Don’t blink or you’ll miss it: The importance of sampling rate in monitoring UV LED curing applications

By Jim Raymont, EIT Instruments

The challenge of measuring a UV process or any process, is collecting a representation of the process that is as close as possible to the actual process. In addition to making sure that your radiometer has an optical response and dynamic range to match the LED, you also need to account for physical differences between broadband mercury and LED sources when making UV measurements.

We trust that the values on our car speedometer to avoid speeding tickets. Police officers must also trust the data from their laser/radar gun to monitor your speed.

Traffic lawyers scrutinize the officer’s training, data collection techniques, ticket writing history, weather conditions and the performance data/calibration certificate of the radar gun in order to avoid a speeding ticket for their clients.

Some drivers seem to have a sixth sense (radar detectors where legal and more recently applications such as Waze) of law enforcement locations and slow down just in time. By the time their speed is checked, they have slowed to the posted speed limit. Does this radar reading represent their peak speed? Clearly not. The average speed? No. It represents a single sample of the cars speed at the moment in time when the radar reading was taken.

Capturing the car’s peak speed would require a measurement at that precise moment. If peak speed occurs for a thousandth of a second, then we must take a measurement at that exact instant, like the image that captured the projectile to the right.

If we want a picture of the car’s speed profile over a longer time period, we need to take a series of measurements over time.

The ability to accurately and repeatedly measure a UV source depends on using radiometer matched to the source and the ability to gather and store an adequate number of observations (samples) under the UV source.

The rate at which a radiometer collects samples can be referred to as the frequency (Hz) of the instrument. In practical versus technical terms (with apologies to EIT’s electrical engineers), an instrument with a data collection frequency of 128 Hz collects data at a rate of 128 samples per second.

How often should I measure?
The instrument sample rate should not be confused with how often (frequency) you need to measure your process or source. Considerations to help you decide how often to measure the source include:

- **Type of product, process window and risk factors**: Are you curing a coating on a medical catheter or printing on a golf ball? How big is the process window? What are the associated risk factors if you are outside of the process window? What reporting requirements are passed down from your customers?

- **Value of product, line speed and risk tolerance:** In the words of Dirty Harry: "You've got to ask yourself one question: Do I feel lucky? Well, do ya, punk?" Faster line speeds generate more products (good or bad) than a slower line speed. If the UV conditions change between measurements what is your potential exposure? Like an investor or gambler, what is your tolerance for risk?
- **Stability of the UV System/Process:** Err on the side of caution and measure more frequently when you first start out. Get to know and understand the behavior of your system and process. A UV system or process that consistently runs the same usually does not need the same frequency of measurement as one that changes more often. Taking frequent measurements on a stable system and process is less revealing since each measurement no matter when it is taken, should reveal the same value. Audit your system and process for sources of variance. Common mechanical factors include, changes in the UV irradiance due to aging, reflector/quartz window contamination and fluctuations in the power supply, dwell time/conveyor speed or application of cured material to the substrate.
- **Human Error**: How prone is your process to changes made by your operators? Does your line run multiple parts with different curing profiles that need to be "dialed in"? Common process changes include changing applied power settings, repositioning lamps or LED heads and making conveyor speed changes. In some application processes, film thickness may also depend on the skill of the operator and cause unexpected variations.

The interval between physical measurements should be established to minimize undetected changes in the UV conditions. In applications where the conditions can rapidly change and/or high value products are being manufactured, sensors that are permanently installed can be used for continuous monitoring of the relative intensity. Sensors are available for both broadband (mercury) and LED sources.

Instrument Sample Rates

The peak irradiance of a UV source occurs for only a brief instant. Accurately measuring the peak irradiance (W/cm^2) requires an adequate number of samples, regardless of whether it is a UV broadband (mercury) or LED source. Precisely capturing this short moment in time requires either extraordinary lucky timing or a high sample rate i.e. very short sampling intervals.

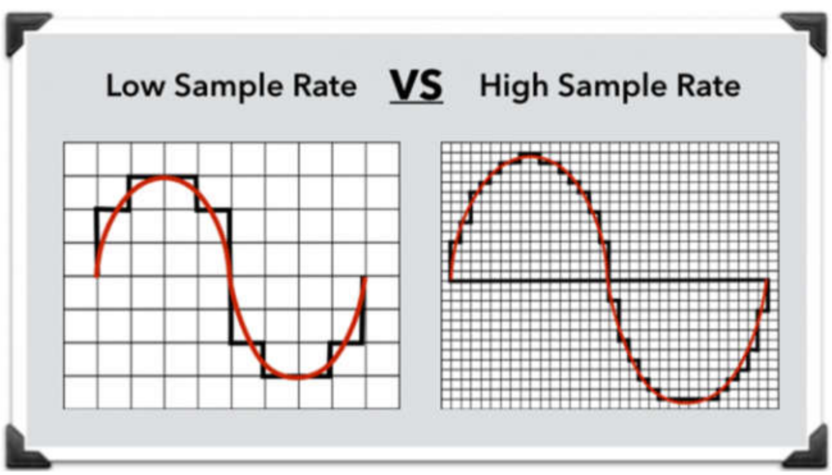


Figure 1: The above graph is a good example of sample rate and resolution.

Figure 1 illustrates the differences between a low sample rate and high sample rate. A higher sample rate on the right better captures dynamic changes in the process.
Radiometer sample rates of 25 Hz (samples per second) were the state of the art 30 years ago. This sample rate placed a 'speed limit' of +/- 40 feet (or 12 meters) per minute on the radiometer to allow the instrument to gather enough samples to 'catch' the peak irradiance.

Exceeding an instrument's recommended 'speed limit' risked missing the true peak irradiance and could cause wide variations in the peak irradiance value.

Today, some radiometers sample at extremely high rates (e.g., >30,000 Hz), and through the use of electronic/data (not optical) filters, effective (equivalent) sample rates ranging from 128 to 2048 Hz can be set by the user.

Faster sampling rates provide greater resolution, especially as the speeds of some applications (such as digital printer or optical fibers) approach 400+ feet (122 meters) per minute. The ability to collect data at faster productions speeds does not mean it is always practical to do so. Use common sense to place, secure and retrieve a radiometer from the process without causing damage to the equipment, instrument or personnel taking the measurements.

The sample rate of the instrument can impact:

1. Reported irradiance value
2. Validity of the data collected based on the line speed/source type

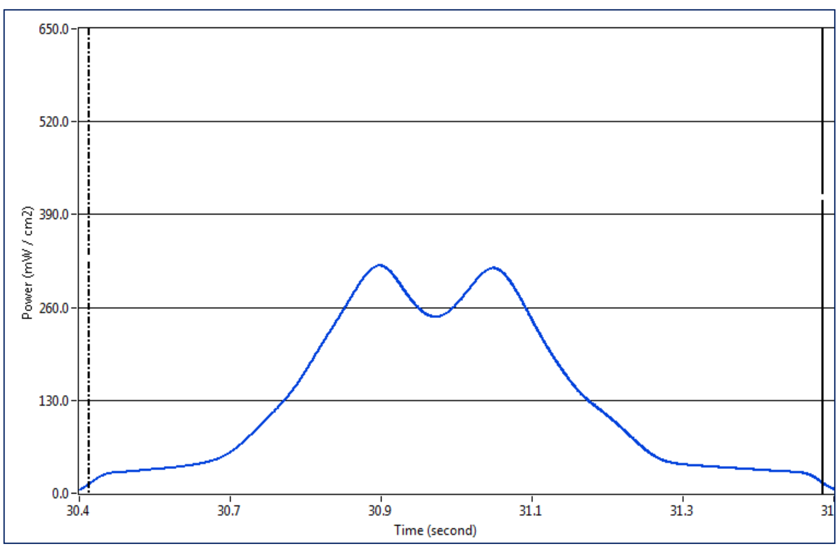
Sample Rate Impact on Reported Irradiance Values

Our brain 'sees' room lights as being either 'on' or 'off'. An instrument or sensor with a very fast sample rate can show Alternating Current (AC) room lights and/or UV systems driven at 50/60 Hz cycling.

Figures 2 and 3 show data for a single non-focused broadband UV lamp, collected under identical conditions except for the effective sample rate of the radiometer. Only the UVA EIT 320-390 nm band is shown. The X-Axis is time, Y-Axis is UV Irradiance.

The data in **Figure 2** was collected at an effective sample rate of 128 Hz. The peak irradiance is **318.3 mW/cm^2**, and the energy density is **139.9 mJ/cm^2**. The irradiance values and profile show the average peak or RMS intensity.

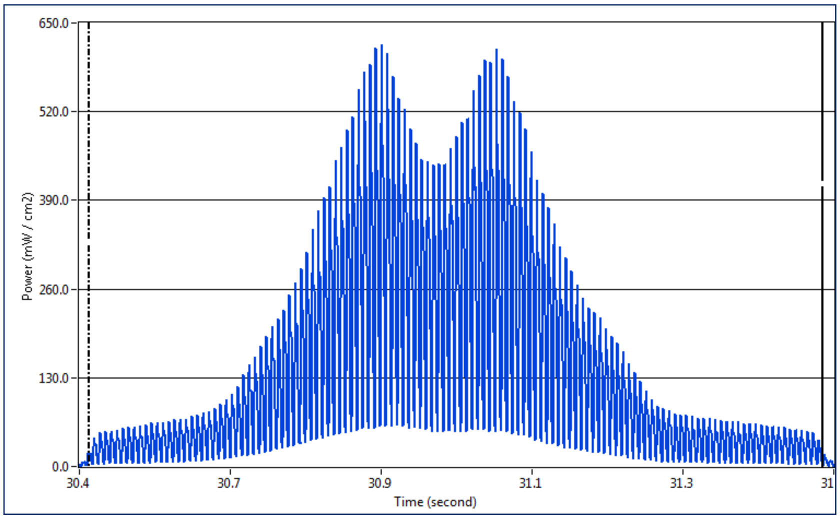
Figure 2



The data in **Figure 3** is of the same broadband source measured at an effective sample rate of 2048 Hz.

The peak irradiance in this example is **618.0 mW/cm²** and the total energy density is **139.9 mJ/cm²**. There is a 94% difference in the peak irradiance value while energy density values have remained the same. The irradiance values and profile shown are often referred to as the instant peak.

Figure 3



Zooming in on a 0.30 second portion of **Figure 3** allows you to see in **Figure 4** the lamp irradiance cycling based on the frequency (50 or 60 Hz) of the alternating current (AC). **Note:** This AC ripple normally occurs at twice the line frequency (100 or 120 Hz) in most power supplies.

Figure 4

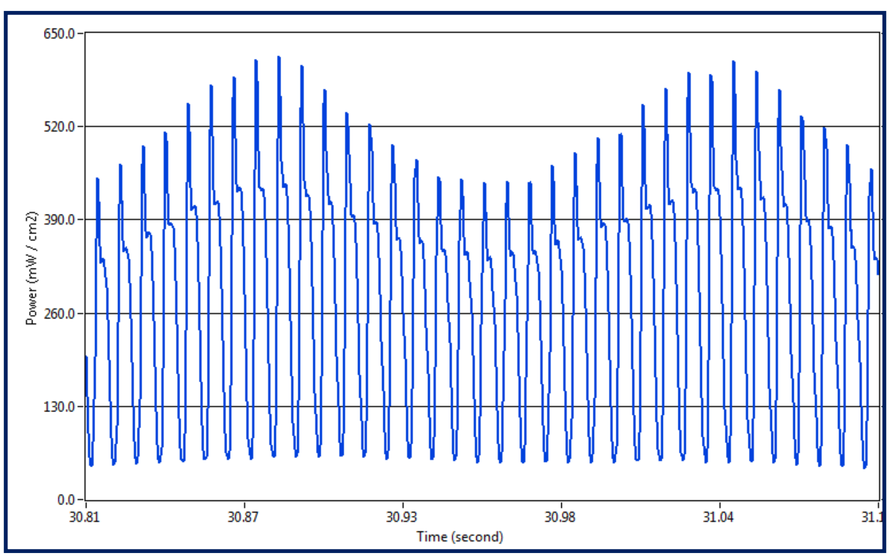
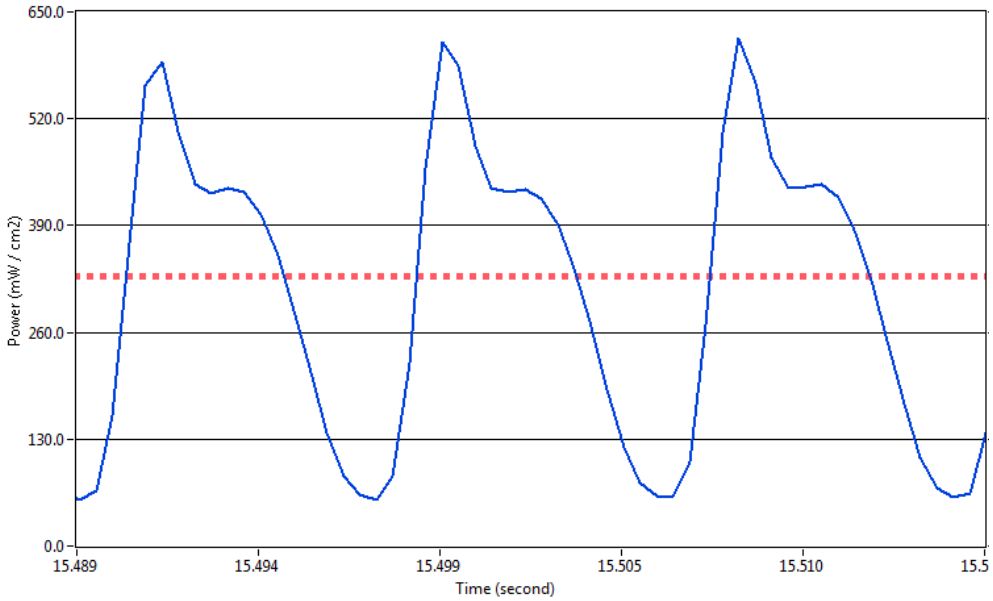


Figure 5 combines two irradiance profiles of another lamp at effective sample rates of 128 Hz and 2048 Hz.

- The time on the X-Axis is approximately 0.026 seconds
- The blue irradiance profile with a peak of 618 mW/cm² shows data collected at 2,048 Hz
- The red irradiance profile with a peak of 329 mW/cm² shows data collected at 128 Hz

- Energy Density values are the same
- Both irradiance values are correct, based on the how the UV was sampled and is reported

Figure 5

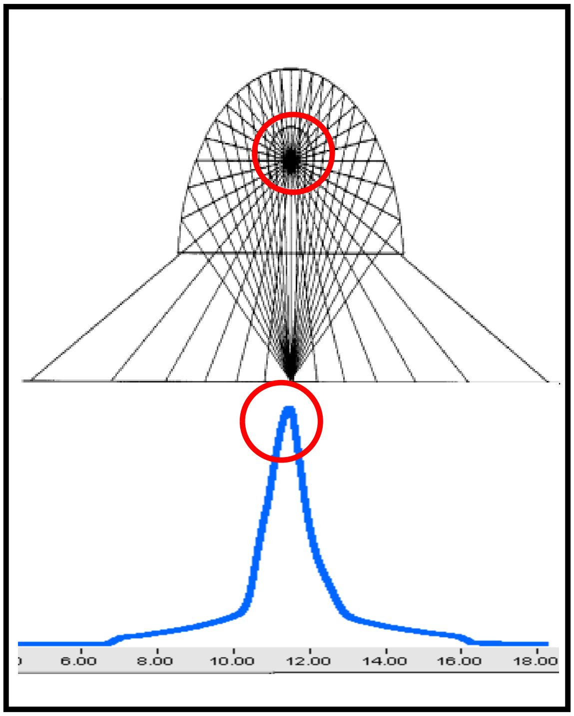


Note: The shape of an irradiance profile collected on a high frequency AC power supply and/or DC power supply (LEDs) at high sample rates will vary. In general it does not show the cycling as shown above with only a slight ripple effect.

It is best to be state the sample rate that the irradiance values were collected.

Validity of the Data Collected Based on Line Speed and Instrument Sample Rate

Figure 6 Typical Broadband arc lamp in a focused position



Accurate, repeatable radiometric measurements require being able to collect an adequate number of samples.

Broadband Mercury Sources

With a broadband focused UV system, a radiometer collects samples when it is under the reflector and bulb. The peak irradiance area corresponds to the bulb diameter; typically 0.35-1.02” (9-26 mm). The overall distance from one side of the reflector to the other will vary based on the design of the lamp housing and reflector.

Figure 6 shows the peak irradiance area which corresponds to the diameter of the bulb in red. The UV collected under the reflector is also shown.

Table 1 estimates the number of samples that a radiometer would 'see' at different sample rates and line speeds for a broadband lamp with a 0.75" diameter bulb and a 6" reflector width.

Table 1: Values based on a broadband mercury bulb, 0.75" diameter and 6" reflector

Line Speed (Feet per Minute)	Instrument Sample Rate (Hz)	Estimated Number of Samples collected under the Reflector Used to help calculate Joules/cm^2	Estimated Number of Samples collected under the Peak Used to determine the Watts/cm^2
25	128	154	19
50	128	77	9.6
100	128	38	4.8
200	128	19	2.4
400	128	9.6	1.2
25	2048	2458	307
50	2048	1229	154
100	2048	614	77
200	2048	307	38
400	2048	154	19

With a sample rate of 128 Hz, line speeds above 100 feet per minute may start to show variation in the data because of the sample rate. With a sample rate of 2048 Hz, the number of data points is not an issue. The actual number of samples collected will depend on your bulb/reflector and instrument sample rate.

In the example illustrated in Table 1, peak irradiance samples can be relied upon at high sample rates (like 2,048 Hz) since at least 19 samples are collected even at the fastest (400 FPM) production speed. However, if using an instrument with a lower sample rate (e.g., 128 HZ) only 1.2 samples are collected under the peak. Clearly this means you are rolling the dice at fast production speeds.

LED Sources

The UV output area on an LED is generally smaller than the corresponding output area on a broadband source. In general, LEDs do not utilize reflectors. Common widths of the active "LED chip" area for LED sources can vary between 0.4-2.0" (10-50 mm) based on the LED type and application.

Figure 7 Typical LED Source (Photo courtesy of Excelitas)

Active LED area with collection of data in a 0.4" to 2.0" (10-50 mm total)

Consequently, the "window" or area to collect radiometric data with an LED is much smaller compared to most broadband sources. Most LED's do not have a large area of reflected UV energy.

Table 2 estimates the number of samples that a radiometer would 'see' at different samples rates and lines speeds for a LED with a 1" (25 mm) quartz window.

Table 2: Values based on a LED window of 1" or approximately 25.4 mm

Line Speed (Feet per Minute)	Instrument Sample Rate (Hz)	Estimated Number of Samples collected under the LED
25	128	25.6
50	128	12.8
100	128	6.4
200	128	3.2
400	128	1.6
25	2048	410
50	2048	205
100	2048	102
200	2048	51
400	2048	25.6

Similar to the discussion of Table 1, at fast sample rates, reliable peak irradiance measurements can be obtained across a wide range of process speeds. However, with a lower sample rate of 128 Hz, line speeds above 50 feet per minute could start to show variation in the data because of the sample rate.

Check with the manufacturer of your radiometer to see if the sample rate can be adjusted.

If your sample rate cannot be adjusted, can you collect the data at slower speeds?

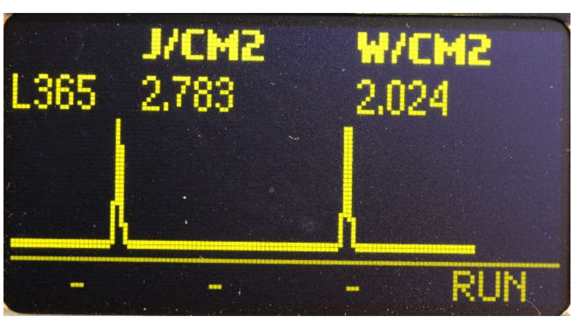
Figure 8 Adjusting the instrument's sample rate

Some radiometers provide the user with a means of adjusting the sampling rate. For example, the EIT LEDCure® can be adjusted to an effective sample rate of 128 Hz in "Profiler" mode (shown in Figure 8) or 2048 Hz in "Smooth Off" mode".

The irradiance data shown on the display will be the highest of any of the LEDs the instruments passes under.

The energy density data shown on the display will be the sum of all LEDs the instrument passes under.

Figure 9 LEDCure Instrument Display



The display to the right shows that the radiometer passed under two LED sources. The highest measured irradiance value from either LED is 2.02 W/cm^2

The total energy density of 2.78 J/cm^2 is a combination of both LEDs-in this case LED one plus LED two.

In this illustrative example, while the sample rate can be adjusted between 128 Hz and 2048 Hz., the irradiance profile transferred to a computer with the LEDCure is fixed at 128 Hz.

A common application for LEDs is for curing inks in digital printing. Digital printers utilizing LEDs continue to evolve to run at faster speeds. Most digital printers utilize two LEDs, one on either side of the print head. In addition to the print head moving back and forth, the print bed may also move. It is not practical to measure a single pass and sometimes it is important to analyze the pattern of the irradiance including the irradiance profile from each LED.

For such high-speed applications, an instrument with a fast sample rate is required. A device like the LEDMAP™ shown in Figure 10 was developed to provide the correct LED optical response in addition to having a user adjustable sample rate that can exceed 2048 Hz. With a small enough physical profile that it can be secured to the bed of the printer.

Figure 10: EIT LEDMAP

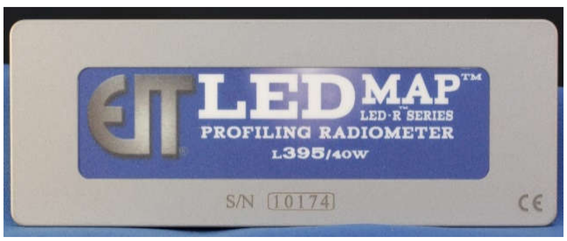
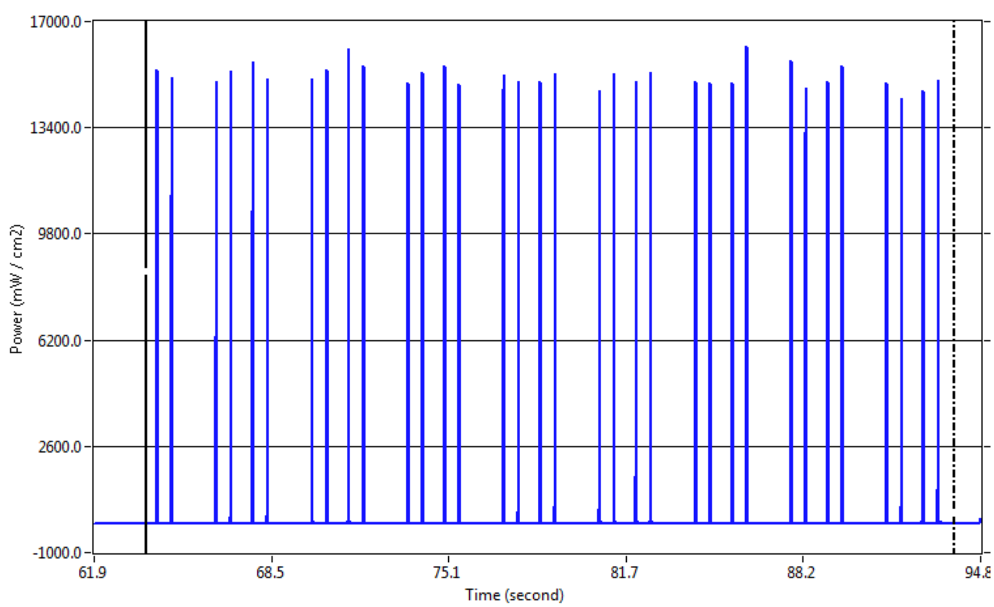


Figure 11 shows data collected from a two-lamp LED system at a speed of approximately 400 feet per minute. Time is on the X-Axis and UV irradiance on the Y-Axis.

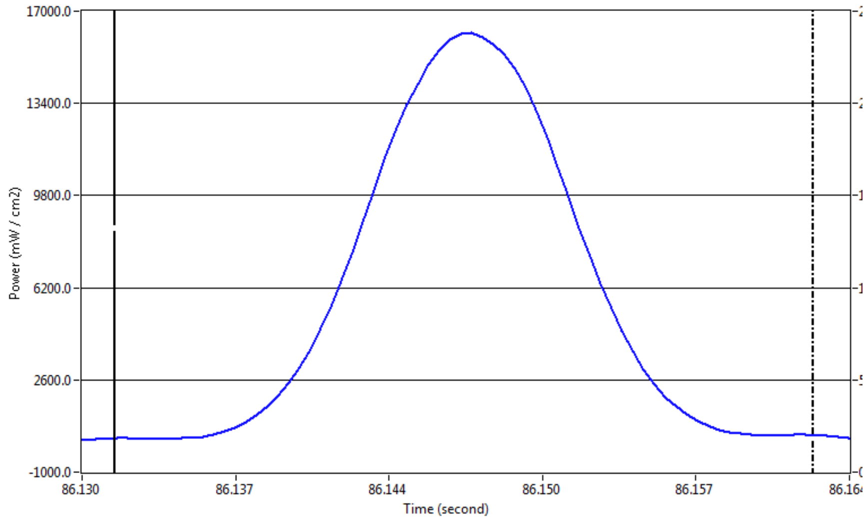
Figure 11 below shows 34 individual peaks collected over a 30 second (time between the cursors) interval. The sample rate was 2130.5 Hz.

Figure 11: LED Printer with data collected over a 30 second interval.



There is enough resolution to look at a single pass as shown in Figure 12.

Figure 12: Single pass from LED printer at 400 feet per minute



The time between the cursors is 0.03 seconds (86.162 seconds to 86.132). At a sample rate of 2130.5 Hz, this equates to 64 individual sample points on the irradiance profile in Figure 12

The software and cursors allow the irradiance and energy density to be calculated for each individual pass.

The maximum sample rate in EIT's LEDMAP is at 2130.5 Hz. The width of the LED and process speed will determine if this sample rate needs to increase for the next generation of digital printers using LEDs.

Summary

- The fast, user-adjustable effective (equivalent) sample rate found in many of today's high-quality production radiometers allows users to collect more samples and obtain better resolution than radiometers from only a generation ago.
- Users will benefit from taking time to understand your radiometer and its limits for data collection. Wide variations in irradiance values from one run to another may indicate an insufficient sampling rate. If the instrument has an adjustable sample rate, select a sample rate that is most appropriate for the application and collection speed.
- When comparing irradiance values, indicate how they were collected. It is important that everyone speaks the same language when it comes to measurement procedures. It is wise to clarify all values used in the supply chain and on formulator data sheets.
- Remember to collect data in a manner that does not damage the process equipment, instrument, or injure the person trying to 'catch' the instrument.
- Follow speed limits and avoid going to UV traffic court