Module Scale Electroluminescence of PV devices: Measurements and Image Quality

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Abstract

Electroluminescence (EL) imaging is a fast and comparatively cheap method for spatially-resolved and non-destructive analysis of photovoltaic (PV) devices. To enable a quantitative use of captured images and support a common standard on EL measurements, this paper focusses on parameters defining the quality of EL images. The image quality is determined and tracked for different EL measurements during various processing steps. It is shown, that although simple post processing methods, e.g. spatial filters, can enhance the visual appearance of EL images, they do not improve the quality of the signal itself.

1. Introduction

Electroluminescent emission from a PV device differs significantly from the captured signal of the CCD camera due to distortions within the camera sensor or lens. However, methods to quantify and enhance the quality of EL images or to relate the camera and EL signal are generally not utilised or described. When they are employed, they differ widely from each other and follow no common standard. In order to assess the measurement uncertainty of parameters derived from EL images, this article discusses the parameters that are required to define the image quality as relative signal distortion (RSD): signal-to-noise ratio (SNR), signal range (SR) and intensity manipulation ratio (IMR). Last but not least, the effects of typical image processing methods on those parameters are demonstrated and discussed.

2. Signal-To-Noise Ratio (SNR)

The signal-to-noise ratio (SNR) represents the quality of the captured signal (here EL) over a noise signal. Depending on the definition of signal and noise, different approaches to calculate the SNR are available. In the simplest form the signal can be described as the mean pixel value of an image I divided by its standard deviation [1]:

$$SNR_0 = \frac{\bar{I}}{\sigma_I} \tag{1}$$

<u>Using a defined background area</u>

For image based SNR values the noise can be defined as a combination of shot-, thermal- and readout noise. For every pixel signal x_i the SNR can be calculated using the average of a representative dark or background area $\bar{x}_{BG}$ of the image as well as its standard deviation σ_{BG}. In this case [2] defines the SNR as:

$$SNR_{BG} = \frac{\sum_i (x_i - \bar{x}_{BG})}{i \cdot \sigma_{BG}} \tag{2}$$

However, this approach requires the location of a representative background-area to be known. Additionally erroneous/'hot' pixels have to be removed from the background area in order not to overestimate σ_{BG} and therefore decrease SNR.

<u>Using two similar images</u>

As discussed in [3] the noise can also be determined as the difference between two images I_1 and I_2 of the same setup captured with the same excitation time. Therefore Equation (1) can be rewritten as:

$$SNR_{diff} = \frac{\bar{I_1}}{\sigma_{(I_1 - I_2)}} \tag{3}$$

<u>Using the histogram</u>

The histogram of most EL images allows a separation of signal and (background) noise due to the two different intensity levels. These levels can be approximated as maximum of two Gaussian distributions. In this case the SNR can be expressed with the EL signal and background peak positions μ_{EL}, μ_{BG} and the standard deviation of the background peak σ_{BG} as follows:

$$SNR_{hist} = \frac{\mu_{EL} - \mu_{BG}}{\sigma_{BG}} \tag{4}$$

The background/noise peak will also include areas around the DUT irradiated by environmental light or by reflected EL light. This can lead to an asymmetric distribution and a decreased SNR, which is as should since those are unwanted signals.

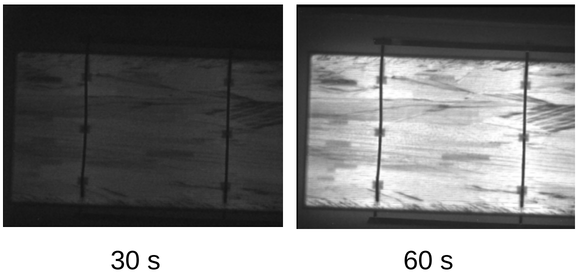


Figure 1: EL image of an EFG mini module for two different excitation times

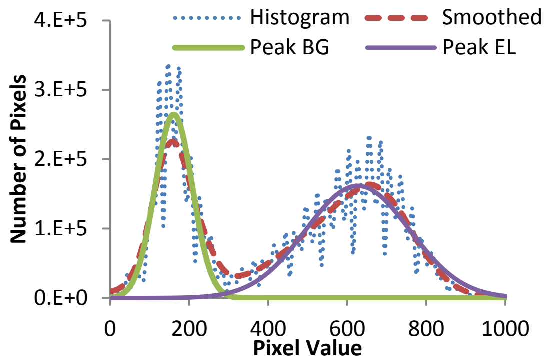


Figure 2: Histogram of Figure 1 (left). Trend fitted using two Gaussian distributions.

As visible in Figure 2, the histogram needs to be smoothed to supress secondary peaks and to detect initial peak positions for the fitting procedure.

<u>Comparison of different SNR approaches</u>

In order to suggest a SNR parameter suitable for EL measurements, the mentioned approaches are compared using a set of measurements of the device under test (DUT) seen in Figure 1 at different excitation times. Results in Figure 3 show that the SNR differs greatly between the different methods. This underlines the importance of using one standardised method for characterising EL images.

With its steady trend the simple SNR_0 is unsuitable for characterisation. A major criterion for choosing the right parameter is derived from the definition of noise:

If confined to camera based noise sources SNR_d parameters using the differences of two images might be best.

If noise is to be defined by the background of an EL image it should be made clear whether to represent as:

- Area of fixed size at the border of an EL image that is not influenced by the EL signal, or as
- First peak within the smoothed histogram of an EL image (which would also include EL reflections around the DUT).

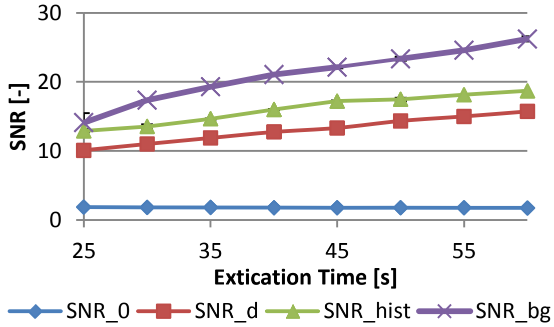


Figure 3: Comparison of different methods to estimate SNR using a set of EL measurements with variable excitation times

3. Signal Range (SR)

Although EL images can have a bit depth of 8 to 16 bit, giving 255 to 65535 possible pixel values, the difference in signal between the sample EL and the background is less. The following equation quantifies the signal range (SR) as difference of EL and averaged background signal:

$$SR_i = \Phi_{EL,i} - \bar{\Phi}_{BG} \qquad \textbf{(5)}$$

Assuming a normal distribution of the different EL signals within the image, the spatial averaged SR can be determined as follows:

$$SR_{hist} = \mu_{EL} - \mu_{BG} \qquad \textbf{(6)}$$

Figure 4 compares exemplary SR_{hist} and SNR_{hist} for the DUT shown in Figure 1 for variable excitation times. Due to the linearity of the camera sensor the trend of the SR is linear. However, EL reflections within the measurement chamber increase σ_{BG} and therefore decrease the SNR.

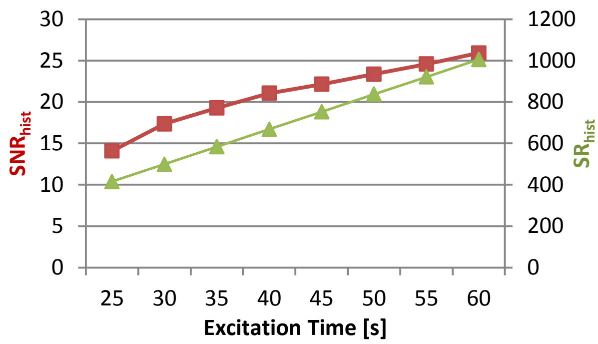


Figure 4: Comparison of SNR and SR for the DUT shown in Figure 1 at different excitation times

<u>Quantisation error</u>

The quantisation error of a signal digitized between two discrete states e.g. 0 and 1 is its mean: ± 0.5 [4]. If the signal range is much bigger than the discretization states, a uniform distribution of all values within the range can be assumed. In this case the standard deviation becomes $\frac{1}{\sqrt{12}} \cong 0.289$ [4]. An increasing value range decreases the relative distance between the discrete states.

Normally this error is based on the absolute signal, respectively the image intensity, and can be neglected at high bit depths of EL cameras. Nevertheless, the usable signal needs to be scaled within the SR and therefore the standard quantization or round-off error QE should be expressed as:

$$QE = \frac{1}{\sqrt{12} \cdot \mathrm{SR}} \quad \textbf{(7)}$$

4. Intensity Manipulation Ratio (IMR)

Every image correction method modifies the signal information to a certain extent. This change can be evaluated using the average of a normalised differential image $\overline{\Delta I_n}$. The manipulated Image I_m as well as its origin I_{orig} needs to be normalised using their respective values for μ_{BG} and μ_{EL-max}:

$$I_n = \frac{I - \mu_{BG}}{\mu_{EL-max} - \mu_{BG}} \quad \textbf{(8)}$$

$$IMR = \overline{\Delta I_n} = \overline{|I_{n,m} - I_{n,orig}|} \quad \textbf{(9)}$$

5. Image Quality as Relative Signal Distortion (RSD)

The signal quality of EL images can be derived using the relative signal distortion (RSD), which ultimately describes part of the imaging uncertainty. However, it is not possible to describe the full uncertainty of EL measurements only using the resulting EL images because systematic effects from background radiation, readout noise, lens and perspective distortion as well as variations in the power supply of the DUT and thermal effects remain unknown.

Assuming the parameters mentioned so far are independent and uncorrelated, the relative signal distortion is defined as:

$$RSD = \sqrt{SNR^{-2} + N_{shot}^{-2} + QE^2 + IMR^2} \quad \textbf{(10)}$$

where ${N^{-1}}_{shot}$ represents the Poisson- or shot noise as described in [5]. If signal and noise within the SNR are distributed normally its inverse represents the standard deviation of noise relative to the signal.

6. Comparing the Image Quality of processed EL images

To validate the concept of describing quality of EL images as a combination of the above mentioned effects, EL images of different PV devices were compared before and after the application of common image enhancing methods, like denoising and hot pixel removal (Figure 5). For the purpose of automation, the signal intensity and standard deviation of EL signal and background were determined using the histogram based method as explained in Section 2. All images were processed as follows:

<u>Step 1:</u> EL image as captured. Image intensity given in arbitrary units (A.U.).

<u>Step 2:</u> ‘Hot’ / erroneous pixel removal using a thresholded median filter [6, 7]. Pixels were set to their median if the relative difference exceeded 10 % of their neighbouring pixels.

<u>Step 3:</u> Denoise using a spatial median filter (kernel size = 3).

<u>Step 4:</u> Downscaling of all image values in order to save the image in a common 8-bit image format. Minimum set to μ_{BG}, maximum set to $\mu_{EL-max} \approx \mu_{EL} + 3 \cdot \sigma_{EL}$. Values were bounded from 0 to 255.

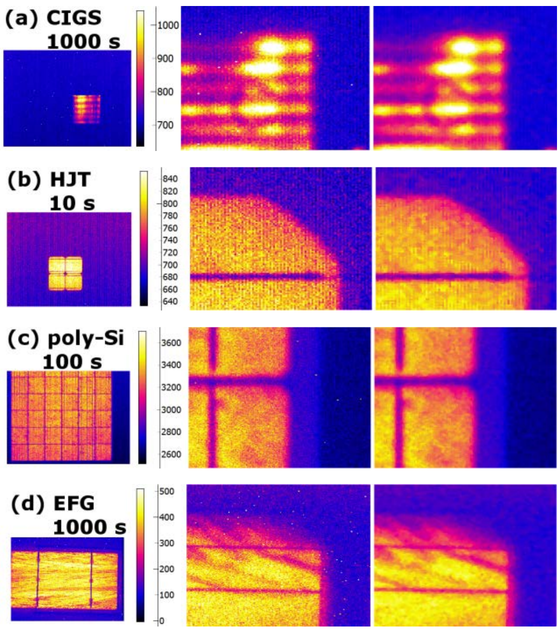
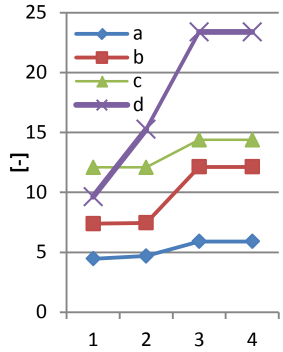
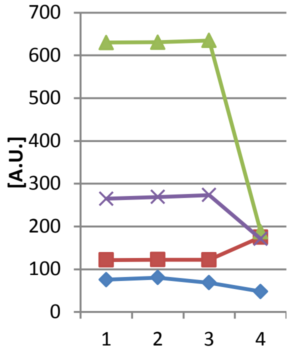


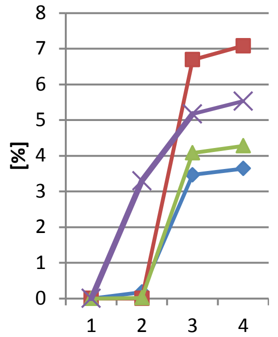
Figure 5 Examined EL images of four different devices, captured under different excitation times. Left: total, middle: detail, right: detail after post processing (Step 3)



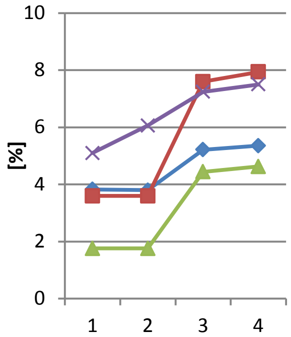
(A) Signal-to-noise ratio (***SNR***)



(B) Signal range (***SR***)



(C) Image manipulation ratio (***IMR***)



(D) Relative signal distortion (***RSD***)

Figure 6: Resulting parameters for step 1-4 as described in Section 6

7. Results and discussion

Figure 6 displays the effect of the image enhancing steps 2-4 for the presented parameters. All applied processes increase the IMR and to a different extend the RMD (Figure 7.C-D**Error! Reference source not found.**). Particularly:

Step 2: The thresholded median as a selective filter only removes high gradients. Except of DUT (d) with its comparable low signal and high signal variations the IMR stays low (Figure 8.C).

Step 3: It can be seen, that denoising/smoothing filters can be used to artificially increase the SNR (Figure 9.A). This could give the impression that this method is sufficient for decreasing the signal distortion as well. However, spatial filters remove information from images. Consequently the IMR increases between steps 2-3**.**

Step 4: All images have a bit depth of 16 bit which allows signal intensities up to 65536. However, the chosen images show that the EL signal with maximum values between 500-3600 is far below that. If rescaled, the IMR can be slightly increased when parts of the unwanted background signal are removed as done in step 4 for out-of-bound values and for values that are rounded when the image is saved to file.

Conclusion

This article underlines the differences between various approaches to determine signal-to-noise-ratio (SNR) and proposes a novel and automatable method for determining the SNR from one image without the need for defining a representative background area. With the signal range (SR) another source for calculating the quantisation error is given. The article discusses the need of tracking the image quality to allow a realistic evaluation on the imaging error introduced by the image itself or during post processing. The application of common image enhancing methods increased the SNR about 2 to 14 counts. However, these methods also distorted the signal about 1 to 4 %, decreasing the quality of the examined images. Measuring the image quality will led to better repeatability and comparability on EL images and systems, paving the way for future quantitative EL analysis.

References

[1] F. D. van der Meer and S. M. de Jong, *Imaging Spectrometry: Basic Principles and Prospective Applications*. Springer Science & Business Media, 2007, p. 403.

[2] J. M. B. Jerrold T. Bushberg, *The Essential Physics of Medical Imaging*. Lippincott Williams & Wilkins, 2011, pp. 91–92.

[3] J. Mullikin, L. van Vliet, and H. Netten, “Methods for CCD camera characterization,” in *H.C. Titus, A. Waks (eds), SPIE vol. 2173, “mage Acquisition and Scientific Imaging Systems,”* vol. 2173, 1994, pp. 73–84.

[4] W. Kester, “MT-001: Taking the Mystery out of the Infamous Formula,‘SNR = 6.02N + 1.76dB,’ and Why You Should Care.” Analog Devices, pp. 1–7, 2008.

[5] D. Dussault and P. Hoess, “Noise performance comparison of ICCD with CCD and EMCCD cameras,” *Proc. SPIE*, vol. 5563, pp. 195–204, Oct. 2004.

[6] M. Bliss, X. Wu, K. Bedrich, T. R. Betts, and R. Gottschalg, “Spatially and Spectrally Resolved Electroluminescence Measurement System for PV Characterisation,” in *IET-RPG, accepted 2015*.

[7] M. Bokalič, J. Raguse, J. R. Sites, and M. Topič, “Analysis of electroluminescence images in small-area circular CdTe solar cells,” *J. Appl. Phys.*, vol. 114, no. 12, p. 123102, 2013.