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What is your temperature? Remote sensing of temperature using black-body radiation spectroscopy

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Abstract

Infrared thermometers sense body temperature without making contact with the body. The method they use is optical spectroscopy, in the infrared region. At higher temperatures, the peak intensity shifts to the visible part of the spectrum, and a webcam-based optical spectrometer can be used to measure the resulting blackbody emission spectra. Comparing these spectra to the theoretical predictions, the correct temperature can be determined. Several LED light bulbs are tested to verify their advertised spectral temperatures. Calibration procedures for both wavelength and intensity is described; careful calibration of the spectrometer is necessary to measure the temperature accurately.

Keywords

Optical spectroscopy — Blackbody radiation

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Contents

1. Introduction

As COVID-19 hit I saw IR thermometers everywhere, taking my temperature without ever touching me. This seemed like magic, and I wanted to understand how they could do this. It also reminded me that earlier I had noticed that many light bulbs have temperatures written on them. These temperatures were very high, for example 2700K, 3000K, and 5000K, but whenever I held a light bulb in my hand, it was not very hot. It turns out that these two things are related.

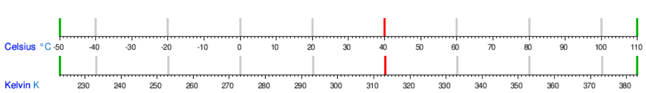

Figure 1. Temperature scales in comparison. Here, $T_C = T_K - 273K$, so $T = 5,000$K becomes $5,000 - 273 = 4,727$°C. Reproduced from [6] under Creative Commons license.

A reminder is in order: K, or Kelvin is a unit of temperature, just like °C (degree Celsius), and there is a relationship between the two, as seen in Fig. 1. Another name for the Kelvin scale is the absolute temperature, and that is because there are no negative Kelvin temperatures. Zero Kelvin is the absolute zero, where all internal energy is gone from the object. Room temperature is about 300K but the light bulbs are labeled with thousands of Kelvin. That's hot!

It turns out that it's all about the light emitted by heated bodies. All heated objects glow and emit light in a broad combination of colors. Some of the colors are invisible - they are in the infrared (longer wavelength than red, like the heat from a campfire we feel on our face), or in the ultra-violet (wavelength shorter than purple, like the sun's radiation that gives us sunburns). This combination of light of different colors is the so-called black-body radiation spectrum, shown

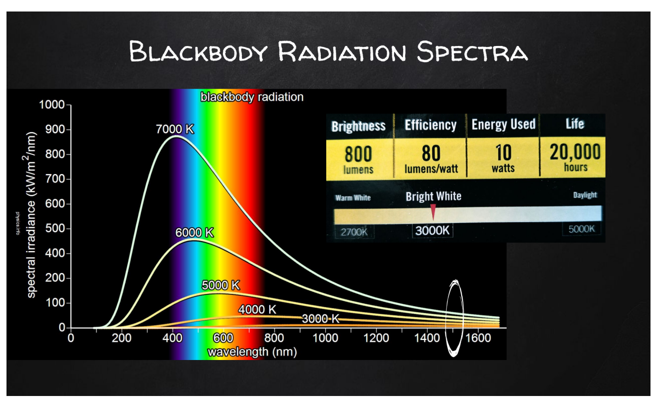

Figure 2. Black-body radiation spectra show the intensity of light as a function of wavelength, for various temperatures. As the temperature changes, the peak intensity shifts, and the color that we perceive changes. The highlighted area near 1500 nm points out that even far away from the peak intensity, the curves for different temperatures differ from each other. Reproduced from [1]. The insert shows a typical label from a commercial LED light bulb package.

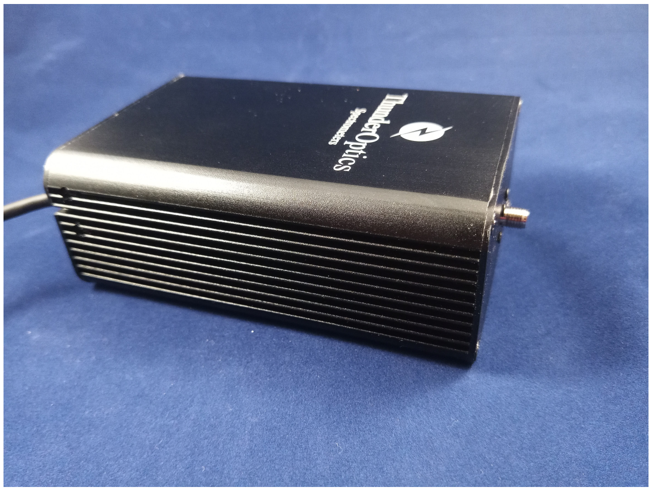

Figure 3. Optical Spectrometer used for measurement of intensity of light at different wavelengths, *i.e.* a spectrum.

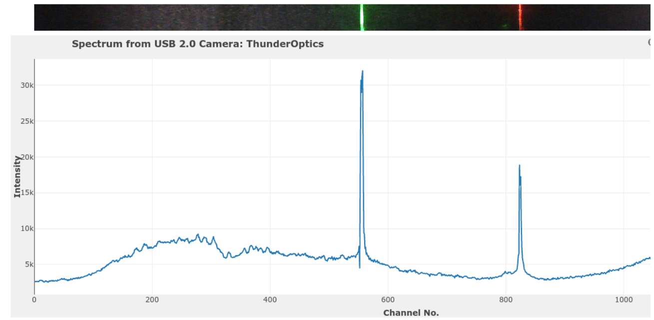

Figure 4. A spectrum of light from two laser pointers shows two sharp lines of single color (monochromatic), one green and one red. Knowing their true wavelengths as written on the laser pointers, tells us which pixels on the webcam correspond to which wavelength. The spectrum obtained using online software [5].

in Fig. 2. A spectrum is a graph of the intensity of light at different wavelengths, and the name "black-body" means that all the light that we see is emitted by the body itself, and it does not reflect any light from anywhere else. The peak intensity changes color as temperature changes, turning more blue at higher temperatures and more red at lower temperatures. Ironically, the labels on higher-temperature blue light bulbs say that they emit "cold light", and for the red lower-temperature ones the labels promise "warm light". The language can be tricky sometimes! As the peak of brightness shifts to a different wavelength it gives us the impression of what the dominant color is. But even far away from the peak intensity, the curves for different temperatures differ from each other, as shown in Fig. 2 with a white highlight near 1500 nm, which is in the infrared.

2. Materials and methods

I performed several experiments to measure the light spectra emitted by various light bulbs, with various temperature ratings. I was able to borrow an optical spectrometer, shown in Fig. 3. It is built around a webcam so I could see the image directly on a computer: the spectrum showed up as vertical stripes of color (visible near the top of Fig. 4), and by measuring their brightness at different wavelengths I could record the spectrum. To properly measure the brightness I first needed to calibrate my spectrometer.

2.1 Calibration of wavelength

To figure out which pixels on the webcam correspond to which wavelength, I first used two different laser pointers, one red and one green. Lasers have very special spectra, each a narrow line of a single color, just a few pixels wide on the screen. Using two laser pointers allowed me to measure the true wavelengths for two pixels, and drawing a straight line between these two points gave me calibrated values for all pixels between them. Fig. 4 shows a spectrum of light from a combination of two laser pointers. The sharp lines represent one single color each, meaning they are monochromatic.

Other light sources have many colors in them. For example, a tanning lamp contains vapor of mercury. As the mercury atoms emit light, the wavelengths of that light is fixed and can be found in reference books. The strongest lines are at 365.0153, 398.3931, 404.6563, 435.8328, 546.0735, 576.9598, and 579.0663 nm [2]. So, an even better calibration can be obtained by using a mercury spectrum with many lines, as shown in Fig. 5. After mapping the pixels along the webcam image of known spectral lines to their wavelengths we know where the particular color is. The line on that graph shows how we translate pixels to wavelengths for all spectra measured after this calibration.

2.2 Calibration of intensity

Mapping the pixels along the webcam image to known wavelengths gives calibration along the x-axis, in other words we now know *where* the light is. In addition, we also need to calibrate the intensity along the y-axis, a representation of *how strong* the light is. That is because the pixels in the camera may have different sensitivity to light of different wavelengths. To do that, I used a stabilized tungsten-halogen light source SLS201L (ThorLabs, NJ) which is known to produce a perfect black-body radiation at a temperature of 2796K. The spectrum measured by the webcam, as shown in Fig. 6. It does not look like a perfect black-body, so I calculated a correction factor for every wavelength and multiplied all other spectra by the same correction factor before analyzing them. The corrected intensity of light follows the ideal black-body curve for that temperature.

3. Results

3.1 Spectra emitted by LED light bulbs

With the spectrometer calibrated, I can point it at any light source and measure its spectrum. I measured the spectra for three different light bulbs. They are shown with solid lines

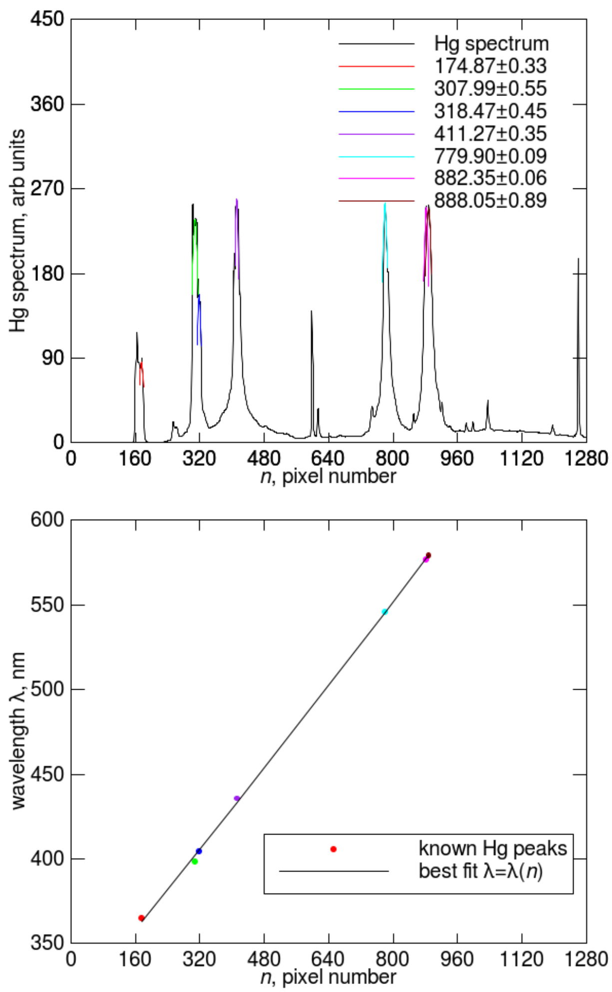

Figure 5. A spectrum containing well known lines of mercury from a tanning lamp. As the mercury atoms emit light, the known wavelengths of that light can be used for a multi-point calibration, better than the two-point calibration using laser pointers. I had to get help preparing these plots [4].

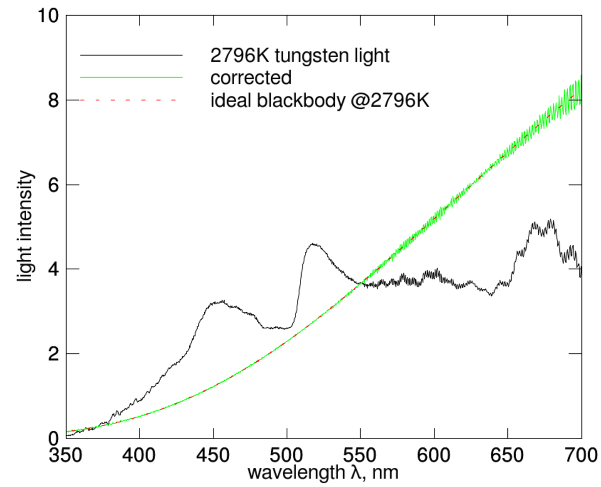

Figure 6. Intensity calibration was performed using a spectrum of a tungsten light bulb glowing at a calibrated temperature of 2796K, and correcting the measured intensity of the light to follow the ideal black-body curve for that temperature. The same correction was applied to all other measurements.

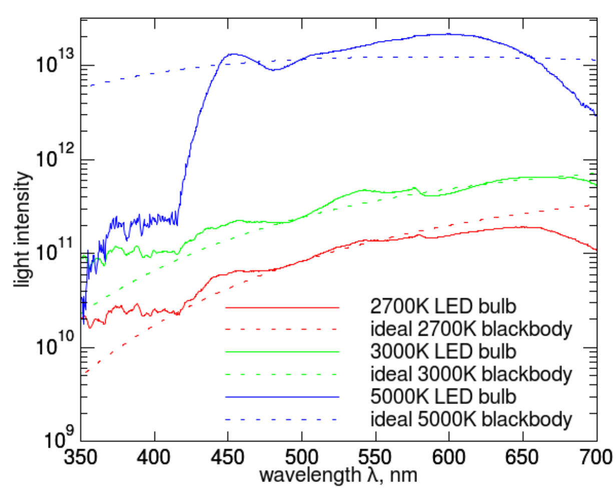

Figure 7. LED light bulb spectra. Measured emission spectra for three different light bulbs are shown with solid lines. The dashed lines represent ideal black-body spectra at the temperatures marked on the light bulb labels.

in Fig. 7. The dashed lines represent an ideal black-body spectrum at the appropriate temperatures. The spectra are not exactly those of ideal black-bodies but they do look similar in the visible range which is the most important for our eyes.

The vertical scale in Fig. 7 is logarithmic, with one division representing not a step of $+1$, but a step of $\times 10$ in intensity. I had to use this scale because the blue line is several hundred times more intense than the red line! This is a problem, because it means that we cannot directly compare different light bulbs, as they may have very different brightness. But the curves in Fig. 7 are not only different in the overall intensity, but also in the way that intensity changes with wavelength, or their *slope*. Measuring the entire spectrum, or at least a ratio of intensities at two different wavelengths, can tell us the slope of the curves and in this way we can determine the black-body temperature.

4. Discussion and conclusions

IR thermometers measure temperature by looking at the intensity of radiation coming from an object or, more precisely, at how that intensity changes with wavelength. When temperatures are high, the strongest light in that radiation is in the visible range, 400-700nm, and we can measure those temperatures with a light spectrometer. This is the case with light bulbs, which are made to produce visible light. For lower temperatures, like those of human bodies, the strongest intensity is in the infrared (longer than 1000nm), and that is where IR thermometers are sensitive. They are not sensitive in the visible, so pointing them at a lightbulb produces a false result.

Figure 8. Foldable cardboard spectrometer [3] can be built with a smartphone camera, a piece of an old DVD, and some cardboard.

This is how I resolved the mystery of “cold” light bulbs rated at thousands of Kelvin. During this project I also learned about a spectrometer that you can build with cardboard and a smartphone [3]. There is a diagram of how to build one in Fig. 8. I was lucky enough to borrow a good instrument but anyone can do optical spectroscopy of the world around them!

Acknowledgements

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