

Radiometric and Actinometric Traceability for Photopolymer Processing

Irradiance, spectral dose, geometry and calibration transfer

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Abstract

Photopolymer processes are often described by an irradiance, exposure time and nominal wavelength. Those quantities are not sufficient to establish what radiation reached a sample. Detector responsivity, spectral bandwidth, spatial non-uniformity, angle, distance, window transmission, temporal modulation and sample geometry can produce different exposures while the displayed settings remain identical. Chemical actinometers add a valuable reaction-based measurement but do not remove these dependencies; they introduce their own absorption, quantum-yield, conversion and analytical boundaries.

This review develops a traceability architecture for radiation used in photopolymer processing. It distinguishes spectral irradiance, band-integrated irradiance, radiant exposure, spectral photon exposure and chemically measured photon quantity. It connects national-scale spectral-irradiance calibration to working instruments, sample-plane mapping and in-process checks while preserving uncertainty at every transfer. Radiometers and actinometers are treated as complementary: the former measures a physical radiation field through a calibrated responsivity, whereas the latter reports a photochemical response under a defined spectral and geometrical condition. The review proposes procedures for spectral mismatch, pulsed or modulated sources, imaging systems, area mapping and cross-platform transfer. The central conclusion is that an exposure setting becomes comparable only when the measurand, plane, spectrum, geometry, timing and uncertainty are fixed.

Keywords: radiometry; actinometry; spectral irradiance; radiant exposure; photon flux; calibration; traceability; uncertainty; vat photopolymerisation; LED

1. Significance and scope

Radiation is a process input, but it is measured through an instrument whose spectral and geometrical response may differ from that of the resin. A broadband radiometer can display the same value for two spectra that deliver different absorbed photon rates to a photoinitiator. A point measurement can miss spatial structure in an imaging engine. A value measured at an accessible window can differ from the field at the resin plane.

Traceability is an unbroken calibration chain with stated uncertainties, not a brand name or a recent calibration sticker. Its engineering purpose is to make the measurement result refer to a defined quantity and location.

1.1 Corpus boundary

ER-203 owns radiometric and actinometric traceability at a declared time. ER-174 owns longitudinal degradation of light engines and consumables. ER-181 owns post-cure chamber dose delivery and process engineering. ER-035 owns interpretation of working-curve parameters, and ER-002 owns broader cross-platform process equivalence. ER-202 owns the link from absorbed photons to photoinitiator action.

2. Define the optical measurand

Spectral irradiance $E_{e,\lambda}$ is radiant power incident per unit area and wavelength interval. Band-integrated irradiance is:

$$E_e = \int_{\lambda_1}^{\lambda_2} E_{e,\lambda} d\lambda$$

For a time-dependent source, spectral radiant exposure is:

$$H_{e,\lambda} = \int_{t_0}^{t_1} E_{e,\lambda}(t) dt$$

and spectral photon exposure follows from photon energy:

$$H_{p,\lambda} = H_{e,\lambda} \frac{\lambda}{hc}$$

These quantities are defined at a plane, over an area and within a geometry. A reported “dose” without those qualifiers is incomplete. For an imaging system, pixel or local-area exposure may be the relevant measurand; for a flood source, an area average and its non-uniformity may be required.

3. SI traceability and calibration hierarchy

NIST SP 250-89 describes realisation and dissemination of a spectral-irradiance scale traceable to electrical power through an electrical-substitution cryogenic radiometer and to length through aperture area and distance measurements [1]. An industrial laboratory normally does not reproduce that realisation. It uses a calibrated standard lamp or detector, a transfer instrument and documented comparison conditions.

A practical hierarchy is:

- 1 national or accredited spectral-irradiance reference;
- 2 calibrated transfer standard with certificate and uncertainty;
- 3 working spectroradiometer or radiometer compared under controlled geometry;
- 4 sample-plane measurement or validated transfer from an accessible plane; and
- 5 routine checks with stable controls.

Every transfer adds uncertainty. A working meter's calibration at one spectrum and geometry does not make all later readings traceable if spectral mismatch, range, angular response or temperature are uncontrolled.

4. Spectral mismatch

A broadband detector reports a weighted integral of the incident spectrum:

$$\int S = \int E_{\lambda}(\lambda) R(\lambda) d\lambda$$

where $R(\lambda)$ is its spectral responsivity. Two instruments with different $R(\lambda)$ can disagree even when both function correctly. A scalar correction derived from one source may fail when the source spectrum changes with temperature, drive current or position.

The preferred route is to measure the spectrum with a calibrated spectroradiometer and calculate any band-integrated value from the recorded data. When a broadband working meter is necessary, its calibration should use a sufficiently similar spectrum, and a spectral-mismatch correction and uncertainty should be documented.

5. Geometry and plane transfer

Distance, source size, divergence, angle, aperture and intervening optics affect irradiance. The inverse-square law applies to an ideal point source in free space; it is not a general transfer rule for extended LEDs, collimated systems or near-field imaging engines. A reading above a vat window cannot be assigned to the resin plane without window transmission, reflection, angle and spatial structure.

The measurement plane should be located by a physical datum. Detector active area and acceptance angle should be compatible with the optical field. If the detector replaces the vat or build plane, the disturbance to optical distance and interfaces should be evaluated. A transfer fixture should control lateral position, height and orientation.

6. Spatial and angular mapping

Caplins and co-workers mapped irradiance, spectral characteristics and optical divergence across a nominally 405 nm LCD-based vat-photopolymerisation light engine and found position-dependent differences large enough to affect polymerisation and surface texture [3]. A centre-point reading therefore cannot represent an imaging plane by default.

A map should specify grid spacing, detector footprint, edge treatment, warm-up, sequence and correction for drift during the scan. Report the mean, extrema and a uniformity metric, but retain the map because equal summary statistics can hide different spatial structures. Angular divergence may matter even when scalar irradiance is uniform, especially through masks, windows or resin interfaces.

7. Temporal behaviour

Exposure time multiplied by one irradiance reading is valid only when irradiance is stable and the timing definition matches the optical output. LED drivers may use pulse-width modulation, ramps or frame sequences. Shutters and projectors have latency. A slow detector can display an average while missing peak power or duty-cycle errors.

Temporal characterisation should record optical onset, waveform, repetition rate, duty cycle and exposure integration. For pulsed sources, specify whether reciprocity is assumed and whether the chemistry responds to peak intensity. Radiant exposure remains a physical integral, but equal exposure does not guarantee equal cure when kinetics are intensity dependent.

8. Chemical actinometry

A chemical actinometer converts absorbed photons into a measurable chemical change with a known quantum yield over a stated range. If product amount nP and quantum yield Φ_P are valid under the experiment, the absorbed photon amount is related by:

$$n_{ph,abs} = \frac{nP}{\Phi_P}$$

IUPAC guidance emphasises selection of an actinometer appropriate to wavelength, conversion, geometry and analytical method [2]. Actinometry is not universally source independent. The actinometer's absorption spectrum weights the source; its quantum yield can depend on wavelength, temperature and conversion; and inner-filter or mixing effects can matter.

An actinometer is particularly useful for validating an integrated photochemical exposure within a reactor geometry that is difficult for a detector. It should not be used to infer a full spectral distribution unless the experiment is designed to resolve it.

9. Radiometry and actinometry are complementary

Radiometry measures the physical field through calibrated detector responsivity. Actinometry measures a chemical response through calibrated photochemistry. Agreement within uncertainty can validate an exposure model. Disagreement can reveal spectral mismatch, geometry, incomplete mixing, actinometer degradation or detector limitations.

The two results should not be forced to match by an undocumented scale factor. First confirm that they refer to the same plane, time interval and absorbed or incident quantity. A radiometer may measure incident radiation while the actinometer reports absorbed photons.

10. Uncertainty budget

An uncertainty budget should include calibration certificate uncertainty, spectral interpolation, wavelength accuracy, linearity, dark signal, stray light, angular response, detector-area definition, positioning, temporal sampling, source repeatability, spatial sampling and plane-transfer corrections. Actinometry adds quantum-yield, concentration, path length, product-analysis, conversion and temperature terms.

For radiant exposure calculated from repeated samples, correlation matters: a shared calibration uncertainty does not decrease with more map points. Random spatial sampling error and common systematic uncertainty should be kept separate.

11. Calibration transfer between laboratories

Cross-laboratory transfer should use a travelling standard or a stable source–detector pair, fixed geometry and a shared analysis script. A transfer exercise should include:

- 1 certificate and pre/post transfer checks;
- 2 mechanical drawings or datums for the measurement plane;
- 3 raw spectral and temporal data;
- 4 detector responsivity or correction model;
- 5 a spatial map or justified sampling plan;
- 6 uncertainty budgets using common quantity definitions; and
- 7 a discrepancy rule defined before results are revealed.

A printer setting should not serve as the travelling standard. It is the object being measured.

12. Interpretation matrix

Observation	Supported interpretation	Unsupported leap
Calibrated spectral irradiance at the sample plane	Physical radiation field is quantified within stated uncertainty	Resin receives the same absorbed photon rate everywhere
Equal band-integrated irradiance from two sources	Total radiant power per area in the defined band is equal	Spectra or photochemical effectiveness are equal
Actinometer product agrees with prediction	Integrated chemical photon accounting is consistent under that actinometer's conditions	Every photoinitiator receives an equivalent exposure
Centre reading is stable	One position is temporally stable	Whole imaging area is uniform
Equal radiant exposure at different peak intensities	Physical energy per area is equal	Polymerisation response is equal

13. Minimum reporting set

Report quantity and units; wavelength interval; calibration chain and date; detector or actinometer identity; plane, area, distance, angle and optics; source spectrum, warm-up and drive mode; temporal integration; spatial sampling; raw-data reduction; mismatch and plane-transfer corrections; uncertainty and coverage; and whether the result is incident, transmitted or absorbed.

14. Knowledge boundary

Traceable radiometry can establish the radiation field, not the resulting polymer state. Actinometry can establish a chemical photon measure for a declared reaction, not a universal cure dose. Complex scattering formulations and dynamic optical changes may require coupled optical and chemical measurements beyond a single plane.

15. Limitations

This review does not prescribe calibration intervals, printer maintenance thresholds or post-cure chamber recipes. Calibration frequency must reflect stability evidence and risk. It does not address laser-safety controls or biological exposure limits.

16. Conclusions

An exposure setting is comparable only after the measurand, spectrum, plane, geometry, time and uncertainty are declared. Spectroradiometry provides the most direct route to wavelength-resolved physical traceability; broadband meters are useful working instruments when mismatch is controlled; actinometers provide complementary chemical integration within their validated range. Spatial and temporal mapping are essential for modern imaging engines. These elements turn nominal irradiance and time into a defensible exposure record without confusing radiation delivery with cure outcome.

References

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