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Bringing the Digital Camera to the Physics Lab

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We discuss how compressed images created by modern digital cameras can lead to even severe problems in the quantitative analysis of experiments based on such images. Difficulties result from the nonlinear treatment of lighting intensity values stored in compressed files. To overcome such troubles, one has to adopt noncompressed, native formats, as we examine in this work.

Linearity is a well-known issue in an extremely wide field of concern when dealing with measurement techniques in science. There are of course countless circumstances in which linear response (i.e., the direct proportion relating input versus output signals) is suited for modeling a given phenomenon. It is also evident that the analyzing apparatus itself needs to behave in a linear way if one wants to reproduce the actual response of the experiment at issue.

Here we address the behavior of light sensors, which are the active core of modern digital cameras. These devices, usually referred to as CCDs (charge-coupled devices¹), are built with solid-state materials coupled to appropriate electronic circuitry capable of providing a linear response in terms of the input light, i.e., the number of photons.² A feature that is familiar to most photography professionals as well as to astronomers,³ but much less to physics and science educators or to nonprofessional photographers, is that video or image recording hardware has built-in software that compresses the output video or image. All of us obviously appreciate the memory saving coming from JPEG compression. Depending on the native image size, related to the number of CCD single sensors/pixels, the produced file can be squeezed down from many to some megabytes, the reduction factor also being a function of the specific compression algorithm and of the specific nature of the image. As a welcome result, it is possible

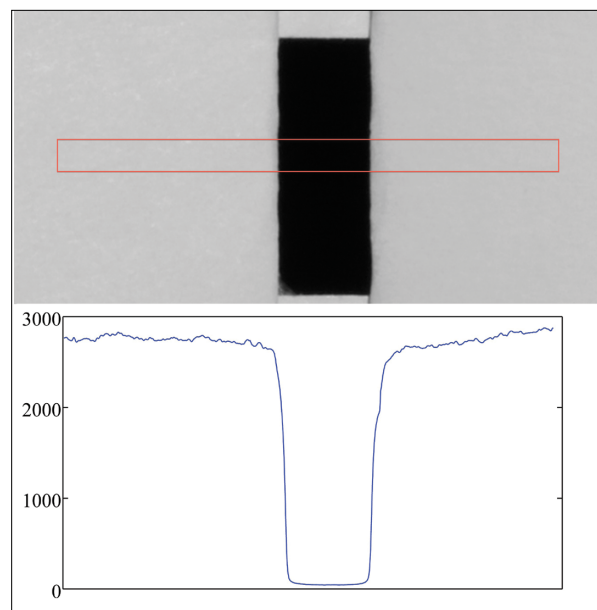


Fig. 1. A “black hole” cut in a sheet of white paper (upper part) and its intensity profile (lower part) averaged through the red rectangle (size about 1000 x 50 pixels, 12 bit). Exposure values: 1 s, f/16.

to accommodate many more images in a single digital memory card or hard disk. Yet, there is a counterpart to this advantage: JPEG compression algorithms, as well as other kinds of digital image processing addressing the aspect of size reduction, act in a nonlinear way on the stored information. More specifically, one observes that in conditions of wide changes of light exposure, the JPEG file does not reproduce linearly these changes or, equivalently, in the case of doubling/halving of light intensity, the JPEG file does not lead to doubling/halving of values associated with the digital information ex-

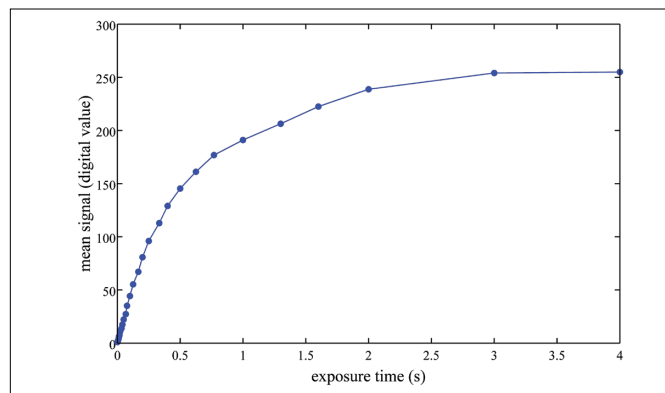


Fig. 2. Digital light signal as a function of exposure time for a white sheet of paper (see text). JPEG, 8-bit, compressed format. All shots taken at f/16.

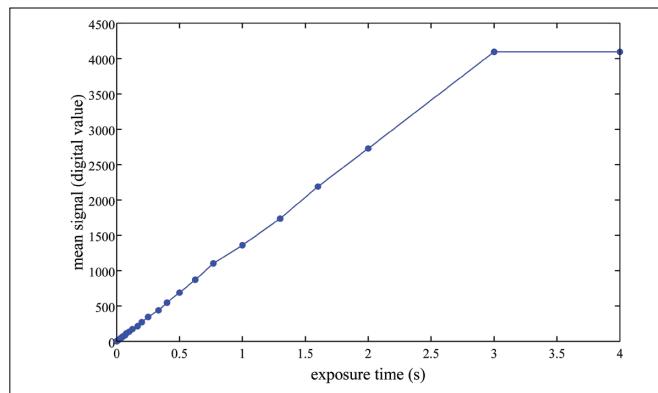


Fig. 3. Digital light signal as a function of exposure time for a white sheet of paper (see text). RAW, 12-bit, uncompressed format. All shots taken at f/16.

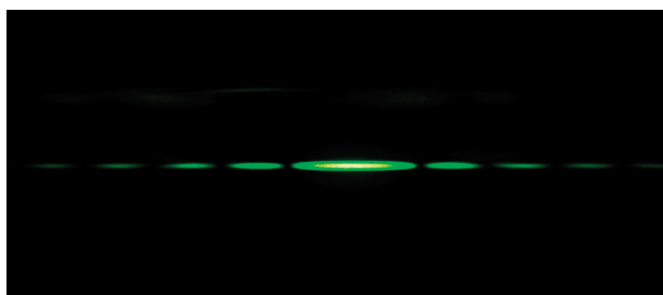


Fig. 4. Single-slit diffraction image.

pressing the image.

To show how these problems happen, we have taken a series of pictures⁴ of a hole cut in a sheet of white paper, covering a black box. A typical shot is shown in Fig. 1, along with the light intensity profile obtained with a freeware photo editing software, ImageJ (rsbweb.nih.gov/ij/). The intensity values span ranges from 0 to 2^n , where n is the number of bits adopted in the image digitalization. These values have been determined by adopting an averaging rectangular window as that shown in Fig. 1, whose size is of the order of 1000×50 pixels. We took several pictures with the corresponding “white” pixel values of Fig. 1 at various exposure times with fixed diaphragm at $f/16$. We plot in Fig. 2 the sequence of average “white” intensities for JPEG images when the exposure values—here time of exposure—change in a linear way. We see in this plot a marked departure from linearity. Yet the very same photographs, saved in an uncompressed (RAW) format, show a completely different behavior, as depicted in Fig. 3, where linearity is preserved. In both pictures, Figs. 2 and 3, the plotted data are affected by a very low statistical error, which is not shown. Moreover, notice the different ranges of the two plots, corresponding with 8- and 12-bit depths for JPEG and RAW formats: associated saturation values are 256 and 4096, respectively.

How could this phenomenon affect science educators’ lives? Pretty seriously, indeed. Digital cameras are nowadays and for quite a number of years a standard measuring device in didactic laboratories.⁵ Suppose we need to track the position of a mass moving under the action of gravity: a long time exposure along with a stroboscopic light unit, exactly as in the past of analog photography, will do the job. But suppose we need to make a quantitative measurement in which the intensity of light is of concern. We could be interested, for instance, in the determination of how light energy varies with the distance from the source or how electromagnetic radiation is dispersing its intensity through a prism or a diffraction grating.

We will consider here how problems in analysis can arise if one does not account for a possible nonlinear behavior of the camera/software instrument in a typical, well-known situation taken from standard case studies in optics.

As a specific example, we address the diffraction of light through a single slit of width a . The intensity for monochromatic radiation of wavelength λ observed at the angle θ is

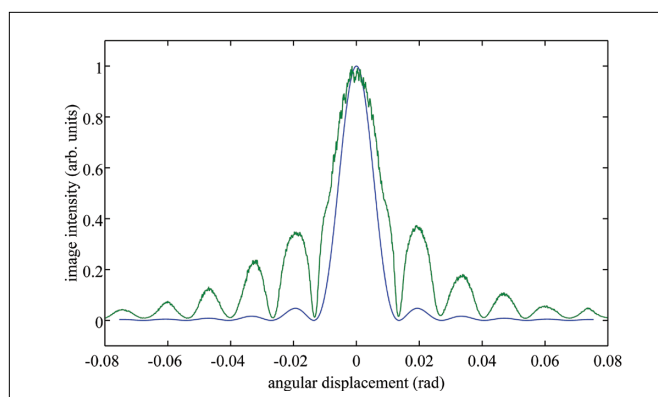


Fig. 5. Comparison between computed intensity diffraction curve [Eq. (1), blue line] and observed JPEG image (green line, taken from photo of Fig. 4, 8-bit version).

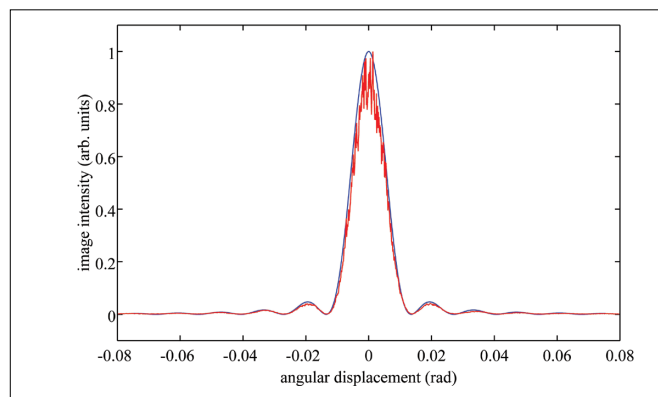


Fig. 6. Comparison between computed intensity diffraction curve [Eq. (1), blue line] and observed RAW image (red line, taken from photo of Fig. 4, 12-bit version).

given by

$$I(\theta) = I_0 \left[\frac{\sin\left(\frac{\pi a}{\lambda} \sin \theta\right)}{\frac{\pi a}{\lambda} \sin \theta} \right]^2. \quad (1)$$

We made a straightforward measurement of an actual diffraction through a slit ($a = 4 \times 10^{-5}$ m) with a HeNe laser beam, green line at $\lambda = 542$ nm. A typical result is shown in Fig. 4. The technique to obtain intensity values is the same adopted for the “black hole/white paper” of Fig. 1 and discussed above.

In Fig. 5 we show the computed pattern of Eq. (1) along with the observed values emerging from the digital JPEG file associated with Fig. 4. A noticeable disagreement between computation and observation appears here. Such a disagreement is to be ascribed to the fact at issue in this work, i.e., that the JPEG image is affected by nonlinear pixel treatment in terms of their values at different exposure levels. If we had used the JPEG version of Fig. 4 to compute a numerical table giving intensities of light diffraction maxima, results would have been seriously “wrong” for post-processing reasons and not for other kinds of instrumental and procedural mistakes.

We can also see from Fig. 5 that the widths of the diffraction peaks (FWHM, for example) do not agree with the computed values, once again for the very same reason as above.

As already suggested in this work, the solution to this problem consists of avoiding a compression treatment of the native (RAW) file produced by the CCD/electronic amplifier. The unmodified file, even if expectedly larger than the compressed one, is a linear representation of the actual light intensity coming from the photographed image, as already discussed when comparing Figs. 2 and 3. This can clearly also be seen in Fig. 6, in which we compare the theoretical pattern of Eq. (1) with the observed uncompressed RAW file coming from the same digital camera. We stress that the used photo is always that shown in Fig. 4, i.e., the same as that analyzed in Fig. 5, the only, key difference being the compression format.

Similar conclusions can be drawn for other quite typical standard optics experiments at the introductory high school or college level. We mention, for example, the quantitative study of line spectra coming from a dispersing device such as a prism or a diffraction grating. In this case one has to be very careful in considering how the different wavelengths building the spectrum are treated by the sensing device. In the case of nonprofessional digital cameras, the CCD has a highly linear response for the independent RGB pixels, which are the same physical sensors covered with different colored filters. As a result, with the aim of avoiding false intensity measurements of peaks at various wavelengths, it is very much appropriate to use RAW files that are the superposition of the three RGB components automatically made by the camera. The easiest way to do so is to instruct either the camera or the tracking/analyzing software to work in black and white modality and not to analyze the independent RGB channels.

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