Ophir Power/Energy Meter Calibration Procedure and Traceability/Error Analysis

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1. General Discussion

This document discusses the interpretation and basis for stated measurement accuracy of Ophir Laser Power/Energy meters.

The total accuracy of measurement of a laser power/energy meter is affected by the following factors:

1. The calibration[1] uncertainty of the measuring sensor at the power level, energy level and wavelength at which it was calibrated.
2. The energy calibration uncertainty, i.e. the extra error that is due to the extra calibration step necessary to calibrate energy. This is of concern only for thermal sensors, not for pyroelectric energy sensors.
3. The wavelength dependence of the sensor, i.e. if it was calibrated at one wavelength and the measurement is with a laser of a different wavelength, how much this affects the accuracy of the measurement.
4. The linearity of the sensor, i.e. if we increase the input power or energy by a factor of say 2, do we get twice the reading.
5. The uniformity of reading over the surface, i.e. if the sensor is calibrated with a small laser beam in the center of the absorber, how much will this change if the beam is not centered or is large sized?
6. The pulse rate dependence in the case of pyroelectric sensors, i.e. how much does the reading vary depending on what is the pulse rate of the laser.
7. The calibration uncertainty of the display unit.
8. Damage done to the absorber surface
9. Electromagnetic interference

Before focusing on (1) and (2), the primary subject of this document, we will go over the other factors in measurement accuracy.

Wavelength: All absorbers used in power/energy measurement are not entirely flat spectrally, that is, they vary in absorption with wavelength. For this reason, Ophir measuring sensors are usually calibrated at more than one wavelength. If the absorption changes

[1] The term 'Calibration' is used in this document for both procedures that include adjustments and those that do not. 'Calibration uncertainty' always refers to measurements without adjustments.

only slightly with wavelength, then we define wavelength regions such as <600nm, >600nm and give a calibration within these regions. In that case, the error in measurement between the wavelength the device was calibrated for and the measurement wavelength is assumed to be within the primary wavelength calibration error. If the absorption difference between the nearest calibration wavelength and the measurement wavelength is larger than 1-2%, then either we add to the specification an error with wavelength in that region or calibrate over a continuous calibration curve covering all wavelengths in the region. In that case, the error in measurement between the wavelength the device was calibrated at and the various other wavelengths in the defined wavelength region is taken into account in the total error budget. If the absorption difference between the nearest calibration wavelength and the measurement wavelength is larger than 1-2% and cannot be accommodated in the total error, then we define a continuous calibration curve covering the variations at all wavelengths in the region.

Linearity: The linearity of Ophir sensors is always given in the published specification for thermal and pyroelectric sensors and the expected error due to nonlinearity is to be added to the basic calibration error as discussed below. Note that for thermal sensors, the linearity error is in general +/-1% or whatever is in the specification for that particular sensor. For photodiode sensors, the linearity error is not published but it is always less than ±1% except very close to maximum power. If the power level is less than 70% of maximum power for photodiode sensors, then the linearity will be within ±0.5%.

Uniformity: The uniformity of Ophir sensors is in general not given in the specification but in most cases it is ±2% maximum variation for beam position anywhere within the central 50% of the area of the aperture and is better than this in many cases. Since Ophir sensors are always calibrated with the beam centered on the absorber, if the measurement is made with the beam centered and the beam is not larger than 1/4 the aperture, this error can in most cases be ignored.

Pulse Rate and Pulse Width: Pyroelectric sensors have some pulse rate dependence. In general, the pulse rate dependence is low and for pulse rates less than about 70% of the maximum pulse rate. Near the maximum pulse rate you can expect the error to be near the maximum stated. Ophir design pyroelectric sensors have little pulse width dependence so this can usually be ignored.

Display: As can be seen below, in general, the error of calibration of the display is much smaller than the calibration uncertainty and accuracy of the measuring sensor (~0.3%) and therefore can be ignored in most cases in the combination of errors.

Damage Done to the Absorber Surface: Damage done to the absorber surface can effect the reading if the damage causes the absorption to change. One way to check this is to move the beam slightly away from the damaged area and to see if and how much the reading changes. When we specify damage threshold, at this value of power or energy density, there may be cosmetic damage causing some color change on the surface but our spec in general defines damage threshold as that power or energy density that causes a change of more than 1% in reading.

Electromagnetic Interference: Ophir meters and sensors are certified to meet CE requirements for susceptibility to and emission of electromagnetic radiation. At almost all frequencies of radiation of strength up to the limit prescribed by CE, one will not notice any interference. In rare cases, at specific frequencies, there may be some noticeable interference. We have specified the maximum interference that may be seen at any frequency to be less than 0.3% of the full power rating.

2. Combination of Errors and Total Error

Ophir published accuracy and calibration errors are in general 2 Sigma or K=2 error or otherwise using accepted statistical analysis based on guard bands[2]. That means that statistically, in 95% of cases, the error of the system measured will not exceed the stated error. For example, if the stated error is ±3%, then in 95% of the cases, the error will not exceed 3% and in 99% of the cases will not exceed 4%. The total expected error will be in the worst case, the sum of the various contributing errors.

Note that if a sensor is sent for recalibration, then a significant number of sensors can show variation between the first and second calibration more than the stated error. This is because the first time the sensor was calibrated, it may have been -2% error and the second time +2%. Both times, the sensor will be well within the stated ±3% error but will show a before/after variation of 4%.

If you are working at <70% of maximum power or pulse rate, the linearity error can be assumed to be random and if the beam is not larger than 1/4 the aperture and is centered, the uniformity error can be ignored. In that case you may use statistical combination of errors to compute expected total error. For instance if the stated linearity is ±1%, the stated pulse rate dependence is ±1% and the stated calibration error is ±3% then the 2 sigma total error can be taken to be $\sqrt{(0.03)^2 + (0.01)^2 + (0.01)^2} = 3.3\%$. If the pulse rate or power approaches the maximum permitted, then you must take the maximum value as the expected total error i.e. 0.03 + 0.01 + 0.01 = 5% in the above example. Since the display error is so low, it can be ignored in most cases.

3. Analysis of Power and Energy Calibration Errors

Thermal sensors

Ophir measurement sensors are calibrated first for power by substituting the sensor under calibration for the reference master sensor while holding the laser average power constant. The sensors are usually calibrated at two or three specified wavelengths.

At each wavelength, the sensitivity is measured at two or three powers and the sensitivity used for calibration is the average of the measured sensitivities. If the sensitivity varies more than the specified linearity limits, the sensor is disqualified.

The variation in absorption between wavelengths is not ordinarily more than ±2% within a wavelength region and therefore the user can usually just choose the power meter wavelength closest to his wavelength of use. For interpolation, the user can refer to spectral curves in the Ophir catalog.

Single shot energy is calibrated after the sensor is calibrated for power by first measuring the laser power on the sensor, then passing

[2] See documents ILAC-G8 'Guidelines on Decision rules and Statements of Conformity' and JCGM 106:2012 for an in depth explanation of guard bands and decision rules.

the same power for a set period of time and adjusting the reading to equal energy = power x time. The energy accuracy is not specified in our catalog specifications but it can generally be taken to be +/-5% .

4. Detailed Analysis of Power and Energy Calibration Errors

We now analyze how we arrive at the basic power and energy calibration errors as stated in our specification sheets.

Power and Energy Calibration Error and Accuracy Estimation (sensors for powers <1000W)

We use statistical combination of errors to estimate the various sources of calibration error and the total expected error from the various contributions, each device may have a slightly different accuracy based on its various parameters, below is a general estimation of thermal sensor calibration uncertainty and accuracy.

	Item		**Explanation**
1	Uncertainty of NIST calibration	±0.5%	From errors in calibration as stated by NIST in calibration report
2	Transfer of calibration from NIST master to working master	±0.3%	From statistics of deviations between calibration and independent check of calibration for this special calibration
3	Transfer of power calibration from working master to sensor under calibration	±1.0%	From statistics of deviations between calibration and independent check of calibration (RSS of silver master repeatability and UUT repeatability and silver master linearity)
4	Additional error from variation in absorption over wavelength region	±0.5%	From measured variations in absorption over defined wavelength region
	Combined power calibration error	±1.2%	From RSS combination of errors
	Total power calibration error	**±2.4%**	95% of cases are within 2.0 std deviations
5	Additional error in calibration of single shot energy	±1.1%	From statistics of deviations between calibration and independent check of calibration as well as estimated systematic errors
	Total energy calibration error Expanded error K=2.0 (95% confidence level)	**±3.2%**	95% of cases are within 2.0 std deviations

Pyroelectric sensors

Ophir pyroelectric sensors are calibrated for energy by substituting the sensor under calibration with the reference master sensor while holding the laser average power constant. The sensors are usually calibrated at two or three specified wavelengths. The master sensor is a thermal power measuring sensor and is measuring average power while the laser is held to an exact repetition pulse rate, usually

10Hz. Each device may have a slightly different accuracy based on its various parameters, below is a general estimation of pyroelectric sensor calibration uncertainty and accuracy.

Error Estimation

	Item		Explanation
1	Uncertainty of NIST calibration	±0.5%	From errors in calibration as stated by NIST in calibration report
2	Transfer of calibration from NIST master to working master	±0.3%	From statistics of deviations between calibration and independent check of calibration for this special calibration
3	Transfer of calibration from working master to sensor under calibration	±1.3%	From statistics of deviations between calibration and independent check of calibration (RSS of silver master repeatability and UUT repeatability and silver master linearity)
	Combined calibration error	±1.5%	From RSS combination of errors
	Total energy calibration error Expanded error K=2.0 (95% confidence level)	**±3.0%**	95% of cases are within 2.0 std deviations
	Additional error for diffuser type sensors	±0.4%	From comparison of calibrations between different calibration facilities
	Total energy calibration error for diffuser type sensors Expanded error K=2.0 (95% confidence level	±3.7%	95% of cases are within 2.0 std deviations

If the user measures at different energy levels than the calibration energy level, the maximum error is the published linearity limit, usually ±2% This linearity is determined by varying the energy at a given pulse rate and measuring the output versus an average power reading on a precision thermal sensor.

The sensor is calibrated with high accuracy at selected wavelengths. The variation in absorption between wavelengths for the BB (broadband) type sensors is not ordinarily more than ±5% and therefore the user can usually just choose the power meter wavelength closest to his wavelength If the user measures at wavelengths different from the calibration wavelengths, add the additional errors in the table given in the Ophir catalog for the particular type of sensor.

The metallic absorber sensors have a larger variation in absorption over the wavelength range (as much as 50%) and therefore the sensor has stored in it a wavelength curve which has been determined both by spectrophotometer measurements and by measurements at various laser wavelengths. For each sensor, this curve is corrected at two or three points and the calibration curve is then “stretched” to fit the test wavelengths, changing the intervening wavelengths proportionately. The Ophir catalog gives the estimated maximum additional error in calibration for measurement at various wavelengths.

To get the total expected error, you must combine the calibration, linearity, wavelength and pulse rate errors as described in section 2 above.

Photodiode sensors

Ophir photodiode sensors are calibrated first for power by running an automated spectral scan of the NIST traceable sensor at intervals of ~5nm over the spectral range then a scan of the sensor under calibration for the same spectral range. The sensor scan is done twice, with filter out and filter in. The sensor is then calibrated automatically by the data thus gathered. Note that the light source is monitored and small fluctuations in intensity between scans are compensated for.

After the above process, the calibrated sensor is checked against the master at several individual wavelengths of a laser or spectral lamp source. The wavelengths include points near the center of the spectrum, near the edges of the spectrum and points in between. If the discrepancy between the master and sensor is more than the specified tolerance at that wavelength, the calibration is disqualified.

Photodiode sensors have a uniformity of ±2% over 50% of the aperture.

Since photodiode sensors are very linear and are calibrated continuously over the entire spectrum, the total error can in general to be taken as the calibration error without adding any additional errors as long as the beam is well centered on the detector. Each device may have a slightly different accuracy based on its various parameters, below is an estimation of photodiode sensor calibration uncertainty and accuracy for the standard PD300-UV sensor.

Error Estimation for PD300-UV (for filter out and filter in setting)

	Item	Wavelength range					Explanation
		200-230nm	230-285nm	300-420nm	420- 1000nm	1000 – 1100nm	
1	Variation from one NIST calibration to the next	±2.1%	±1.0%	±0.6%	±0.3%	±1.5%	From errors in calibration as stated by NIST in calibration report
2	Transfer of calibration from NIST master to working master	±1.5%	±0.9%	±0.5%	±0.3%	±0.4%	From statistics of deviations between calibration and independent check of calibration for this special calibration
3	Transfer of power calibration from working master to sensor under calibration (filter out)	±3.7%	±1.15%	±0.9%	±0.8%	±2.45%	From statistics of deviations between calibration and independent check of calibration. Long wavelength variation includes temp variations RSS of silver master repeatability and UUT repeatability
	Transfer of power calibration from working master to sensor under calibration (filter in)		±3.65%	±1.5%	±1.1%	±1.9%	From statistics of deviations between calibration and independent check of calibration (RSS of silver master repeatability and UUT repeatability)
5	Combined power calibration error – filter out	±4.6%	±3.26%	±1.2%	±0.9%	±2.9%	From RSS combination of errors
	Filter in		±3.9 %	±1.7%	±1.2%	±2.9%	
6	**Total power cal error** Expanded error K=2.0 (95% confidence level) filter out	**±9.2%**	**±6.6%**	**±2.4%**	±1.8%	±5.8%	95% of cases are within 2.0 std deviations

	Filter in		±7.8%	**±3.4%**	±2.4%	±5.8%

Radiometers

Radiometers measure irradiance in W/cm^2 or energy dosage in J/cm^2. Ophir radiometers are based on our standard Photodiode calibration with apertures that have calibrated diameter. They also have cosine correctors to ensure uniform measurements of light that is incident at many angles, The additional error in measurement of the radiometer is due to uncertainties in aperture size and deviations from ideal cosine response.

Displays

Ophir displays are calibrated with an automated calibration unit which consists of a precision voltage source and a set of switchable precision resistors. This unit injects known currents into the display under calibration in an automated system. The reading of the display is compared to the known current and appropriate correction factors are stored in the display so that the reading will be the same as the known current. This is done for all 16 ranges of the display, where the zero offset is measured and compensated for in each range. At final QC, the calibrated display is tested against a different calibration unit and it must pass on all ranges within the specified limits.

The calibration unit itself is calibrated periodically at an accredited calibration laboratory.

Error Estimation for Display Calibration

	Item		**Explanation**
1	Variation from one calibration of calibration unit to the next calibration	±0.05%	From errors in calibration as stated by Standards lab calibration report
2	Transfer of calibration from calibration unit to display	±0.08%	From worst case permissible error on final QC test on calibrated unit at 100% confidence level.
	Total display calibration error Expanded error K=2 (>95% confidence level)	**±0.19%**	95% of cases are within 2 std deviations

Revised 15 July 2020