A discussion of Laser Beam Profiling and the subject of Accuracy

Question: How can I be certain that my Beam Profiler is measuring accurately? Is there a standard calibration methodology?

Answer: There is no calibration standard from which one can verify their camera based beam profiling measurement accuracy. Spiricon has done the next best thing to provide customer confidence in reliable and consistent results from its camera based profilers. The issue can be broken down into two major areas; 1) the input (camera), and 2) the output (from software algorithms).

1) The input (camera) has two parts; a) the physical imager, and b) the electronic processing and A/D conversion accuracy.
    a. **Camera, the Physical Imager**
       Each digital camera has an array of a fixed number of pixels in the X and Y direction. These pixels are made using a very precise semiconductor photolithography processes and pixel pitch accuracy (pixel-to-pixel distance) is in the angstroms range (1 X 10^-10). This amount of pixel-to-pixel distance variation is so inconsequential that any resulting beam profiling measurement accuracy will not be affected.
       However not all imagers are created equally and as a result some are better suited to operating at certain wavelengths and under different conditions than are others. An imager can thus provide better or worse accuracy based on how it is used.

    b. **Electronic Processing and A/D Conversion Accuracy**
       Electronic processing and A/D conversion covers areas like: gain, black level, linearity, signal to noise, and the A/D conversion into a number of bits that represent the light intensity from each pixel. In the old days a camera that had an 8 bit converter was high end. (8 bits is 2^8th or 256 independent levels of light intensity) Today most cameras have 12 or 14 bit converters yielding 4096 or 16,384 independent levels of intensity. With a modern camera optimized to control all of the above variables most will yield signal to noise ratios of from 58-63dB rms. Using 60dB for a typical 12 bit camera will yield about 24 counts of peak to peak noise out of 4096. Cameras with higher signal to noise ratios that can digitize well into the noise have improved capability when making accurate quantitative measurements.

To confirm the signal to noise error effects on accuracy you can use Spiricon's BeamMaker® mathematical laser beam/camera simulator that comes with BeamGage®. BeamMaker is a mathematical beam modeling tool that can generate a perfect synthetic laser beam using TEM mode values. Camera signal to noise can be superimposed on the beam and accuracy checked at various bits per pixel levels. By simulating a 12 bit camera and using the generated image as input BeamGage can compare the resulting measurement accuracy against the known input model value. This test also validates the software algorithms discussed in the next section.

2) The output (from software algorithms) must be accurate and repeatable. While cameras do what good cameras do, the accuracy of results will ultimately rely on how the camera's image data gets processed and the integrity of the computational algorithms applied to the data. These algorithms divide into 2 major topics, image processing, and data computations.
   a. **Image Processing**
      Spiricon was a leader in recognizing that proper image processing with regards to establishing a zero baseline was essential to making good laser beam measurements. Our patented Ultracal baseline correction algorithm was employed 9 years in advance of ISO recommending the procedure in ISO 11146-3:2004. Second moment beam width measurements are nothing more than good approximations unless correct image processing precedes the computational algorithms.

   b. **Data Computations**
      BeamGage, Spiricon's latest beam profiling software employed two independent algorithm verification methods.
      i. Each algorithm was independently compared to a MATLAB® simulation of the same input data. The algorithms employed by the MATLAB designer were written independently of the BeamGage programmer so as not to cross contaminate the process. This technique confirmed that the results reported by BeamGage were the same as those generated by MATLAB.
      ii. A second confirmation was made using the BeamMaker utility within BeamGage. BeamMaker generates a mathematically perfect laser beam that can be used as the input data for BeamGage measurements. Measurements from BeamGage were then

compared to the known modeled input parameters and confirmed to be the same.

These two methods confirmed that BeamGage image processing and computational algorithms were reporting correct and repeatable results. These two test systems are incorporated into Spiricon's regression test suite, and verified on each software release.

So what kind of accuracy can one expect from a Spiricon Laser Beam Analyzer?
This is not a simple question to answer, even in light of all the good cameras and attention to details that were discussed above. Unlike a power meter or a caliper that can be subjected to an industry standard of some type, there is no industry standard laser that we can all refer to. Lasers are not that easy to tame, reproduce, quantify and standardize. Spiricon's invention of a "BeamMaker" was an attempt to deal with this fact of life about lasers. Actually it goes back many years, and its incorporation into our new BeamGage product is what's new. This was done to assist you, the user, to determine for yourself some confidence in your results based on a wide range of conditions that are beyond the scope of this short discussion.

The following is a list of issues, each deserving of its own discussion on its effects on accuracy:

1. Camera gain setting as it impacts s/n ratio
2. Camera/Laser drift with temperature
3. Camera blooming or smearing effects based on beam brightness, wavelength and exposure settings.
4. Proper use of baseline correction
5. Beam is ≤ ½ the imager size in each direction.
6. Laser beam second moment width is ≥ to 10 pixels
7. Laser noise and other time varying properties such as shot to shot variability of pulsed lasers or pointing stability of CW lasers
8. Beam amplitude variability over the cameras dynamic range
9. Beam attenuation and external beam handling distortion effects
10. Where in the beam propagation path one performs the measurement, or am I measuring the right thing in the right place
11. Knowledge of the user to understand what is being measured and what choice of methodology is being employed
12. Proper use of aperturing to improve accuracy
13. Proper trigger mode selection and exposure timing when capturing pulsed lasers
14. Camera damage, especially due to over exposure and extended UV exposure

15. Failure to employ a Manual or an Auto Aperture

Assuming you have taken most of the above applicable items into account and you have made a good effort in reducing external sources of error and present your beam to the camera with good signal vs camera dynamic range, you can expect the following:

Second moment Beam Width Accuracy using Ultracal and Auto-Aperture, +/-2%, all modes and mode mixes. The above reduces to about +/- 5% when employing Auto-Xposure or other good but less favorable beam presentation conditions such as significantly reduced beam size or intensity.

Centroid Accuracy approximately 1/10th pixel pitch, adjusted for scaling factors.

Power tracking over the range from 5-98% of dynamic range, +/- 5%.

Accuracy of other beam measurement methods.
Knife-Edge second moment equivalent methods will produce similar accuracies for TEMoo beams, but have variable systemic errors as the beam mode mix changes. 90/10 approach is slightly more accurate than the ISO method.

% of Peak and **% of Power/Energy** are less susceptible to noise but have no industry traceable results for beams other than circular TEMoo diameters. Mixed mode results are not particularly meaningful except in terms of a user defined context.

Encircled Power Smallest Aperture and **Encircled Power Smallest Slit** are also less susceptible to noise but have no industry traceable results for beams other than circular or elliptical TEMoo diameters/widths. Mixed mode results are not particularly meaningful except in terms of a user defined context.

Divergence measurements only relate to beam propagation theory when computed using second moment beam widths. Other methods and user defined results require the user to verify for their own purposes.

Besides the above what else can I do to maintain confidence in my beam analysis system?
As a camera designed to provide the best performance for imaging laser beams, the ‘window’ has been removed from the front of the sensor array. As a result the unprotected array is a target in a laser beam shooting gallery, and is susceptible to damage, deterioration and abuse. Unprotected and exposed to the effects of your local

environment the imaging array, and subsequent images produced from the array, may deteriorate based on the elements. Such deterioration may be minor, such as increased appearance of single bad pixels; or in the most extreme cases corrosion and fractures that can lead to major degradation or catastrophic failure.

To help you maintain camera performance Spiricon recommends that customers return their camera on a regular basis (every 12 months is recommended under normal use) for a verification and recertification process. This process will correct bad pixels when possible, clean the imager, and certify that your camera is still performing to factory specifications. Or you will be advised of any changes that may be serious enough to require limiting use, repair or replacement. Call 435-753-3729 or email service@ophir-spiricon.com for an RMA and to schedule this process.