UV Measurement and Process Control Instruments

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Subject: **L-Band Optics Overview and Performance**

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Summary
This paper provides an overview of EIT's L-Bands optics including insight on their design and performance. The L-Band optics incorporated in EIT's LEDCure®, LEDCure® Profiler and LEDMAP™ line of instruments are used to measure UV LEDs accurately and absolutely in curing applications.

Topics Covered in this L-Band Optics Overview and Performance include:

- Introduction
- Historical Radiometer Approaches
- LED Output
- Radiometer Band Approaches: Wide & Narrow Band Responses
- EIT L-Band Total Measured Optic Response (TMOR)
- EIT L-Band Performance
- EIT L-Band Instrument Overview

Introduction
The first commercial UV LEDs were mainly 395 nanometers (nm) with low intensity levels. In a short time, LED sources evolved in irradiance (W/cm^2) and energy density (J/cm^2) values. The output levels (approaching 30W/cm^2) of commercially available LEDs give users more flexibility than was previously available.

A large selection of LEDs with spectral outputs in the 365 nm, 385 nm, 395 nm and 405 nm regions are commercially available while work continues in other bands including shortwave (270-280 nm) UVC LEDs. The choice of the appropriate LED band depends on the application, chemistry and desired cure characteristics required for the final product.

The following industry trends have been noticed with LEDs

1. There are a variety (365, 385, 395, 405) of LEDs being used and you need to verify and not assume that you have a 395 nm LED source.
2. LED uniformity and commercial binning practices to a stated bandwidth, typically +/- 5 nm vary markedly from supplier to supplier.
3. Variations in spectral output and intensity between modules might cause issues if working across multiple lines, multiple locations and with multiple suppliers.
4. Production lines with LEDs have started to optimize and use different wavelength LEDs in different locations, much like production lines with different mercury sources (mercury, mercury-iron, or mercury-gallium).

Given these industry trends, proper and absolute LED measurement is an important consideration in research & development, prototyping/process development and in production.

Historical Radiometer Approach

The stated response(s) of radiometers have historically been described solely by the response of their optical filter(s). A radiometer utilizes multiple optic components (stack), each with their own response. The energy from the source is impinged on this stack.

Energy from the source is passed through multiple optic components and is converted at the photodetector to an electrical signal suitable for measurement and display by the radiometer. Figure 1 below shows a diagram of a generic optical stack.

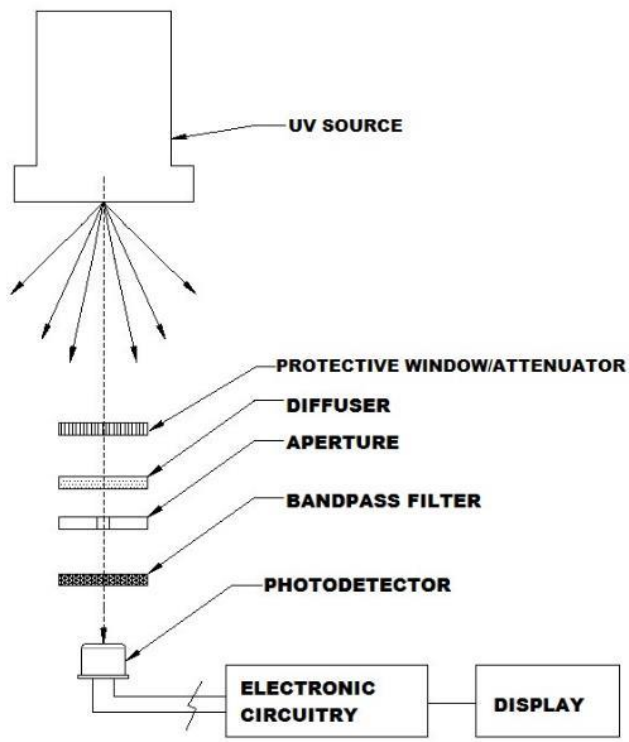

Figure 1–Diagram of a generic UV Radiometer optical stack (Courtesy EIT LLC)

The summary function of each optical component in the generic stack is described below:

1. **Protective Window/Attenuator**
   - Outer surface which receives the energy (UV, visible, IR) from the UV source
   - It has a response and functions to:
     - Pass some wavelengths and reject others
     - Attenuate the energy level to protect the optical components
     - Protect the components inside the instrument from external contamination
2. **Diffuser**
   - Works to diffuse the energy that made it past the Protective Window/Attenuator
   - Diffusers have transmission values which vary with wavelength
   - Works to provide a Cosine Response for the instrument
     - Coatings are thought to react in a cosine manner. Energy arriving perpendicular to the coating surface are assumed to be able to penetrate further than the energy arriving at other than right angles.
3. **Aperture**
   - Reduces total energy to the filter/detector combination to an acceptable level and to eliminate light leakage around the edge(s) of the filter(s)
   - Based on the design, the aperture may or may not be spectrally flat
4. **Bandpass Filter**

- Used to transmit the wavelengths which are to be measured and to strongly reject all other wavelengths.
- There are two distinct filter types used:
  - **Cut Glass Filter**
    - Cut Glass Filters have transmission values which vary substantially over the wavelengths
    - A typical Transmission Curve (normalized transmission versus wavelength) plot for a commonly Cut Glass Filter is shown in Figure 2
    - Note the lack of a rectangular response

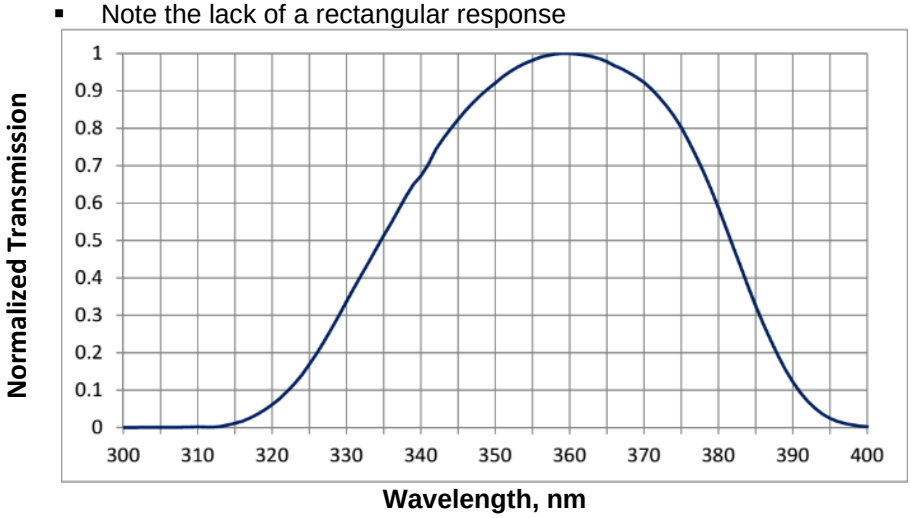

Figure 2 – Transmission Curve for a Typical Cut Glass Filter (Courtesy EIT LLC)

  - **Color Interference Filter**
    - Color Interference Filters can be used and designed to provide good to excellent (rectangular) response in the passband of interest and very good rejection outside of it
    - A typical Transmission Curve (normalized transmission versus wavelength) plot for a common Color Interference Filter is shown in Figure 3 below
    - There is excellent in-band response and out of band rejection with steep transitions from passband to out of band
    - The response of a Color Interference Filter can 'shift' to shorter wavelengths if the stack is not properly designed. Energy arriving at a low angle of incidence (AOI) is more susceptible to this shift if the optics stack is not properly designed.

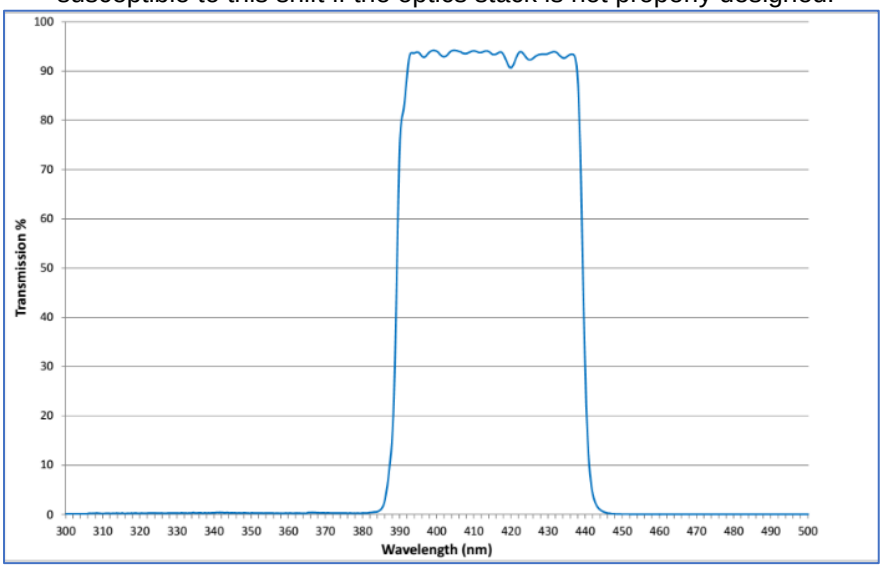

Figure 3 – Transmission Curve for Typical Color Interference Filter (Courtesy EIT, LLC)

- Figure 4 illustrates the response curves for such a filter when the energy incident on its front surface is at 0º, 15º and 30º angle of incidence (AOI). Note the dramatic shift in cutoff wavelengths for angles larger than about 15º.

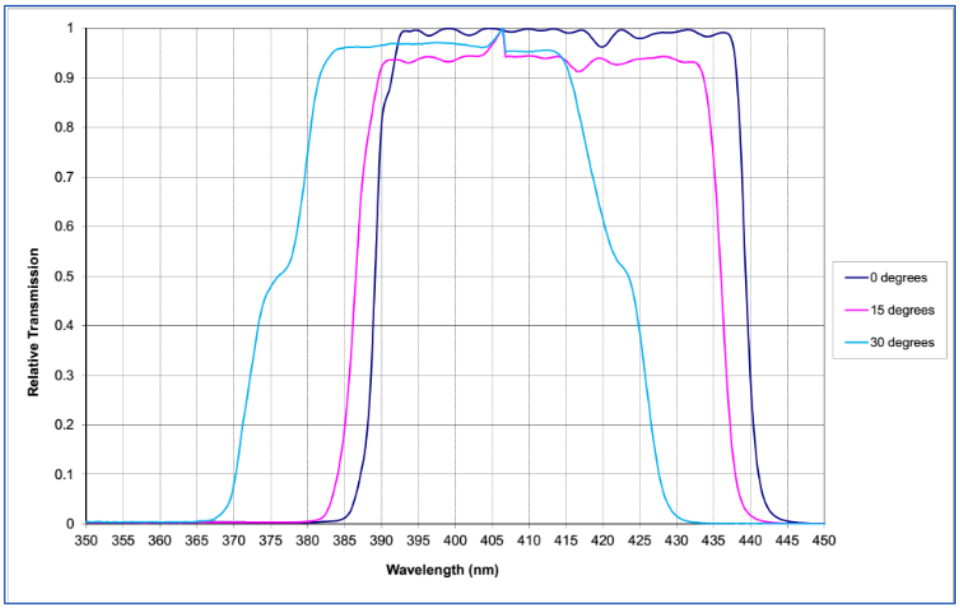

Figure 4 – Color Interference Filter Response for 0º, 15º, & 30º Degrees Angles of Incidence (Courtesy EIT LLC)

5. <u>Photodetector</u>

- UV energy is converted to a current which is proportional to the intensity at the photodetector. The response of the photodetector varies (non-linear) with wavelength, generally decreasing in responsivity at shorter wavelengths.

LED Output

Commercial LEDs are specified according to their Center Wave Length (CWL) which is the expected center point of their peak power. Most manufacturers use a tolerance of +/- 5 nm to describe their CWL. Verify the CWL specification with your source supplier and confirm the CWL of your LED array.

For accurate measurements, it is critical to have an instrument with a flat response that covers the expected of the CWL (+/- 5 nm) variation of the LED.

- For a 395 nm LED, the **CWL** is expected to fall between 390-400 nm.
- At the **50% power level**, the spectral output may spread to out to a distribution of +/- 15-20 nm wide
- At lower levels, the distributor may spread to 40 nm or more as shown in Figure 5 below.

The CWL is expected to be +/- 5 nm for a typical LED

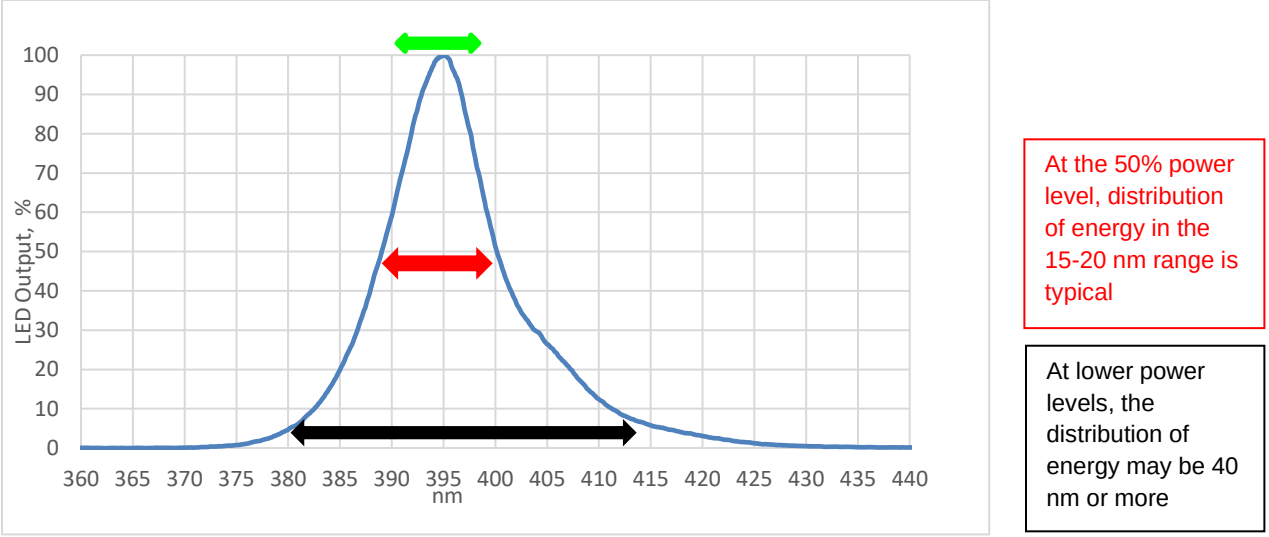

Figure 5: Typical 395 nm UV LED Energy Distribution (Courtesy EIT LLC)

Radiometer Band Approaches

Commercially available industrial radiometers typically show the spectral response of the bandpass filter and neglect the optical response of all other optical components described earlier including the Protective Window/Attenuator, Diffuser and Photodiode.

With instruments using Cut Glass Filters, the Angle of Incidence (AOI) factors are not relevant. Instruments using Color Interference Filters seldom make provisions for optical response changes caused by the Angle of Incidence (AOI).

The ideal response with both approaches (Cut Glass & Color Interference) would be a spectral response that is rectangular.

The resulting instrument response is substantially different from the filter response which manufacturers typically publish as representing the overall optical response of their instrument(s). While this practice does not prevent the instruments from being used in a relative measurement mode, the results obtained can be much different from the desired rectangular response and generally do not provide accurate irradiance and absolute energy measurements.

There are two common approaches to measuring UV LED light sources:

1. A one-size-fits-all, Wide Band, response
2. A selective, Narrow Band response

Note: The term 'Wide Band' is being used to avoid confusion with the term 'broadband' which is often used to describe mercury-based sources which emit energy over a 'broad' (UV, visible, IR) band or portion of the electromagnetic spectrum.

Wide Band Response

A wide band response for the purpose of this paper features an instrument response that may be 100-300+ nm wide, with the instrument manufacturer determining the actual width and response shape of the band. The attraction of a wide band response approach is that it allows the user to have one instrument. The shape of the filter on an instrument with a wide band can vary significantly. It is extremely hard to achieve a flat response over the width of a wide band filter.

Instruments with wide band responses have been used for many years with mercury-based sources. There is one irradiance (W/cm^2) and one energy density (J/cm^2) value provided when measuring a source with a wide band instrument. This makes the wide band instrument easy to use and understand.

Radiometers perform best when calibrated using the same source type that the instrument will measure. A wide band source will use an UV source and a point somewhere along the instrument response curve to generate values in the instrument. For LEDs, if a 395 nm LED source is used to calibrate a wide band instrument, the instrument will match best when it measures a 395 nm source.

A wide band instrument in limited in identifying bulb types in both broadband (i.e., mercury, mercury-gallium or mercury-iron) and LED (365, 385, 395, 405) based systems. Examples include:

- The wrong bulb or LED array in your process
- The wrong location for a bulb or LED

A wide band instrument has limited ability to alert you to changes in the spectral output of a bulb. Examples include:

- Aging of a mercury-gallium bulb. The spectral output changes and when it ages it looks more like a mercury bulb than a mercury-gallium bulb. This could impact your adhesion or cure through opaque colors.
- When reflectors or quartz plates are hazy or dirty, the shortwave UVC drops off. This could impact your product's surface cure properties especially if your process relies on the shortwave UVC for these properties.

Narrow Band Response

We define a narrow band response as one that is less than 100 nm wide. It could be as narrow as 10 nm wide, with the instrument manufacturer determining the actual width and response shape of the band.

It is much easier to control the design and shape of a filter response or even the total instrument response with a narrow versus a wide band response. A narrow band instrument will also use a calibration source that closely matches the instrument response. A 395 nm LED is used to calibrate the L395 band and 365 nm LED source is used to calibrate the L365 band. This leads to better instrument performance in a production environment. If you cure using UV LEDs that have different spectral outputs, a narrow band approach requires that the user to either have an instrument for each LED band or have a multiband LED instrument.

EIT LED-Band (L-Band) Total Measured Optic Response (TMOR)

Traditionally, the optic filter response the has been used to describe the overall instrument response. A more realistic approach to an instrument response is to specify the response based on <u>all</u> optical components in the instrument and not just the optic filter.

EIT's *Total Measured Optic Response* (*TMOR*) is a patented[1] approach used in our LEDCure® and LEDMAP™ family of instruments that does this. It provides accurate and absolute UV energy measurements of commercial UV LED sources with excellent readings source-to-source, run-to-run and instrument-to-instrument.

[1] May, J.T. and Lawrence, M., Inventors, "Radiometry Instruments and Technology" US Patent 9,778,103 Issued October 3, 2017

EIT has chosen to designate these new bands developed specifically for LEDs as “LED-Bands” or “L-Bands”. The “L” is intended to denote an LED type source with attendant spectral distribution while the numeral denotes the nominal central wavelength of the source in nanometers (nm). The LED notation is intended to be analogous to mercury lamp band notation, A, B, C and V.

Each L-Band is matched to Center Wave Length (CWL) of the LED source. Each L-Band response is flat in the area covered the +/- 5 nm variation in the CWL. To obtain accurate irradiance readings, it is important to use a radiometer with a response as flat as possible over this 10 nm CWL range of interest.

The overall response for each L-Band is 52 nm to support the expected pattern of energy distribution in commercial UV LEDs. Each L-Band is rectangular in shape and the width of the band allows the total optical response to be very well controlled and to be repeatable.

A summary of each L-Band is shown in Figure 6.

EIT L-Band	LED Source CWL	Wavelengths +/- 5 nm CWL variation	Overall Response Range
L-405	405 nm	400-410nm	380-432nm
L-395	395 nm	390-400nm	370-422nm
L-385	385 nm	380-390nm	360-412nm
L-365	365 nm	360-370nm	340-392nm

Figure 6: EIT L-Bands

It is easier and more reliable to achieve a flat response over the width of a narrow band than it is to achieve a flat response over a wide band.

Figure 7 below shows the L395 band response for the new L395 instrument design. This is an actual measured response reflecting all optical components in the instrument. The response is essentially flat across all wavelengths associated with a 395 nm source.

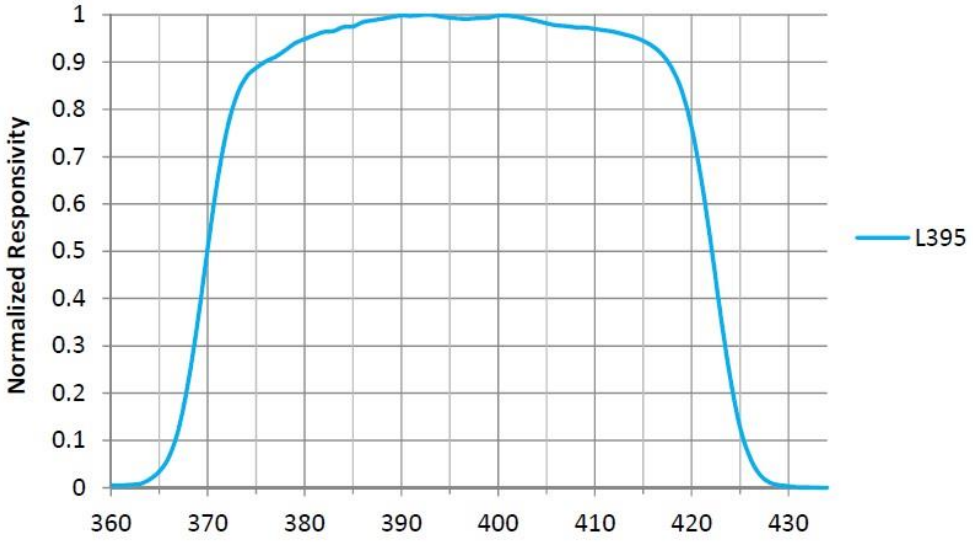

Figure 7: L395 Total Measured Optic Response (Courtesy EIT LLC.)

Instruments with the L-Band utilize newer patented techniques to achieve a total optical response that is rectangular in shape. Each L-Band provides a nearly flat overall response curve over the pass band of the entire optical stack.

EIT L-Band Performance

The L-Band optics in the LEDCure and LEDMAP provide accurate and absolute UV energy measurements of commercial UV LED sources with excellent readings source-to-source, run-to-run and instrument-to-instrument.

The following data was collected by source manufacturers and EIT as indicated.

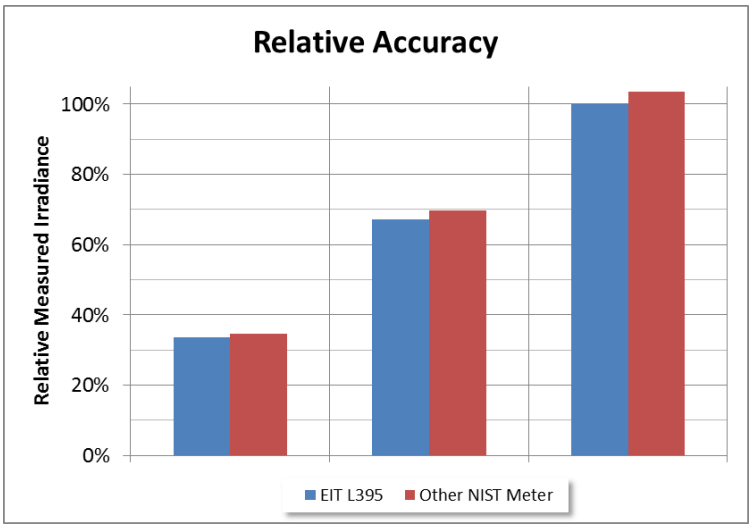

Figure 8: A 395nm UV LED source was calibrated to 16W/cm² using the EIT L395. The UV LED source was then measured with another NIST traceable radiometer. The two radiometers matched to within 4% at different irradiance levels. (Courtesy Phoseon)

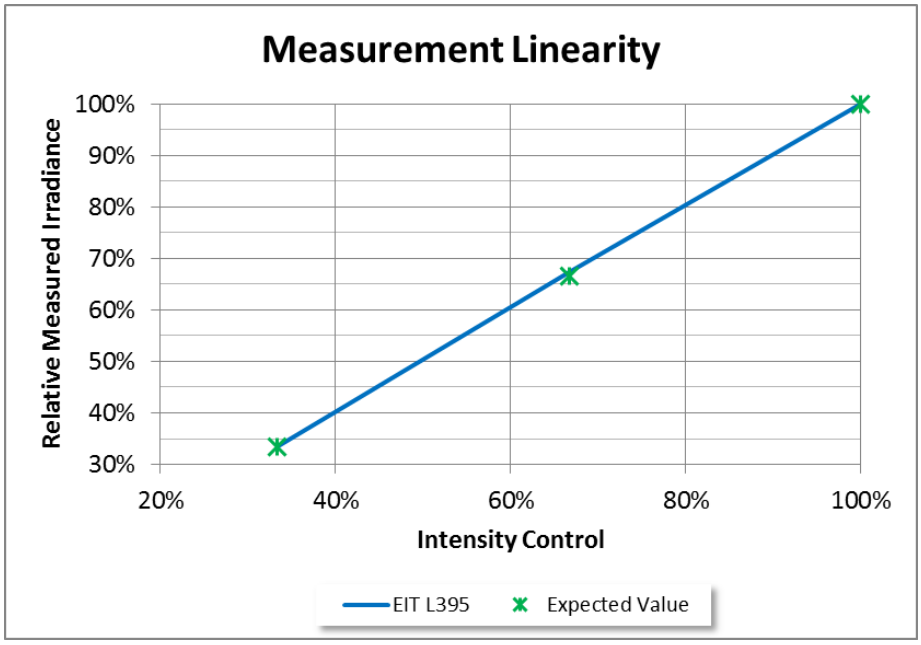

Figure 9: Measurements at different irradiance settings were made with the EIT L395 radiometer and compared to the expected values. The L395's linearity across a 3:1 dynamic range is excellent. (Courtesy Phoseon)

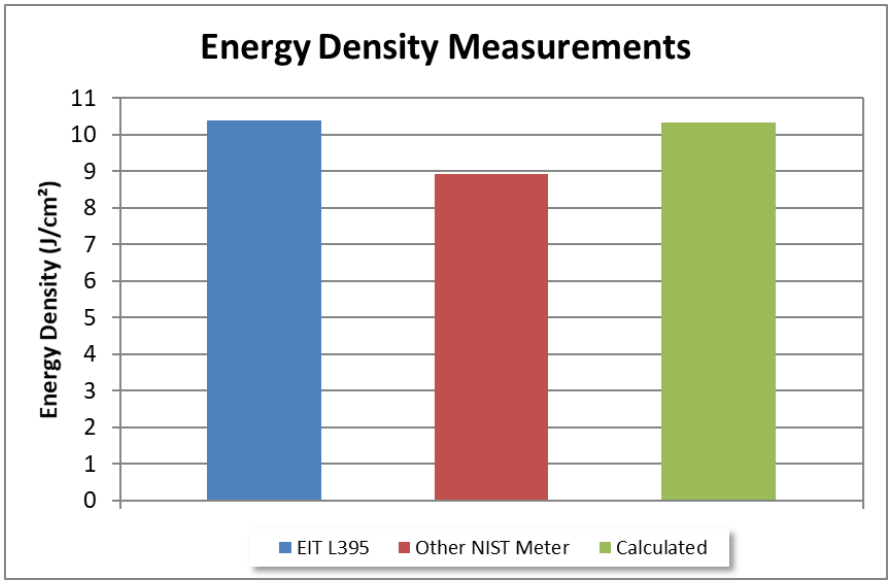

Figure 10: Energy Density measurements were taken at a speed of 20mm/sec (1.2m/min) and compared to the calculated value based on the short axis spatial response. The EIT measurement differed from the calculated value by less than 1%. The other NIST traceable radiometer differed from the calculated value by more than 13%. (Courtesy Phoseon)

Working Distance (mm)	Primary Standard: Integrating Sphere (W/cm^2)	LEDCure L395 (W/cm^2)	Difference
5	9.01	9.23	2.4%
10	7.74	7.74	0.0 %
15	6.66	6.63	- 0.5%
20	5.74	5.83	1.6%
25	5.04	5.08	0.8%

Figure 11: Comparison of the LEDCure values to the values from an integrating sphere at different distances. (Courtesy Lumen Dynamics/Excelitas)

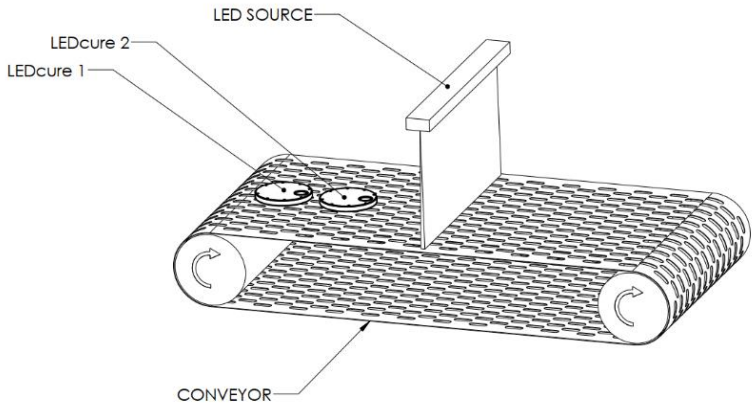

Figure 12: Set up for the comparison of two LEDCure units to each other. EIT compared two LEDCure instruments to each other on a conveyorized system in our lab. Data from each unit was collected for 20 runs and is shown in Figure 13 below.

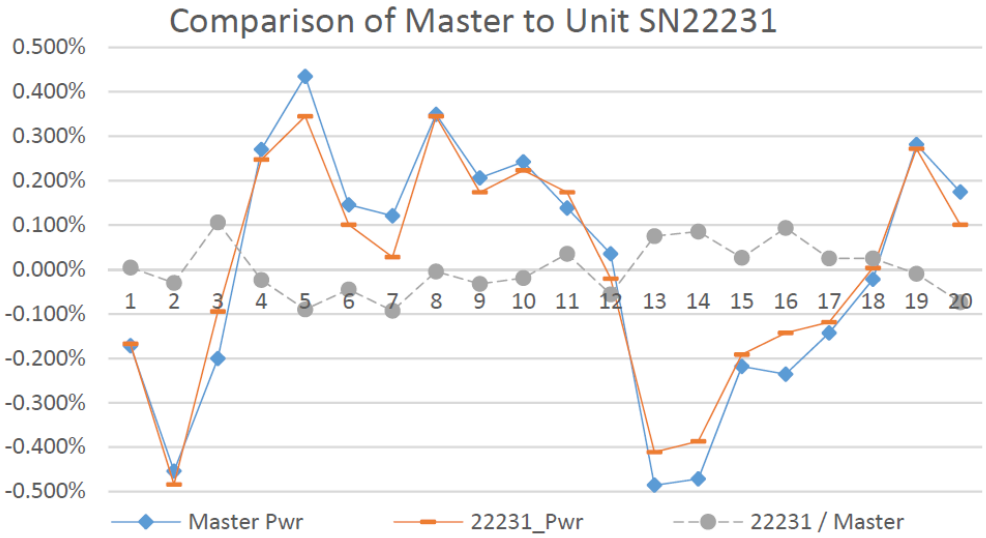

Figure 13: Results of 20 runs with two LEDCure L-395 radiometers. (Courtesy EIT LLC)

The overall difference in the values collected by the two instruments in Figure 13 was less than 1%. When the readings were compared to each other, the difference between the two readings was less than 0.2%. The data shows excellent repeatability and unit-to unit matching.

EIT LED L-Band Instrument Overview

There are several choices when it comes to EIT's LED measurement solutions. The following section gives a brief overview of the instruments that are available.

EIT LEDCure

The LEDCure is a single band with L-365, L-385, L-395 or L-405. The L-Band and decision to purchase a Standard or Profiler unit is specified at the time of order.

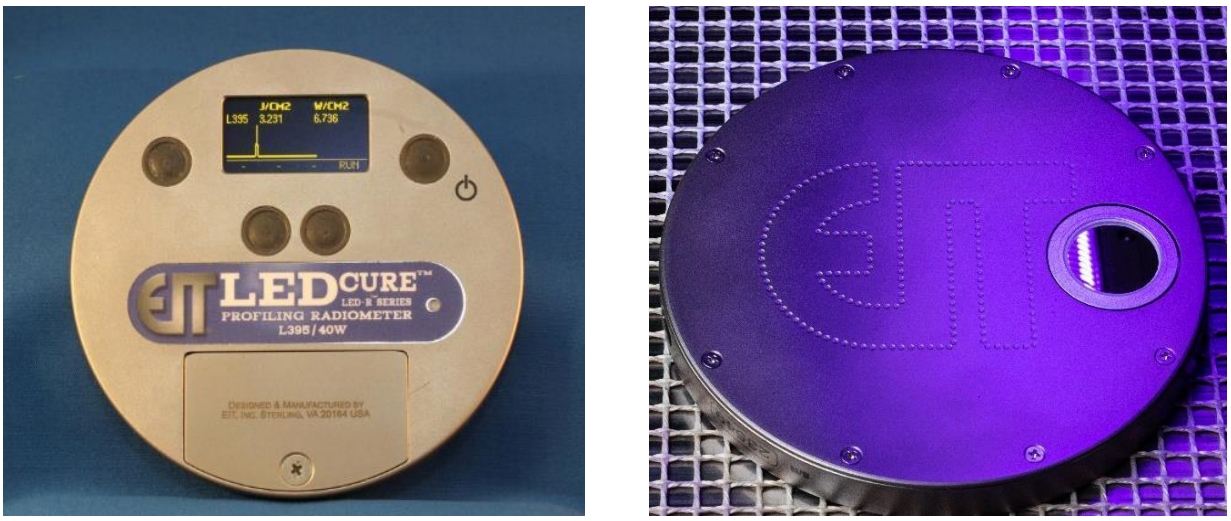

Figure 14: Display and Optics side of EIT LEDCure®

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LEDCure Standard Version

The LEDCure Standard version has all information on the display. This includes the Energy Density (J/cm^2), Irradiance (W/cm^2), band measured and the number of arrays the instrument passed under.

Figure 15: Display from LEDCure that shows the collected values and that the instrument passed under one array

In the case of multiple sources (Figure 16) the Irradiance value will be the peak of the highest LED source while the Energy Density value will be the sum of the two LEDs.

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Figure 16: Display from LEDCure that shows the collected values and that the instrument passed under two arrays

The effective sample rate can be adjusted to 25, 128 or 2048 samples per second in the Set-up Menu.

The LEDCure Standard Version also has the option to display a saved Reference value. The percent difference from the saved Energy Density and Irradiance values is calculated and displayed.

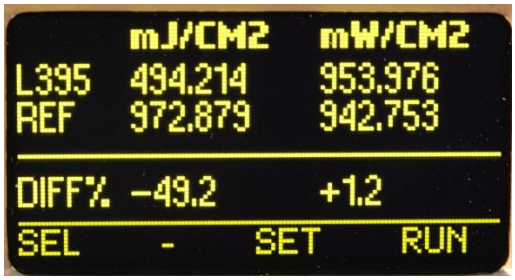

Figure 17: Reference Mode display shown

The peak Irradiance values are nearly identical. The Energy Density value when compared to the Reference show a drop of +/- 50% which indicate a difference in time of exposure or increased line speed.

LEDCure Profiler Version

The LEDCure comes in a Profiler Version which must be specified at the time of order. The LEDCure Profiler Version display functions in the same way as the LEDCure Standard Version.

A Profiler-enabled unit will allow you to download the irradiance Profile to EIT's UV PowerView® III Software program at a sample rate of 128 samples per second. The irradiance profile is helpful to:

- Look at each array and obtain the individual Energy Density and Irradiance values from each
- Look for changes in height, applied power, process speed (exposure time)
- Compare different brands of LEDs
- Look for uniformity across the array and compare to stored data

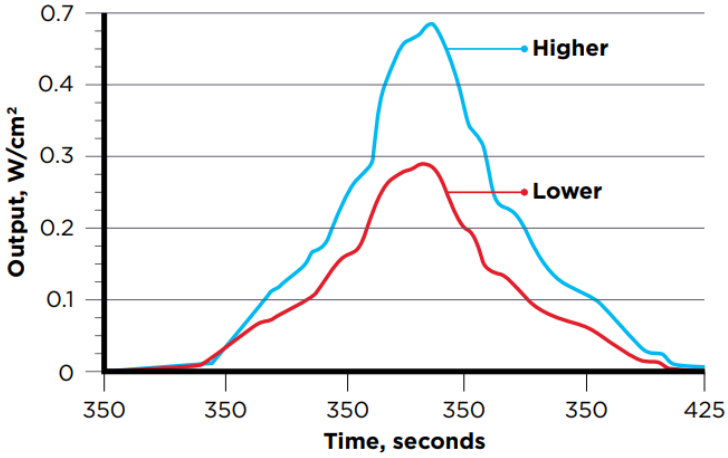

Figure 18: Changes in the irradiance with applied power changes

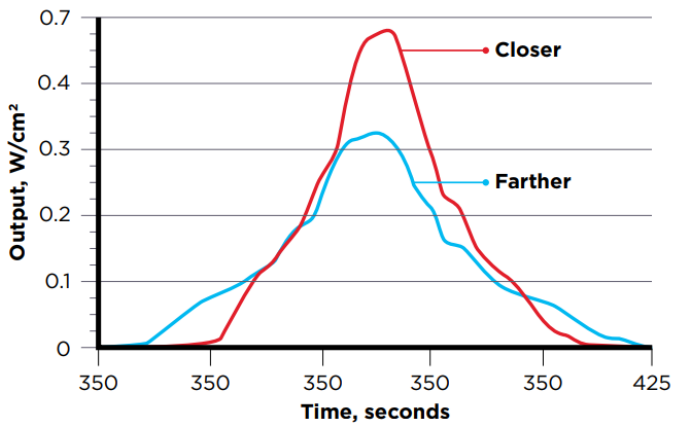

Figure 19: Changes in the intensity when the distance from the array to the instrument changes

The Profiler will allow you to break down individual passes under an LED to get the irradiance and energy density values from that LED.

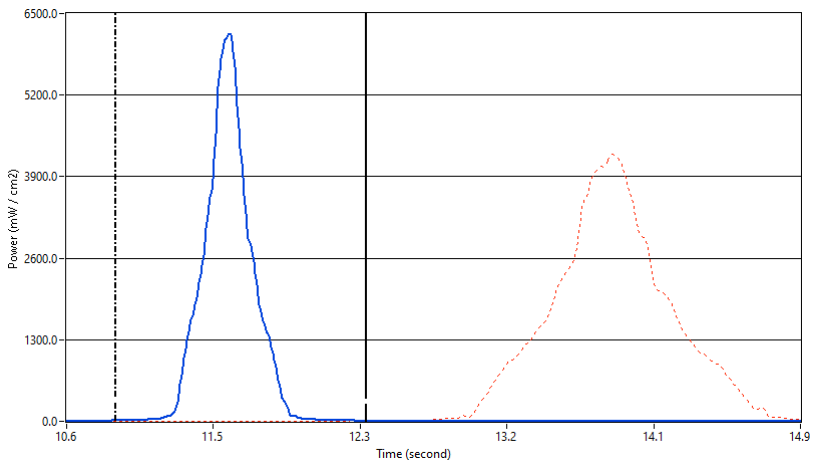

Figure 20: Two passes under an LED. Cursors around the LED on the left to determine the values from that LED

LEDCure Four Band Profiler

The LEDCure Four Band Profiler includes all four L-Bands (L-365, L-385, L-395 and L-405) in one unit. The LEDCure Four Band Profiler is not for everyone but will be beneficial for coating formulators, field service technicians, corporate R&D teams and LED source suppliers who routinely deal with multiple LEDs in the course of a day.

Figure 21: LEDCure Four Band Profiler and Display

Production lines with LEDs are starting to use LEDs with multiple wavelengths. Figure 22 shows the corresponding irradiance profile from a production line that was collected with the LEDCure Four Band Profiler. On the screen, the peaks of the different LED units are shown in different colors. One instrument run down the line identifies the different LED types. The Profiler function and use of cursors allows you to isolate each lamp and compare it to the values established when the process window was established.

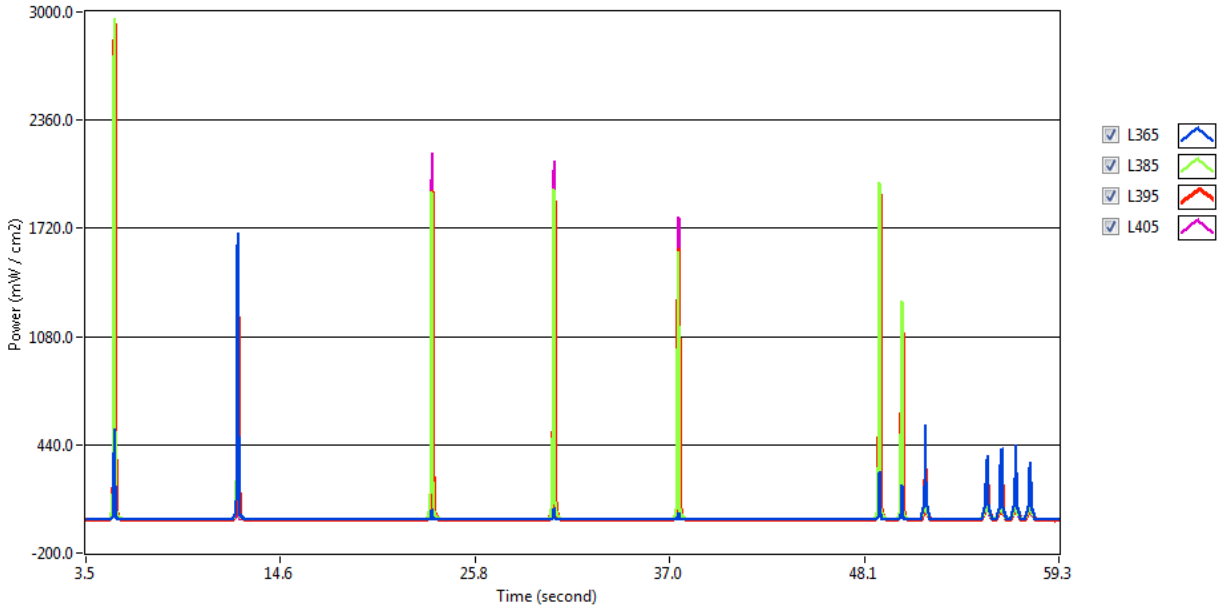

Figure 22: Irradiance Profile collected on production line with multiple LED types with the LEDCure Four Band Profiler.

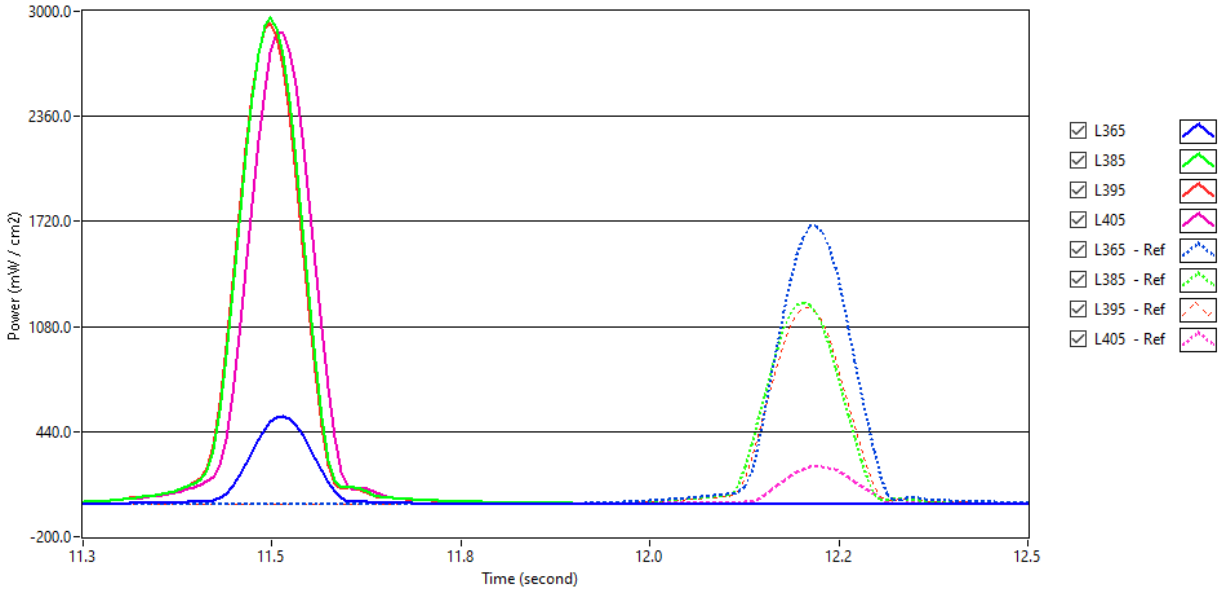

Figure 23: Two different LED types from the file above shown. The LED on the left is a 395 nm LED while the LED on the right is a 365 nm LED.

LEDMAP™

LED arrays that can deliver high irradiance (W/cm^2) and energy density values (J/cm^2) have allowed production speeds to increase. Digital printers, running at 400+ feet (122 meters) per minute are commercially available.

With an LED on either side of the print head, it is not practical to measure a single LED pass. Some printers do not have the ability to run at a slower speed. Analyzing the array values on a fast-moving printer requires a profiling radiometer with a fast sample rate. The LEDMAP™ (Figure 24) was developed with the EIT L-Band(s) and a user adjustable sample rate that can exceed 2048 Hz. It has a small physical profile to allow it to be secured to the bed of the printer or in other applications. It features and optional thermocouple which can measure temperature.

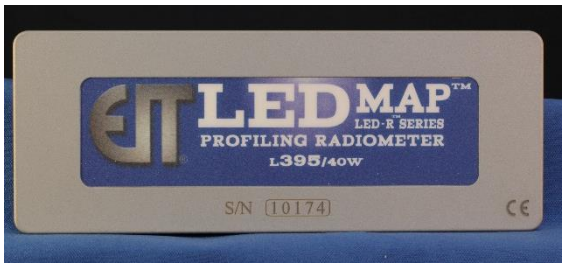

Figure 24: EIT LEDMAP

Figure 25 below shows data collected from a digital printer with an LED system on either side of the print head.

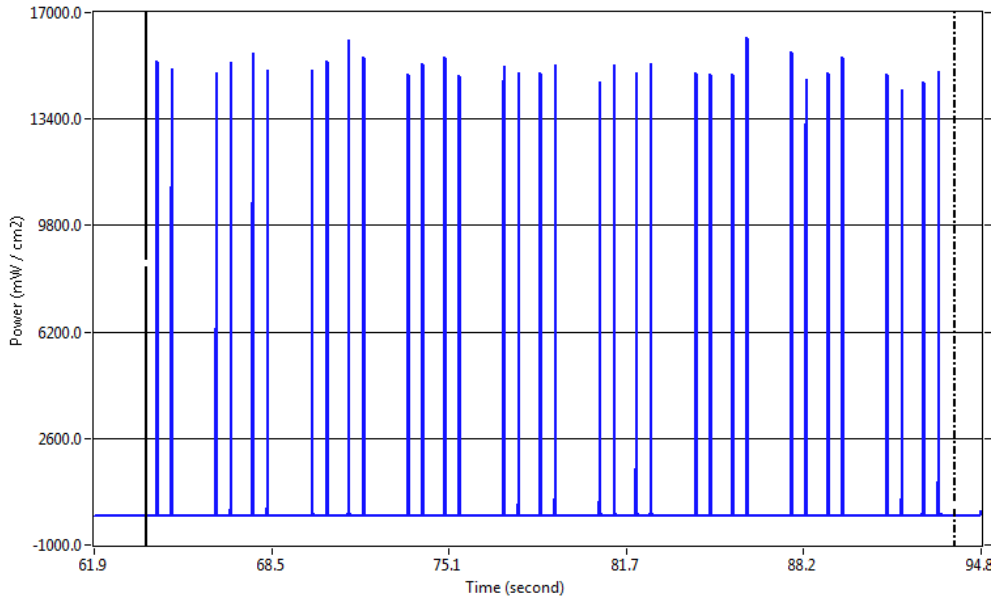

Figure 25: Data collected at a process speed of 400 feet per minute. The Profile below shows 34 individual peaks collected over a 30 second interval. The actual instrument sample rate was 2130.5 Hz. Time is on the X-Axis and UV irradiance on the Y-Axis.

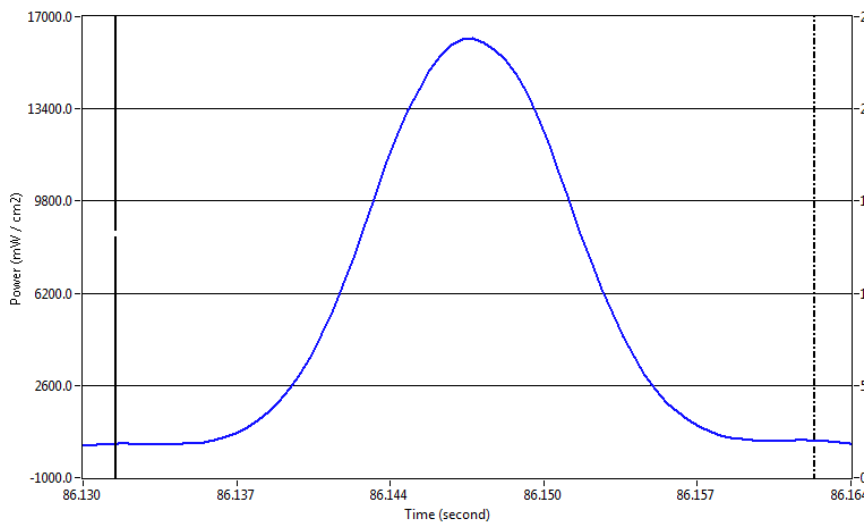

Figure 26: Single pass from LED printer at 400 feet per minute. The time between the cursors is 0.03 seconds (86.162 seconds to 86.132). At a sample rate of 2130.5 Hz, this equates to 64 individual sample points on the irradiance profile above. The software and cursors allow the irradiance and energy density to be calculated for each individual pass.