the "reference meter" throughout the remainder of this report.

This semi-automated test and measurement setup developed to evaluate the dimming, flicker, and power-quality performance of lighting devices consists of an optically shielded enclosure, a photometric sensor (UDT Model 211[14], consisting of a silicon sensor, a spectrally matched photometric filter to simulate the response of the human visual system and match the spectral response of a standard observer, and a cosine diffuser to reduce directional sensitivity), a transimpedance amplifier (UDT Tramp[15]) with a 5 V output and eight decades of gain ranging between 10^3 and 10^{10}, a digital oscilloscope (Tektronix DPO2014), and software that was custom-developed using National Instrument's LabVIEW. The transimpedance amplifier gain is set for each measurement so as to maximize, but not saturate, the 5 V (peak) output signal. The amplifier has excellent gain linearity but varying bandwidth at different gain settings. However, for all measurements, a gain of 10^5 or 10^6 is used, for which the specified bandwidth is 12 kHz – well above the region of interest for photometric flicker waveforms.

The system samples and digitizes 125,000 or 1,250,000 photosensor measurements to characterize variation in luminous flux, and calculates an average output level as well as various flicker metrics. The absolute measurements of illuminance captured by the photosensor are dependent on the position of the light source in the optically shielded enclosure, which does not function as an integrating sphere. Test samples are generally not positioned in the optically shielded enclosure, to ensure a consistent distance between their emitting surface and the photosensor or a consistent peak output from the photosensor. As a result, the raw data digitized from the photosensor is typically normalized to the maximum value recorded for each waveform (thus resulting in an output ranging from 0 to 1). The transimpedance amplifier gain is adjusted for each measurement, to ensure that the peak output voltage presented to the oscilloscope for digitization stays between 0.5 and 5.0 V. The average value of the photosensor measurements made for each sample when operated by a switch is used to normalize any subsequent dimmed measurements of that sample, facilitating comparisons between products for relative dimmed light output and relative efficacy. Measurements that contain 10 or fewer fundamental frequency periods are cropped prior to analysis, so that they contain an integer number of periods. For longer measurements (i.e., more than 10 fundamental frequency periods), the full measured waveform is used for calculating flicker metrics.

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[13] DOE SSL Program (2015) *Report 22.1: Photoelectric Performance of LED MR16 Lamps*: http://energy.gov/sites/prod/files/2015/09/f26/caliper_22-1_mr16.pdf.
DOE SSL Program (2014) *Report 20.2: Dimming, Flicker, and Power Quality Characteristics of LED PAR38 Lamps*: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20-2_par38.pdf.
DOE SSL Program (2013) *Exploratory Study: Recessed Troffer Lighting*: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_recessed-troffer_2013.pdf.
DOE SSL Program (2014) *Retail Lamps Study 3.1: Dimming, Flicker, and Power Quality Characteristics of LED A Lamps*: http://energy.gov/sites/prod/files/2015/01/f19/caliper_retail-study_3-1.pdf.

[14] UDT Photometric Sensors: http://www.gamma-sci.com/wp-content/uploads/2012/03/Photometric-Sensor-Data-Sheet.pdf.

[15] UDT TRAMP: http://www.gamma-sci.com/wp-content/uploads/2016/02/TRAMP-Transimpedance-Amplifier-Data-Sheet.pdf.

Commercially Available Meters

In order to identify commercially available meters, PNNL surveyed the instrument market, primarily through Internet searching and manufacturer trade shows, but also via inquiries made to independent commercial laboratories currently characterizing or planning to characterize flicker. The focus was on hand-held or bench-top meters; meters designed for more high-throughput production-line characterization were not considered. Once the appropriate commercial meters were identified, PNNL requested manufacturer quotes and product information, along with availability. Three products were selected and ordered based on their price ($2,000 - $5,000) and availability to ship within eight 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 flicker meters and the reference meter. The three products selected are compared for the following performance characteristics: size, measurement time, sampling rate, and calculated outputs.

Meter		Measurement Time	Sampling Characteristics	Calculated Outputs
Admesy Asteria SC-ASTR-01 High Speed Illuminance Photometer[16]	 portable: 69 x 31 x 93 mm, 0.35 kg	0.001 – 1.3 s[17]	up to 250,000 samples; up to 180 kS/s	Illuminance Percent Flicker Flicker Index Fundamental Frequency Other: LCD contrast max/min, RMS LCD JEITA LCD VESA
Gigahertz-Optik BTS256-EF BiTec Sensor Lightmeter[18]	 handheld: 159 x 85 x 45 mm, 500 g	0.0001 - 6 s	2,048 samples[19] (fixed)	Illuminance (avg, max, min) Percent Flicker Flicker Index Fundamental Frequency Other: Harmonic Frequencies Color (x,y; u'v'; X,Y,Z; delta u'v'; CCT; purity; CRI Ra, R1-R15)
EVERFINE LFA-2000 Light Flicker Analyzer[20]	 portable: 425 x 360 x 196 mm, 8 kg	0.1 – 2,000 s	1 kS/s (0.1 - 2000 s); 5 kS/s (0.1 - 400 s); 10 kS/s (0.1 - 200 s)	Percent Flicker Flicker Index Fundamental Frequency
PNNL Photoelectric Characterization System (reference meter)		0.1 – 100 s	125,000 or 1.25 M samples (fixed)	Relative Illuminance Percent Flicker Flicker Index Fundamental Frequency Other: Voltage, Current, Power, Power Factor, Total Harmonic Distortion Current (THD-I)

[16] Admesy Asteria SC-ASTR-01 High Speed Illuminance Photometer: http://www.admesy.nl/product/asteria/.

[17] 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.

[18] Gigahertz-Optik BTS256-EF BiTec Sensor Lightmeter: https://www.gigahertz-optik.de/en-us/product/BTS256-EF.

[19] Gigahertz-Optik has advised that a forthcoming firmware and computer software update (scheduled availability in early summer 2016) will enable the meter to leverage memory available in a personal computer, and thereby raise the maximum number of samples from 2,048 to 64,000.

[20] EVERFINE LFA-2000 Light Flicker Analyzer: http://www.everfine.net/productinfo.php?pid=174&clid=23.

Test Setup

The three commercial meters were set up in the same optically shielded enclosure as the reference-meter photosensor. The test samples were connected to line voltage and allowed to thermally stabilize for approximately five minutes before measurement. Previous experiments have demonstrated that flicker performance is not a strong function of thermal stabilization; thus, in the interests of time, thermal stabilization was limited. Lamp temperatures and other operating characteristics (e.g., power and light output) were not monitored during this warmup time to determine stability, which was less important given the relative nature of the measurements. In order to minimize testing time, dimmable test samples were not allowed to establish a new thermal equilibrium at each dimmed measurement point. Flicker and power-quality measurements were made immediately after establishing each target dimmed-output level. Measurement time per lighting product sample was minimized and relatively consistent between samples, due to the automated data acquisition.

Each test sample was connected to a laboratory power supply set to deliver a RMS 120 VAC. If the test sample called for operating the light source at varying light-output levels, one of five light levels was set using a Lutron Nova T (for the 0-10 V controlled test samples) or manufacturer-specified control, as appropriate. Resultant light levels were verified to be within the measurement range of all commercial meters, if specified. Measurements were first taken using the reference meter and subsequently by each of the three commercial meters. Light-intensity waveforms from test samples specified for operation at varying light-output levels were taken within 60 seconds of establishing the appropriate control setting; time was not allowed for re-establishing thermal equilibrium.

Measurement Protocol

In order to fairly and fully characterize the performance of each commercial meter, two sets of test and measurement conditions were established: a short-duration condition, with a measurement time set to 100 ms (or as close to 100 ms as possible), and a long-duration condition, with a measurement time of at least 1 s. Table 4 below shows the actual conditions (both short and long) used for each meter, including the reference meter. Realizing the target measurement times was fairly straightforward for the two portable meters. However, as noted in Table 3, the Gigahertz-Optik meter was designed for handheld use. As such, its performance in some instances is limited by its internal memory and/or other design tradeoffs. In addition to being able to take handheld measurements, the Gigahertz-Optik meter can also be operated under computer control. The available measurement time settings varied in the two operation modes, however. While the meter provides 50 ms, 100 ms, 200 ms, 500 ms, 1 s, 3 s, 6 s, and 12 s measurement times in handheld mode, these settings were not available when operated under computer control. As a result, the closest settings to the target values were selected: 81.9 ms for the 100 ms target and 2.62 s for the 1 s target.

Table 4 **Test and measurement conditions.** For each meter, the measurement time, sampling rate, and number of samples are specified for both short-duration (first row) and long-duration (second row) conditions. Additionally, the 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)
Admesy	107.2	186,567	20,000	9.3	93,284
	1072	186,567	200,000	0.9	93,284
Gigahertz-Optik	81.9	25,006	2,048	12.2	12,503
	2620	782	2,048	0.4	391
EVERFINE	100	10,000	1,000	10.0	5,000
	1000	10,000	10,000	1.0	5,000
Reference	100	12,500,000	1,250,000	10.0	6,250,000
	1000	1,250,000	1,250,000	1.0	625,000

Results and Analysis

All three commercial meters exported raw data to a Microsoft Excel file (.xls), while the reference meter exported raw data to a text file (.txt). The raw data from each commercial meter was compared with reference meter data using a custom MATLAB program. 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 short-duration (100 ms target) condition, Percent Flicker, Flicker Index, and Fundamental Frequency were calculated. For the long-duration (1 s or greater target) condition, Percent Flicker, Flicker Index, Fundamental Frequency, and SVM (if the sampling rate was sufficient) were calculated. For the test samples that were evaluated at various light-output levels, the full-output waveforms were analyzed together with the full-output waveforms for the remaining test samples; the remaining four dimmed-output waveforms were analyzed separately. The Percent Flicker and Flicker Index analyses depict maximum, median (50%), and minimum deviations (absolute differences) from the reference measurement as well as the 75% (3rd quartile) and 25% (1st quartile) histogram bins.

The Fundamental Frequency analysis simply shows the percentage of commercial-meter values that matched (defined as within 10 Hz) those produced by the reference-meter analysis. For the majority of the test samples and conditions, the difference between the Fundamental Frequency reported by the commercial-meter and reference-meter calculation was either pretty small (e.g., within 10 Hz) or quite large (e.g., thousands of Hz; in some cases in the vicinity of 14,000 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. In some of these instances, the reported Fundamental Frequency was dependent on the test condition (i.e., short or long duration). In other examples, the magnitudes of two or more of the reported frequency components were very similar. In all cases, it appeared that the significant deviations were mostly the result of inappropriate meter configuration resulting from some combination of the test condition (i.e., short or long duration) and a meter constraint (e.g., maximum number of available data points). The determination of Fundamental Frequency is highly dependent on the ability of the meter to accurately capture waveform characteristics. Given that inappropriate sampling conditions make it impossible to do so, a match (defined as within 10 Hz) was deemed to be as a more appropriate metric than absolute difference.

The overall ability of each commercial meter to characterize flicker is evaluated in Figure 1. The flicker metrics calculated by each commercial meter from a waveform it captured were compared with reference-meter calculations made from a corresponding reference-meter waveform capture. Seventy-five percent (3^{rd} quartile) of the commercial-meter Percent Flicker values were at most 3 percentage points different than the reference values. Similarly, 75% of the commercial-meter Flicker Index values were at most 0.066 different. The ability to accurately determine the Fundamental Frequency of the light-intensity waveform varied more significantly across commercial meters. At least 83% of the frequencies matched the reference for the Admesy meter; 58% for the EVERFINE meter; and 71% for the Gigahertz-Optik meter – when waveforms were captured using the short-duration condition. When the Gigahertz-Optik meter was used with the longer duration condition, about half (57%) of the full-output samples matched, whereas only 8% of the dimmed-output samples matched. This is not an unexpected result for test samples with higher fundamental frequencies, given the fixed number of measurement points available with the Gigahertz-Optik meter (2,048 samples) and thus constraint on sampling rate and maximum frequency that can be discerned by the FFT.

Figure 2 focuses on the ability of each commercial meter to calculate flicker metrics from an identical waveform; commercial-meter calculations derived from a waveform from the commercial meter are compared with reference-meter calculations also derived from the same commercial-meter waveform. Seventy-five percent (3^{rd} quartile) of the commercial-meter Percent Flicker calculations were at most 1 percentage point different than the reference – most were the same. Similarly, 75% of the commercial-meter Flicker Index calculations were at most 0.007 different. Thus, the calculations made by the commercial meters were very accurate for both Percent Flicker and Flicker Index. The ability to accurately determine the Fundamental Frequency of the light-intensity waveform again varied more significantly across the commercial meters: at least 93% of the frequencies matched the reference for the Admesy meter; 64% for the EVERFINE meter; and 71% for the Gigahertz-Optik meter – when waveforms were captured using the short duration condition. For the longer duration condition, 64% of the full-output calculations matched, whereas only 25% matched for the dimmed levels.

Figure 3 compares the ability of each commercial meter to measure light-intensity waveforms; reference-meter calculations made from waveform measurements from each commercial meter are compared with measurements from the reference meter. Seventy-five percent (3^{rd} quartile) of the commercial-meter Percent Flicker values were at most 3 percentage points different than the reference values. Similarly, 75% of the commercial-meter Flicker Index values were at most 0.065 different. At least 67% of the commercial-meter measurements yielded the same Fundamental Frequency from the FFT analysis as the reference meter, with some meters matching 100%.

Figure 4 shows the absolute SVM deviation for the two meters that could meet the requisite measurement requirements. Seventy-five percent (3^{rd} quartile) of the commercial-meter values were at most 0.07 different than the reference values for the full-output measurements, whereas 75% of the dimmed-output measurements were no more than 0.49 different.

The Percent Flicker and Flicker Index values used in the above analysis and calculated for each test sample and test condition (full output or dimmed state, short or long measurement duration), are provided in the appendix (Figure 7). Calculated SVM values are provided for the long-duration condition, for meters with sufficient sampling characteristics. Dimmed states are specified according to digital control setting (e.g., 0.25 for 25%) or measured 0-10 V control signal, as appropriate. The data are broken up into three tables, one for each of the three described analysis scenarios.

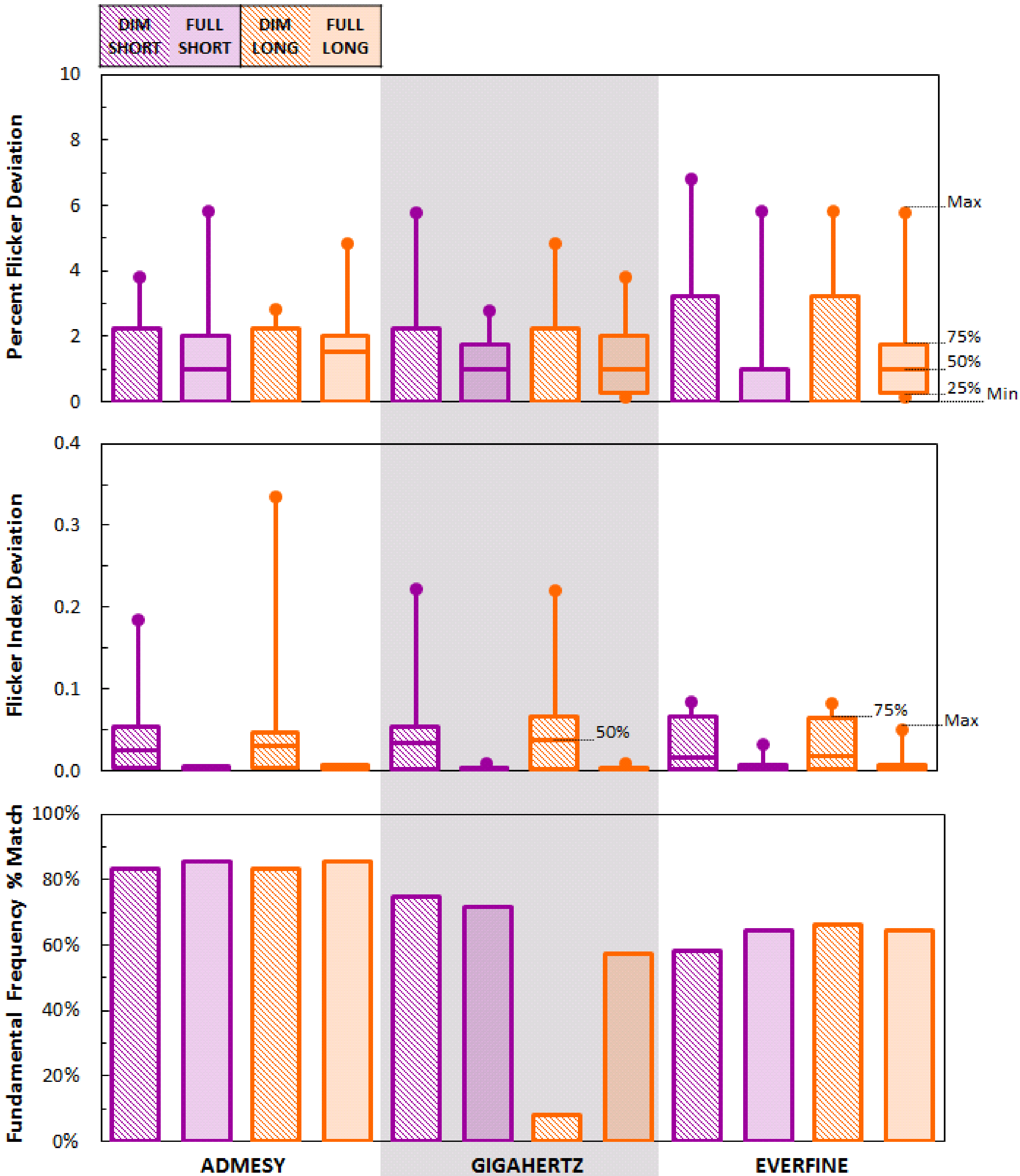

Figure 1 **Comparison of commercial-meter measurement and calculations with those produced by a reference-meter.** Seventy-five percent (3rd quartile) of the commercial-meter Percent Flicker values were at most 3 percentage points different from the reference values. Similarly, 75% of the commercial-meter Flicker Index values were less than 0.066 different from the reference values. The ability to accurately determine the Fundamental Frequency of the light-intensity waveform varied more significantly across commercial meters, from an 8 to 83% match.

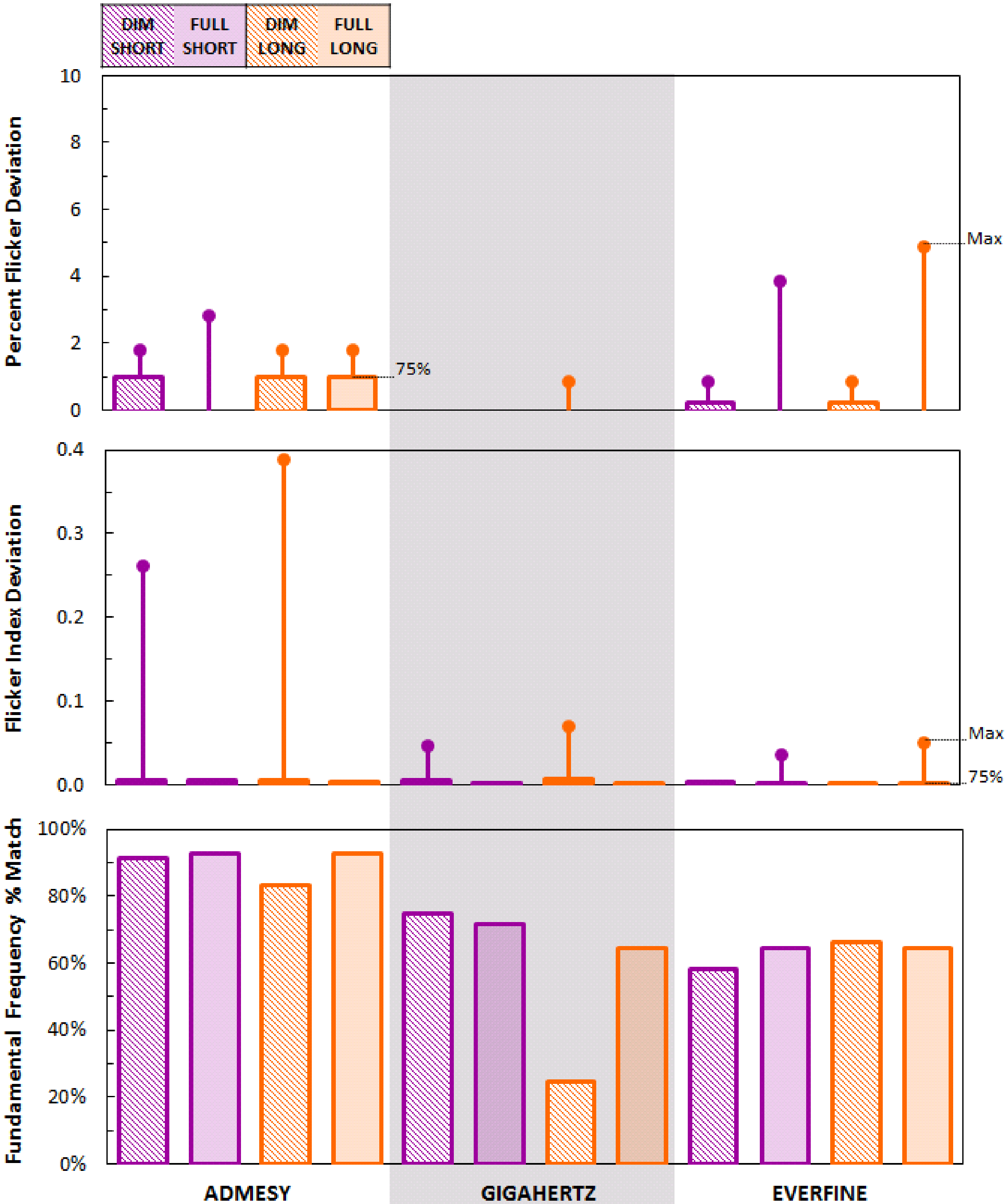

Figure 2 **Comparison of commercial-meter calculations made from a waveform from the commercial meter, with reference-meter calculations derived from the same waveform.** Seventy-five percent (3rd quartile) of the commercial-meter Percent Flicker calculations were at most 1 percentage point different from the reference – most were not different. Similarly, 75% of the commercial-meter Flicker Index calculations were at most 0.007 different from the reference. The ability to accurately determine the Fundamental Frequency of the light-intensity waveform varied more significantly across commercial meters, from a 25 to 93% match.

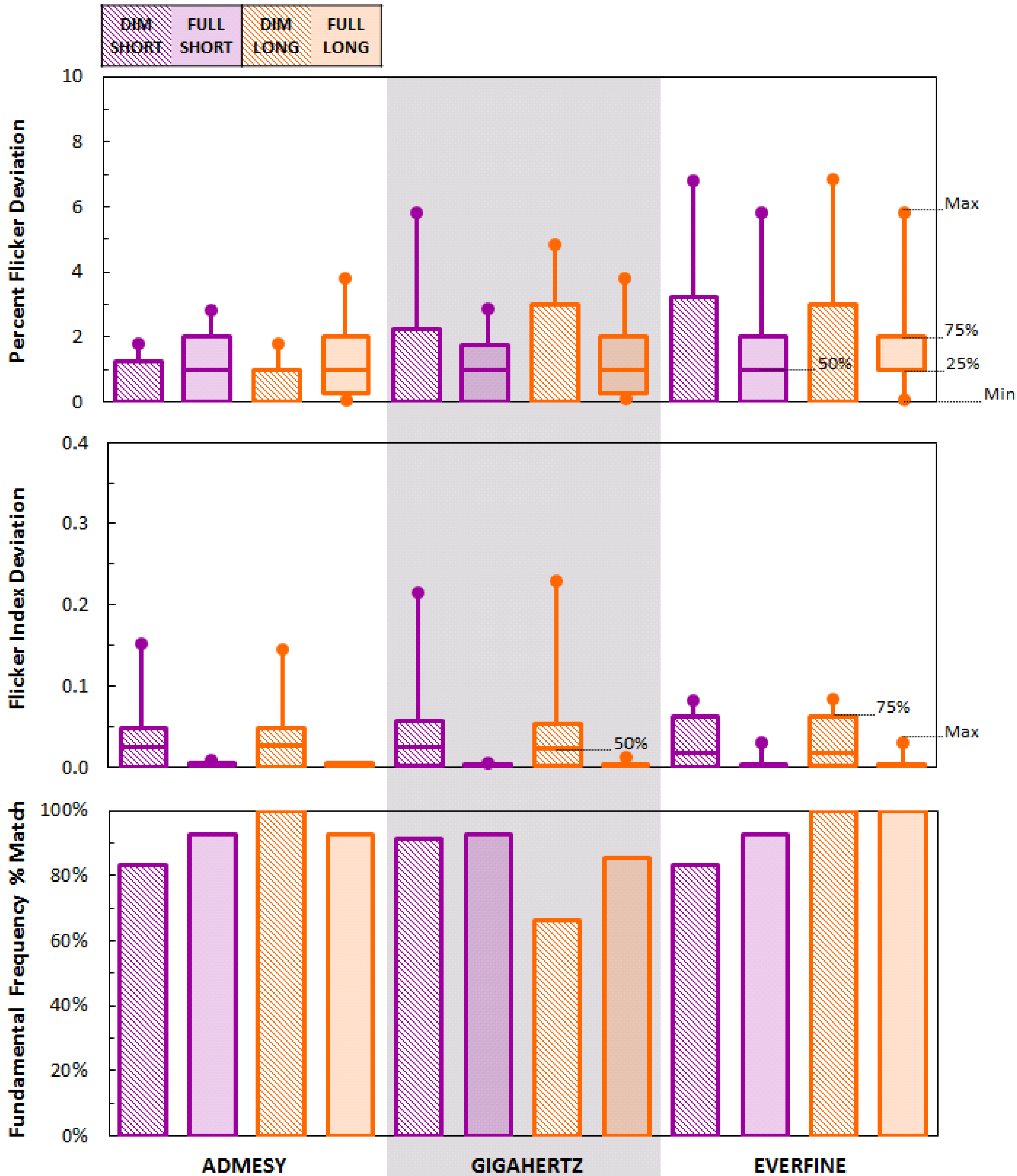

Figure 3 **Comparison of reference-meter calculations made from waveform measurements from each commercial meter, with a measurement from the reference meter.** Seventy-five percent (3rd quartile) of the commercial-meter Percent Flicker values were at most 3 percentage points different than the reference values. Similarly, 75% of the commercial-meter Flicker Index values were at most 0.065 different from the reference values. At least 67% of the commercial meter measurements yielded the same Fundamental Frequency from the FFT analysis as the reference meter, with some meters matching 100%.

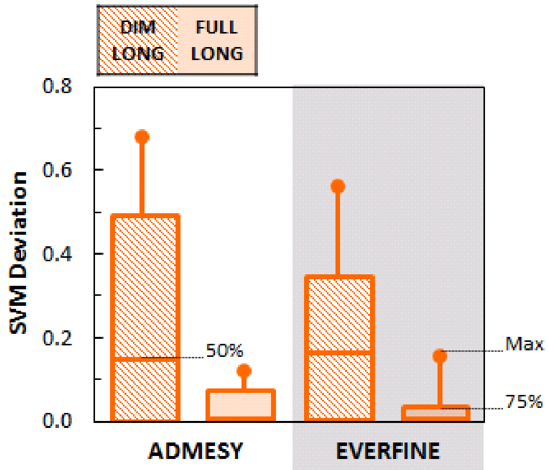

Figure 4 **Absolute SVM deviation for the two meters that could meet the requisite measurement requirements.** Seventy-five percent (3rd quartile) of the commercial-meter values were at most 0.07 different than the reference values for the full-output measurements. Seventy-five percent of the values were only 0.49 different from the reference values for the dimmed-output measurements.

As noted in the Figure 1 and Figure 2 analyses, the ability to accurately determine the Fundamental Frequency of the light-intensity waveform for the dimmed-output measurements was the least accurate when the Gigahertz-Optik meter was set up for the long-duration condition, with only 8% and 25% matching the reference meter, respectively. In order for a digital measurement system to accurately sample a waveform, the sampling rate needs to be sufficient.[21] Referring back to Table 4, the maximum FFT frequency is only 391 Hz for the 2.62 s sample reported by the Gigahertz-Optik meter (the 0.08 s sample has a maximum FFT frequency of 12,503 Hz). The effect of inadequate sampling is perhaps best shown visually; Figure 5 shows both the 0.08 and 2.62 s duration frequency responses and time-domain waveforms for the Gigahertz-Optik meter. Figure 6 similarly shows the 0.08 and 2.62 s duration frequency responses and time-domain waveforms for the reference meter. Comparing the two meters, the Gigahertz-Optik and reference-meter short-duration waveform captures are similar, but the longer-duration results are very different.

For reference, a PDF has been compiled which contains detailed analysis of all test-sample data for each commercial meter, along with the reference meter. Included are Percent Flicker, Flicker Index, Fundamental Frequency, SVM (as appropriate), and graphs (frequency response and waveform).[22]

[21] In order for the Fundamental Frequency to be included in the frequency domain, the sampling rate (Fs) has to be at least twice the Fundamental Frequency, as the number of FFT bins is equal to half the number of samples. The maximum frequency is the number of FFT bins multiplied by the FFT resolution (the inverse of the sample duration).

[22] The PDF is available at: http://energy.gov/eere/ssl/downloads/characterizing-photometric-flicker.

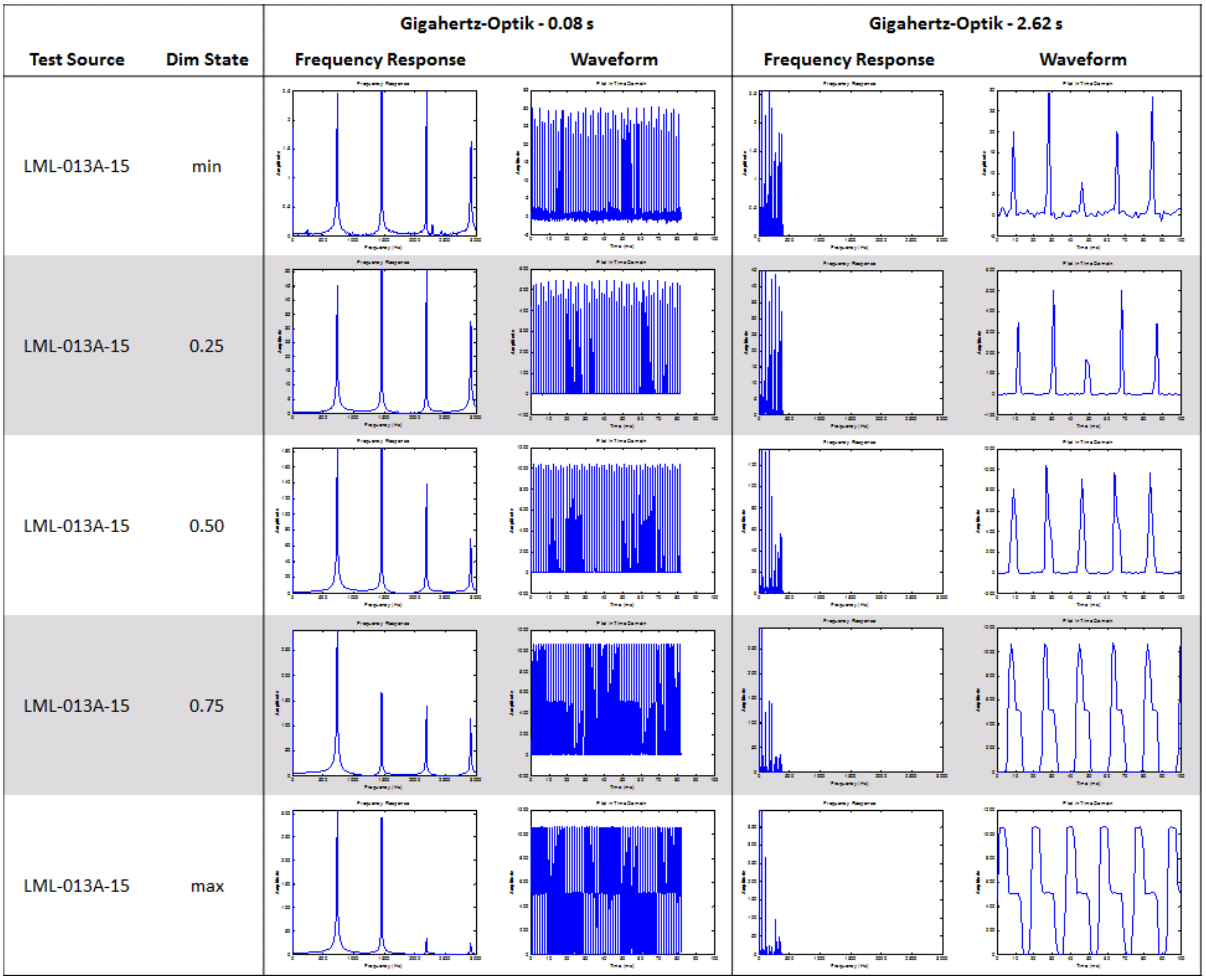

Figure 5 Frequency response and time-domain waveform graphs for the 0.08 and 2.62 s durations captured by the Gigahertz-Optik meter for test sample LML-013A-15 at five light output levels. The 0.08 s sample has a maximum FFT frequency of 12,503 Hz, whereas the 2.62 s sample has a maximum frequency of only 391 Hz. Thus, the frequency response and waveform graphs are very different between the two durations.

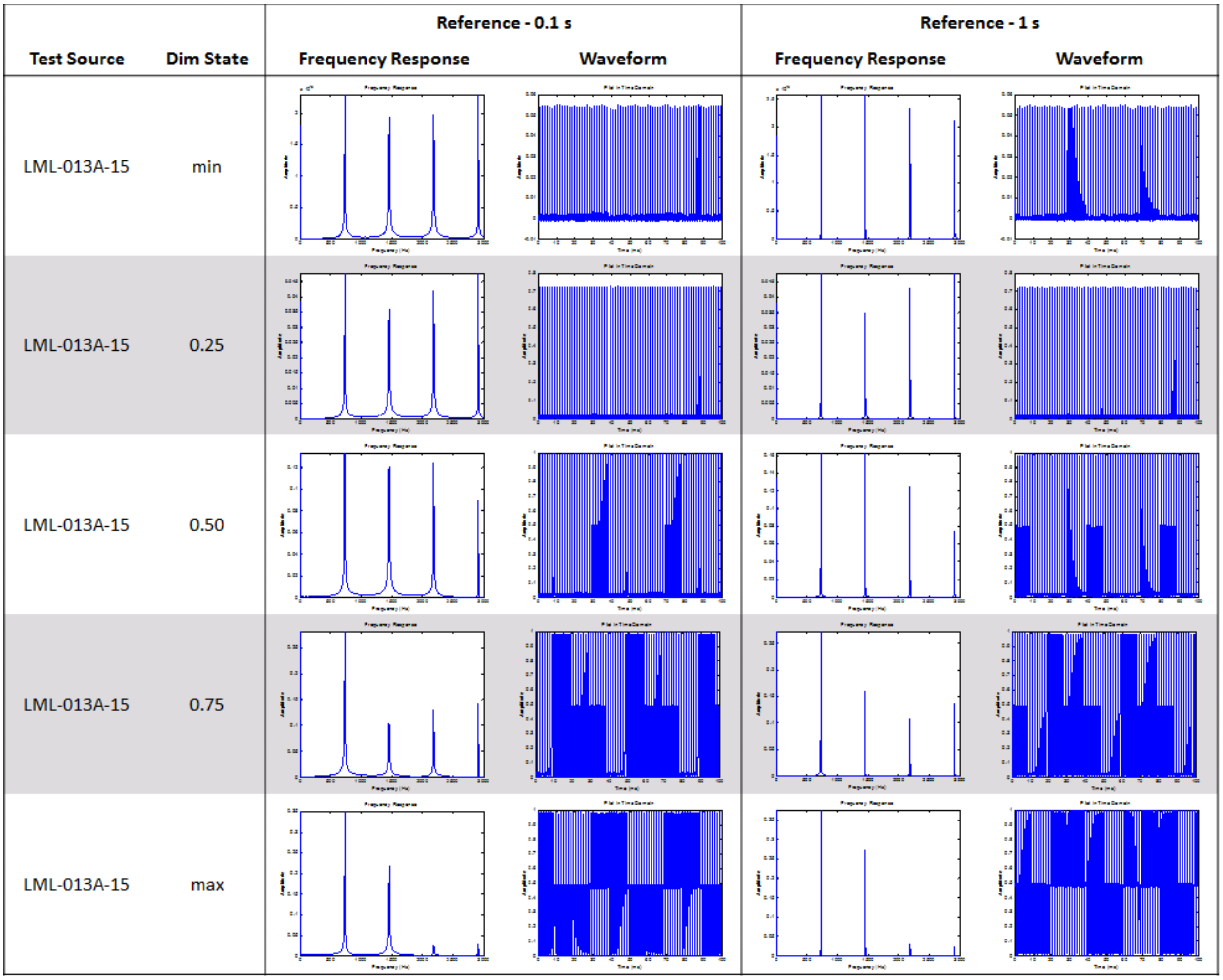

Figure 6 Frequency response and time-domain waveform graphs for the 0.08 and 2.62 s durations captured by the reference meter for test sample LML-013A-15 at five light-output levels. The 0.1 and 1 s samples have maximum FFT frequencies of 6,250,005 and 625,001 Hz, respectively. Thus, the frequency response and waveform graphs are very similar between the two durations.

To investigate the performance of these commercial meters further, potential future analysis could include the following:

- Further analysis of existing short- and long-duration measurement data to explore how each meter determines the waveform Fundamental Frequency and waveform period (i.e., the inverse of the Fundamental Frequency), and how many waveform periods are used in the calculation of the various flicker metrics. The calculation of Flicker Index, in particular, can be sensitive to errors in waveform-period determination, especially if a single waveform period is used. If a measurement, or portion of a measurement, containing less than 10 waveform periods is used in the calculation, it is imperative that the waveform is cropped prior to analysis, so that it contains an integral number of periods in order for the ratio of integrals to be accurate. As the number of waveform periods used is increased, this sensitivity is reduced.
- The capture of multiple short- and long-duration (i.e., 100 ms and 1 s) measurements from each test sample to evaluate the measurement precision, or repeatability of each meter.

- The exploration of commercial-meter special features (e.g., the use of the DELAY function available in the Admesy Asteria SC-ASTR-01) and capabilities enhanced by future firmware and/or software updates.
- The capture of longer waveform measurements (ideally 60 s) to investigate the calculation of flicker metrics (e.g., the short term flicker indicator [PstLM][23]) and evaluate calculation precision (by analyzing different time slices).
- Other to-be-determined sensitivity analyses.

Conclusions

A summary of all evaluated flicker meters, focusing on the minimum expected performance from (these) commercially available products, is shown in Table 5, separated into dimmed- versus full-output states. In addition to the 3rd-quartile performance (75th percentile) shown previously, both 90th and 95th percentile performance are included here for Percent Flicker and Flicker Index. For Fundamental Frequency, the percent-match performance is separated between short and long sample durations.

Table 5 **Commercial-meter performance summary.** The minimum expected performance for each evaluated meter is tabulated below, separated into dimmed- versus full-output states. In addition to the 75th percentile shown in the previous analysis, both the 90th and 95th percentile performances are included for Percent Flicker and Flicker Index. For Fundamental Frequency, the percent-match performance is separated between short and long sample duration.

	State	**Percent Flicker:** Maximum difference (75th, 90th, 95th percentile)			**Flicker Index:** Maximum difference (75th, 90th, 95th percentile)			**Fundamental Frequency:** Minimum percent match (short, long duration)	
Measurement and calculations	Dim	3	5	6	0.066	0.135	0.192	58%	8%
(Figure 4)	Full	2	5	6	0.049	0.029	0.044	64%	57%
Calculations (Only)	Dim	1	2	2	0.007	0.074	0.222	58%	25%
(Figure 5)	Full	1	2	3	0.004	0.004	0.021	64%	64%
Measurements (Only)	Dim	3	4	5	0.065	0.118	0.154	83%	67%
(Figure 6 and Figure 7)	Full	2	6	6	0.006	0.010	0.019	93%	86%

The results and analysis show that the three commercially available flicker meters evaluated for this study measured light-intensity waveforms and calculated essential flicker-performance characteristics and metrics similarly, both to each other and to the reference meter chosen as an accuracy benchmark. For 90% of the full-lighting-output test samples, the reported values were within 5 percentage points of the reference for Percent Flicker and 0.029 for Flicker Index. The test samples that were evaluated at five different light levels exposed some differences between meters, however. These test samples, some of which employed pulse-width modulation to achieve their target light levels (and, in one case, white point), had higher frequency content in their light-intensity waveforms – greater than the dominant 120 Hz found in many products at full output. This higher frequency content did not, in general, affect Percent Flicker calculations. However, for Flicker Index, the deviation from the reference meter was consistently greater for the test samples operated at dimmed light levels. The Gigahertz-Optik meter showed that the percentage of test samples for which the Fundamental Frequency matched the reference meter was much lower for the dimmed output levels and long sample durations, due to restrictions on the Fourier analysis. It should be noted that the Gigahertz-Optik meter was the only handheld meter evaluated, and that its sampling limitations are inherently a function of its limited internal memory.

[23] IEC TR 61547-1 (2015) *Equipment for general lighting purposes - EMC immunity requirements - Part 1: An objective voltage fluctuation immunity test method*: https://webstore.iec.ch/publication/22344.

Recommendations

As a result of this study, the following recommendations are made to lighting designers and specifiers, the standards and specification community, and lighting manufacturers:

- Lighting manufacturers and testing laboratories should start characterizing lighting products for flicker. There are commercially available meters that enable the relatively straightforward characterization of a number of flicker metrics, including Percent Flicker, Flicker Index, and Fundamental Frequency. Manufacturers should report these metrics on lighting-product data sheets.
- When characterizing flicker, take measurements at full as well as one or more dimmed light levels, since dimming can not only increase the flicker seen at full output, but can also introduce different frequency content into the light-intensity waveform for certain lighting products. Be careful to ensure that the dimmed light levels are within the meter operating range, and note that the minimum illuminance level for flicker measurements can be higher than the specification for illuminance measurements. Further, beware that uncertainties for most measurement systems can be greater at extreme measurement conditions; consult the meter specifications to understand expected performance. Additionally, consider the effects that sampling frequency and measurement duration have on the use of various techniques (e.g., Fourier analysis) used to generate flicker metrics, as certain commercial flicker meters have fixed sampling frequencies, or limits on the total number of measurement samples that can be collected, regardless of measurement duration; in both instances, the waveform may not be an accurate representation of performance.
- Lighting designers and specifiers might consider purchasing a handheld meter and starting to characterize the flicker produced by specific products in the real world. When attempting to do so, watch out for ambient light and other conditions that might result in the handheld meter not yielding as accurate a result as it does when used in a laboratory environment, as was the case for this study. For a flicker meter to accurately capture data, there can be no stray light from windows or other luminaires that might affect the light-intensity waveform. On the other hand, it should be recognized that the flicker that affects an individual is the waveform that reaches the eye, and that may be a composite of light from several sources.
- Follow IES, CIE, and NIST developments for flicker terminology; flicker characterization system requirements, including calibration procedures (as there is currently no established reference source for flicker); standardized test and measurement procedures; and new or refined metrics – especially those that consider aperiodic waveform content, or allow weighting factors to be applied to specific frequencies of interest for specific applications, as research becomes available. Note that even currently defined terminology is not used consistently. For example, while many in the lighting industry equate flicker with light modulation, as indeed the IES defines it, it makes sense to some to differentiate between light modulation and the effects of light modulation – and to further differentiate between those effects as flicker, stroboscopic effects, and phantom array effects. Look for flicker meters that incorporate the latest terminology, metrics, requirements, and guidance, and/or are firmware-upgradeable.

Appendix

			TABLE 1						TABLE 2						TABLE 3							
			ADMESY		GIGAHERTZ		EVERFINE		ADMESY		GIGAHERTZ		EVERFINE		ADMESY			GIGAHERTZ		EVERFINE		
	Test Source	Dim State	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	SVM	Percent Flicker	Flicker Index	Percent Flicker	Flicker Index	SVM
Short Duration	LML-021A-15	full	0.0	0.006	0.0	0.011	0.0	0.008	0.0	0.008	0.0	0.008	0.0	0.000	0.0	0.014		0.0	0.003	0.0	0.008	
	LML-022A-15	full	2.0	0.004	2.0	0.003	2.0	0.003	0.0	0.001	0.0	0.000	0.0	0.000	2.0	0.003		2.0	0.003	2.0	0.003	
	LML-18A-15	full	3.0	0.002	2.0	0.001	6.0	0.000	0.0	0.004	0.0	0.001	0.0	0.000	3.0	0.002		2.0	0.002	6.0	0.000	
	LML-19A-15	full	1.0	0.005	1.0	0.001	1.0	0.001	0.0	0.004	0.0	0.001	0.0	0.001	1.0	0.001		1.0	0.000	1.0	0.000	
	LML-20A-15	full	6.0	0.002	3.0	0.002	6.0	0.039	3.0	0.004	0.0	0.000	0.0	0.042	3.0	0.002		3.0	0.002	6.0	0.003	
	LML-24-13	full	0.0	0.007	0.0	0.001	0.0	0.001	0.0	0.002	0.0	0.004	0.0	0.000	0.0	0.005		0.0	0.005	0.0	0.001	
	LML-24A-15	full	0.0	0.001	1.0	0.001	1.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.001		1.0	0.001	1.0	0.000	
	LML-29-15	full	2.0	0.007	1.0	0.001	1.0	0.003	1.0	0.004	0.0	0.000	0.0	0.000	3.0	0.011		1.0	0.001	1.0	0.003	
	LML-013A-15	min	0.0	0.143	0.0	0.035	1.0	0.087	0.0	0.268	0.0	0.054	0.0	0.001	0.0	0.125		0.0	0.019	1.0	0.086	
	LML-013A-15	0.25	0.0	0.190	0.0	0.229	0.0	0.062	0.0	0.029	0.0	0.006	0.0	0.003	0.0	0.161		0.0	0.223	0.0	0.059	
	LML-013A-15	0.5	0.0	0.025	0.0	0.066	0.0	0.078	0.0	0.003	0.0	0.003	0.0	0.002	0.0	0.022		0.0	0.063	0.0	0.076	
	LML-013A-15	0.75	0.0	0.009	0.0	0.014	0.0	0.090	0.0	0.004	0.0	0.003	0.0	0.001	0.0	0.013		0.0	0.017	0.0	0.089	
	LML-013A-15	max	0.0	0.001	0.0	0.000	1.0	0.037	0.0	0.004	0.0	0.001	4.0	0.001	0.0	0.003		0.0	0.001	5.0	0.038	
	LML-23A-15	full	1.0	0.001	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	1.0	0.001		0.0	0.000	0.0	0.000	
	LML-025A-15	0.93V	0.0	0.058	0.0	0.080	0.0	0.014	0.0	0.002	0.0	0.001	0.0	0.001	0.0	0.056		0.0	0.079	0.0	0.013	
	LML-025A-15	3.10V	0.0	0.026	0.0	0.034	0.0	0.001	0.0	0.006	0.0	0.001	0.0	0.001	0.0	0.032		0.0	0.033	0.0	0.000	
	LML-025A-15	5.20V	0.0	0.039	0.0	0.048	0.0	0.021	0.0	0.000	0.0	0.005	0.0	0.004	0.0	0.039		0.0	0.043	0.0	0.025	
	LML-025A-15	7.40V	0.0	0.053	0.0	0.051	0.0	0.040	0.0	0.005	0.0	0.005	0.0	0.001	0.0	0.048		0.0	0.056	0.0	0.041	
	LML-025A-15	9.65V	1.0	0.002	1.0	0.002	1.0	0.002	0.0	0.000	0.0	0.000	0.0	0.000	1.0	0.002		1.0	0.002	1.0	0.002	
	LML-027A-15	0.9V	2.0	0.004	6.0	0.003	7.0	0.004	1.0	0.004	0.0	0.000	0.0	0.000	1.0	0.000		6.0	0.003	7.0	0.004	
	LML-027A-15	3.0V	3.0	0.003	2.0	0.000	4.0	0.002	1.0	0.002	0.0	0.001	1.0	0.001	2.0	0.001		2.0	0.001	3.0	0.001	
	LML-027A-15	5.1V	4.0	0.002	3.0	0.000	5.0	0.001	2.0	0.002	0.0	0.000	1.0	0.000	2.0	0.000		3.0	0.000	4.0	0.001	
	LML-027A-15	7.2V	4.0	0.002	3.0	0.000	3.0	0.000	2.0	0.002	0.0	0.001	1.0	0.001	2.0	0.000		3.0	0.001	4.0	0.001	
	LML-027A-15	9.3V	2.0	0.003	2.0	0.002	0.0	0.002	0.0	0.000	0.0	0.001	2.0	0.000	2.0	0.003		2.0	0.003	2.0	0.002	
	LML-032A-14	full	0.0	0.005	0.0	0.009	0.0	0.008	0.0	0.004	0.0	0.001	0.0	0.001	0.0	0.009		0.0	0.010	0.0	0.009	
	LML-026A-15	full	1.0	0.002	0.0	0.003	0.0	0.002	0.0	0.003	0.0	0.000	0.0	0.000	1.0	0.001		0.0	0.003	0.0	0.002	
Long Duration	LML-021A-15	full	0.0	0.007	0.0	0.012	0.0	0.009	0.0	0.004	0.0	0.006	0.0	0.001	0.0	0.011	0.1	0.0	0.018	0.0	0.010	0.1
	LML-022A-15	full	2.0	0.003	2.0	0.002	2.0	0.002	0.0	0.001	0.0	0.000	0.0	0.000	2.0	0.002	0.0	2.0	0.002	2.0	0.002	0.0
	LML-18A-15	full	3.0	0.002	2.0	0.001	4.0	0.055	1.0	0.003	0.0	0.000	0.0	0.057	2.0	0.001	0.0	2.0	0.001	4.0	0.002	0.0
	LML-19A-15	full	1.0	0.005	1.0	0.001	1.0	0.001	0.0	0.004	0.0	0.001	0.0	0.001	1.0	0.001	0.0	1.0	0.000	1.0	0.000	0.0
	LML-20A-15	full	5.0	0.002	4.0	0.002	6.0	0.003	2.0	0.004	0.0	0.000	0.0	0.001	3.0	0.002	0.0	4.0	0.002	6.0	0.004	0.0
	LML-24-13	full	0.0	0.007	0.0	0.001	0.0	0.001	0.0	0.000	0.0	0.003	0.0	0.000	0.0	0.007	0.1	0.0	0.002	0.0	0.001	0.0
	LML-24A-15	full	2.0	0.001	2.0	0.001	1.0	0.000	1.0	0.002	0.0	0.000	0.0	0.000	1.0	0.001	0.0	2.0	0.001	1.0	0.000	0.0
	LML-29-15	full	2.0	0.007	1.0	0.001	1.0	0.003	2.0	0.004	0.0	0.001	0.0	0.000	4.0	0.011	0.1	1.0	0.000	1.0	0.003	0.0
	LML-013A-15	min	0.0	0.339	0.0	0.063	1.0	0.071	0.0	0.394	0.0	0.077	0.0	0.000	0.0	0.055	0.7	0.0	0.014	1.0	0.071	0.2
	LML-013A-15	0.25	0.0	0.071	0.0	0.229	0.0	0.063	0.0	0.082	0.0	0.007	0.0	0.000	0.0	0.153	0.5	0.0	0.236	0.0	0.063	0.3
	LML-013A-15	0.5	0.0	0.034	0.0	0.076	0.0	0.069	0.0	0.003	0.0	0.002	0.0	0.000	0.0	0.031	0.2	0.0	0.074	0.0	0.069	0.1
	LML-013A-15	0.75	0.0	0.009	0.0	0.014	0.0	0.090	0.0	0.003	0.0	0.002	0.0	0.000	0.0	0.012	0.1	0.0	0.012	0.0	0.090	0.1
	LML-013A-15	max	0.0	0.009	0.0	0.000	0.0	0.038	0.0	0.006	0.0	0.001	5.0	0.001	0.0	0.003	0.1	0.0	0.001	5.0	0.037	0.2
	LML-23A-15	full	0.0	0.002	1.0	0.001	1.0	0.001	1.0	0.000	0.0	0.000	0.0	0.000	1.0	0.002	0.0	1.0	0.001	1.0	0.001	0.0
	LML-025A-15	0.93V	0.0	0.059	0.0	0.077	0.0	0.016	0.0	0.000	0.0	0.009	0.0	0.000	0.0	0.059	0.0	0.0	0.086	0.0	0.016	0.4
	LML-025A-15	3.10V	0.0	0.027	0.0	0.034	0.0	0.002	0.0	0.001	0.0	0.000	0.0	0.001	0.0	0.026	0.6	0.0	0.034	0.0	0.003	0.6
	LML-025A-15	5.20V	0.0	0.037	0.0	0.042	0.0	0.021	0.0	0.003	0.0	0.002	0.0	0.000	0.0	0.040	0.5	0.0	0.040	0.0	0.021	0.5
	LML-025A-15	7.40V	0.0	0.042	0.0	0.056	0.0	0.039	0.0	0.005	0.0	0.007	0.0	0.001	0.0	0.047	0.4	0.0	0.049	0.0	0.038	0.3
	LML-025A-15	9.65V	1.0	0.001	1.0	0.001	1.0	0.001	0.0	0.000	0.0	0.000	0.0	0.000	1.0	0.001	0.0	1.0	0.001	1.0	0.001	0.0
	LML-027A-15	0.9V	3.0	0.004	5.0	0.003	6.0	0.004	1.0	0.004	0.0	0.000	1.0	0.000	2.0	0.000	0.0	5.0	0.003	7.0	0.004	0.0
	LML-027A-15	3.0V	2.0	0.003	3.0	0.001	4.0	0.002	1.0	0.002	0.0	0.000	1.0	0.001	1.0	0.001	0.0	3.0	0.001	3.0	0.001	0.0
	LML-027A-15	5.1V	3.0	0.003	3.0	0.001	4.0	0.001	2.0	0.002	0.0	0.000	1.0	0.001	1.0	0.001	0.0	3.0	0.001	3.0	0.002	0.0
	LML-027A-15	7.2V	3.0	0.002	2.0	0.000	3.0	0.000	1.0	0.002	1.0	0.000	0.0	0.001	2.0	0.000	0.0	3.0	0.000	3.0	0.001	0.0
	LML-027A-15	9.3V	2.0	0.003	2.0	0.002	2.0	0.003	0.0	0.000	0.0	0.001	0.0	0.000	2.0	0.003	0.0	2.0	0.003	2.0	0.003	0.0
	LML-032A-14	full	0.0	0.005	0.0	0.009	0.0	0.008	0.0	0.002	0.0	0.002	0.0	0.000	0.0	0.007	0.1	0.0	0.007	0.0	0.008	0.1
	LML-026A-15	full	2.0	0.002	1.0	0.002	1.0	0.002	0.0	0.002	0.0	0.001	0.0	0.000	2.0	0.000	0.0	1.0	0.001	1.0	0.002	0.0

Figure 7 Percent Flicker, Flicker Index, and SVM (where appropriate) deviation between commercial and reference meters for each test sample and analysis scenario. Table 1 corresponds to Figure 1, Table 2 corresponds to Figure 2, and Table 3 corresponds to Figure 3 and Figure 4.