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Is Your Video Camera Linear?

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1. Is a video camera a measuring instrument?

You may have thought that a video camera, a key device for bioimaging, faithfully reproduces images that it sees. The electronic signal that the camera sends out should be proportional to the light intensity it receives. But if you test your camera, you might be surprised: some cameras do not know that their response should be linear. You have to be particularly cautious if you work with an ordinary CCD (charge-coupled device) camera, or an intensified CCD camera where an image intensifier is coupled to a CCD camera.

In science, you are taught not to trust an instrument blindly. You are expected to cross-examine its performance, by comparison with another instrument(s) or by giving it known and reliable standard signals. But video cameras can be troublesome: controlling illumination conditions is often quite involved. Thus you may be tempted not to doubt a video camera that is *sold* (not necessarily *produced*!) for scientific use and priced high.

Let us show you some examples. In **Fig. 1**, we show the performance of a CCD camera we recently bought for the purpose of quantitative imaging (gray squares). The output of the camera was digitized with an 8-bit frame grabber whose linearity had been confirmed. The vertical axis of the graph is the digitized intensities averaged over a broad area (central 100×100 pixels in the field of view of 512×480 pixels; a pixel is the smallest element, a rectangular or square area, of an image). The horizontal axis is the intensity of the light hitting the camera, precisely adjusted as we will describe in a moment. As you see, the camera output is a nonlinear function of the incident light intensity. We sent the camera back to the manufacturer and asked for readjustment. After several negotiation and inspection cycles, we eventually obtained the curve with open circles, which is acceptable. This camera was not a particularly bad one. Many others display nonlinearity that hampers quantitative imaging; ratio imaging with these cameras, for example, gives erroneous results. A worse example is shown in black triangles in **Fig. 1**; we tested this camera some time ago and decided not to buy.

Some cameras allow the adjustment of the so-called gamma (γ) parameter: the camera output is given by I^γ where I is the incident light intensity. We almost always set γ to one for quantitative imaging, but γ of, say, 0.45 may produce an apparently better-looking image. The nonlinearity we discuss in this article is not the one obtained by setting $\gamma \neq 1$.

2. A device for precise adjustment of light intensity

Controlling the brightness of a light source is not simple. For example, you could easily change the brightness of an incandescent lamp by adjusting the voltage across it, but then its spectrum (color temperature) also changes. So, generally you want to keep the light source untouched. Instead, you could use neutral density filters to reduce the light intensity to desired levels. But such filters must be calibrated carefully at the wavelength used for the camera test. And

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あなたのビデオカメラは線形ですか？

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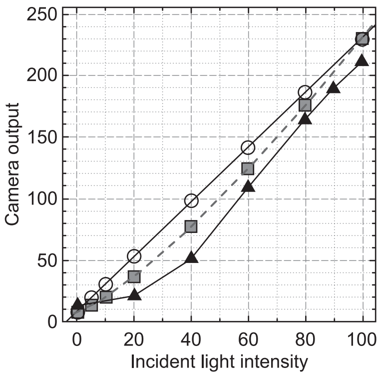


Fig. 1 Examples of nonlinearity. Gray squares, response of a CCD camera upon initial inspection; open circles, the same camera after final readjustment by the manufacturer; black triangles, response of an intensified CCD camera.

your work does not end there, because the calibration must be made each time a camera is tested, since the transmittance of the filters may change gradually with time.

We use the light attenuator shown in **Fig. 2a**. The essential parts are the three polarizers C, D, and E. C and E are fixed orthogonally, say C at 0° and E at 90°, whereas D can be rotated to any angle θ. The transmittance of the composite polarizers, normalized to the maximal value of one at $\theta = 45°$, is given by (**Fig. 2b**)

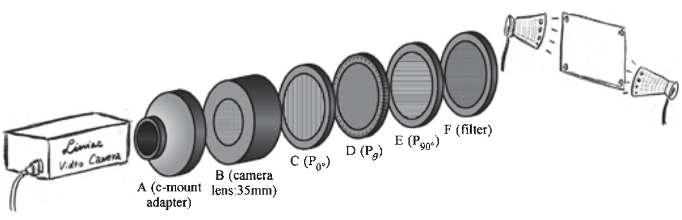
$$T = 4\sin^2\theta\cos^2\theta = \sin^2 2\theta \quad (1)$$

The graduations on the D ring allow reading, by eye, of θ to a precision of $\Delta\theta$~0.2°. From this reading the transmittance is calculated, using Eq. 1, to a precision of $\Delta T = (dT/d\theta)\Delta\theta = (2\sin 4\theta)\Delta\theta \leq 2\Delta\theta(\text{radian}) = 0.007$.

The three polarizers C-E can be attached to an ordinary camera lens (B in **Fig. 2a**), which in turn can be mounted on your C-mount video camera through an adapter (A). The linearity of the video camera is checked by imaging a sheet of white paper on a distant wall, preferably spot-illuminated in a dark room to avoid incidence of oblique stray light rays on the light attenuator. The filter F restricts the wavelengths of incoming light to within the guaranteed range of the polarizers. Note that sheet polarizers work properly in a region in the visible range, but many of them show poor polarization in the ultraviolet and infrared ranges. CCD cameras are quite sensitive to near infrared light (so, often, an IR filter is built in to block long-wavelength components), and an incandescent lamp emits a lot of infrared. Thus, the filter F must at least block near infrared components, unless your polarizers are good to near infrared. We use a broad-band green interference filter that is a standard accessory for microscopes. Be aware that such an interference filter must first be examined with a spectrophotometer, because many of them do not block light outside the visible range.

The orthogonal setting of C and E allows an easy test of the operation of the light attenuator: for both $\theta = 0°$ and 90°, T in Eq. 1 should be zero. To check this, rotate D around 0° or 90°, and find the position where the image becomes most dark. This position must be within ±0.2° of 0° or 90°. Otherwise, at least one of the three polarizers is not oriented properly in the ring. At the darkest position, the brightness must be less than 0.5% of that at ~45°, if you use sheet polarizers of a high extinction ratio, say, Polaroid HN 32. Failure to obtain a dark image, in spite of reasonable darkness when you look through the attenuator with your eyes, suggests that filter F does not block unwanted light. Or, stray light may be entering the camera, possibly through an unnoticed gap in the device-camera connection. After these checks,

(a)



(b)

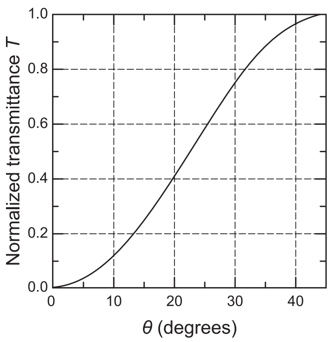


Fig. 2 (a) A light attenuator that we use. A and B are commercial products. Rings C-E, to which filter F can be attached, are made and assembled by a company. (b) Theoretical transmittance of the light attenuator (Eq. 1).

and if the graduations on the D ring are marked properly, you can assume that Eq. 1 holds for your light attenuator. Of course, an independent check with, e.g., a photometer is wise.

Polarizer C assures that, while polarizer D is rotated, the video camera receives light with a fixed polarization; polarizer E selects a fixed polarization component from the incident light. These points are important, because the sensitivity of a video camera may depend on the polarization of incident light, and light sources are often polarized to some extent. Reflection, say, by a mirror, almost always introduces some polarization, and even an incandescent lamp may emit partially polarized light, presumably because of refraction/reflection at the bulb surface. You can check whether the sensitivity of your camera is polarization-dependent, or whether your light source emits polarized light, by rotating the whole light attenuator, either alone or together with the video camera.

3. What to do

Test every camera before you pay for it. Complain if you find significant nonlinearity. In our experience, trying to adjust the performance of a video camera by oneself takes time and often fails. Instead, ask the manufacturer to do that. A typical response from a manufacturer may be, in chronological order, (1) they don’t believe you did the test right, (2) they admit there is a problem but say that the problem is minor, (3) they admit the problem might be serious for you and readjust the camera, alas only to an unsatisfactory level. Be patient. We wish you good luck.

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