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Development of a Video Spectrometer

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ABSTRACT

A simple, low-cost visible light spectrometer, consisting primarily of a video camcorder and an inexpensive diffraction grating, was assembled and found to be of use in work to improve colored pyrotechnic flames. This instrument is all that is needed to collect and store useful, qualitative flame color information. With this simple instrument, the nature of color agents and the sources of interfering chemical species can be determined.

If semi-quantitative data is needed, a video frame grabber and personal computer can be employed. These allow more accurate identification of wavelengths of spectral features (lines and bands). It also makes possible the determination of relative intensities of spectral features. If quantitative intensity data is needed, a suitable calibration source is necessary and calibration corrections must be applied to the intensity data.

In a brief study using the video spectrometer, it has become clear that much of the difficulty in achieving high quality green and blue colored flames is often the result of impurities present in the raw chemicals. Specifically, the presence of sodium and calcium can act significantly to shift green flame colors toward yellow and blue flame colors toward white.

Keywords: spectroscopy, flame color, video

Introduction

The quality and range of colors produced in fireworks has improved significantly in recent years. However, there continues to be considerable interest in further improving colored flame formulations. To date, most efforts have been hindered by the lack of a satisfactory and affordable spectrometer. Without spectral information it is all but impossible to identify the sources of undesirable interferences acting to reduce color purity. Without information about the emitting species present and their relative spectral intensities, researchers are reduced to using little more than trial and error to guide their efforts. (For more information on the physics and chemistry of colored flames, see Modules 6 and 7 in reference 1.)

This article is one of a series being written to share information on the development of a simple and inexpensive, yet surprisingly effective, instrument to collect spectral data. The instrument not only produces reasonably high-resolution spectra, it simultaneously records a series of spectra from the base of a flame to its tips, and does so continuously throughout the period of burning. The apparatus is referred to as a "video spectrometer". The concept was developed and the work initiated at roughly the same time both by the Kosankes and by T. Wilkinson. Since that time, there has been collaboration; however, the development has proceeded along slightly different paths. The work being reported herein and in an earlier article[2] is primarily that of the Kosankes, whereas the work of Wilkinson will possibly be reported in a subsequent article.[3]

The philosophy expressed in the design and application of the video spectrometer has cost, simplicity, and adequacy as central tenets. That is to say, almost everything in this article could be done better with greater expenditures of time and money. However, when adequate results could be achieved using inexpensive items, or using equipment that is already likely to be available, that is what was done. For example, the instrument is constructed using a standard video camcorder because it produces acceptable results, is compact, and is commonly available.

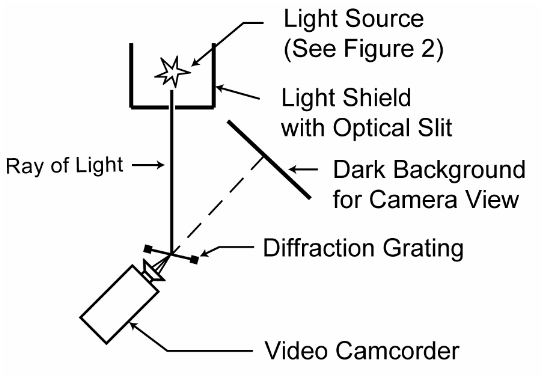

Figure 1. View of the elements comprising the video spectrometer in the horizontal plane (not to scale).

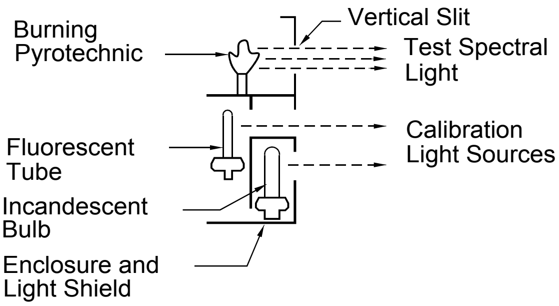

Figure 2. Vertical cut away view, illustrating the arrangement of light sources for the video spectrometer (two calibration sources plus a pyrotechnic flame).

Similarly, a very inexpensive diffraction grating and standard home light sources are used because they are adequate to the task.

Occasionally in this article, alternatives in equipment or methodology are mentioned. For example, the use of a black and white video camera is recommended to overcome some of the problems associated with internal light filters in a color video camcorder. However, most times the reader is left to think of alternatives and ponder their relative merits.

The Instrument

The key components of the video spectrometer and their arrangement are illustrated in a plan view in Figure 1. Light from the calibration sources passes through a slit with a fixed-width of approximately 3 mm. The test source has a manually adjustable slit width ranging from 0 to 3 mm and can be adjusted to control the light intensity from the source. (Typically a width of approximately 1 mm is appropriate.) From there the light travels a distance of approximately 2 m, where it passes through an inexpensive transmission diffraction grating mounted to the lens of a home video camera (camcorder), with the grating aligned vertically (to produce a horizontal dispersion).

Spectral resolution is improved if the diffraction grating is positioned at an angle approximately midway between the camera and the light sources. This angling of the diffraction grating is facilitated with a filter holder such as the “Cokin Creative Filter System”,[4] which is designed to accommodate multiple glass plate filters. The diffraction grating can be inserted somewhat diagonally into the filter holder by using the different grooves on opposite sides of the filter holder. The holder slips onto an adapter ring mounted to the camera lens, making it easy to remove when the camera is used for other applications. This mounting system also facilitates the vertical alignment of the grating because the whole filter assembly is designed to rotate somewhat freely on its adapter ring. (This is especially convenient for those video cameras where the whole lens rotates as the camera is focused.)

The physical arrangement of light sources in the vertical plane is shown in Figure 2. Uppermost is the test source, typically a burning pyrotechnic composition. Below the test source is a pair of calibration light sources. The bottom light source is a clear-glass, 60-watt incandescent light bulb with a vertical tungsten filament.[5] This provides a continuous spectrum of colored light, probably best described as a “gray body” spectrum.[6] Behind and above it is a small fluorescent bulb (Sylvania[7] DULUX–S, CF1306/841). Figure 3 is an example set of spectra recorded with the video spectrometer. (For ease of reproduction in this article, all spectra have been rendered as negative grayscale images.) Uppermost is the spectrum of a burning red star. Below that is the spectrum of the Sylvania fluorescent bulb. On the bottom is the continuous spectrum from the incandescent light.

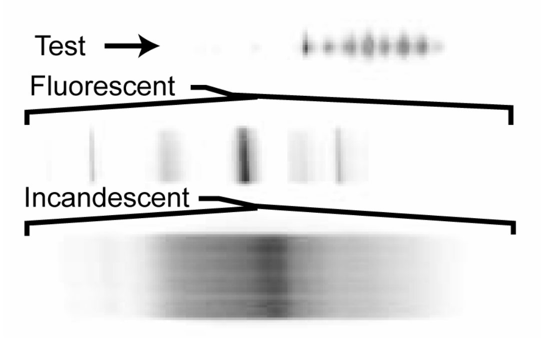

Figure 3. Example of a video spectrometer image (red star plus two calibration spectra) presented as a negative grayscale image (3 mm slit widths).

The calibration light sources are useful, but not essential for most purposes. The fluorescent source can provide wavelength calibration information. But since colored light spectra contain sufficiently prominent and well identified features (atomic lines and molecular bands), the spectra themselves could be used for approximate wavelength calibrations. The incandescent source can provide intensity calibration information. However, for most investigations with the video spectrometer, intensity calibration is not necessary. Beyond their potential use for calibration, the lamps provide a convenient light source for setting up and adjusting the video camera.

Table 1. Wavelength and Relative Intensity of the Major Spectral Features in Figure 3.

Wavelength (nm)(a)	Peak Power (W/nm)(a)	Total Power (W)(b)	Total Intensity (Relative)(c)
404	1.4	7.0	11
436	7.9	15.3	37
487	1.2	9.4	20
546	8.9	51.4	100
612	9.2	31.0	54
708	.5	3.4	5

(a) As reported by Sylvania for the spectral resolution seen in Figure 4.

(b) Areas under the curve for the spectral features.

(c) Relative peak areas corrected for energy (wavelength), using $E \propto 1/\lambda$, and normalized to 100 for the 546 nm peak.

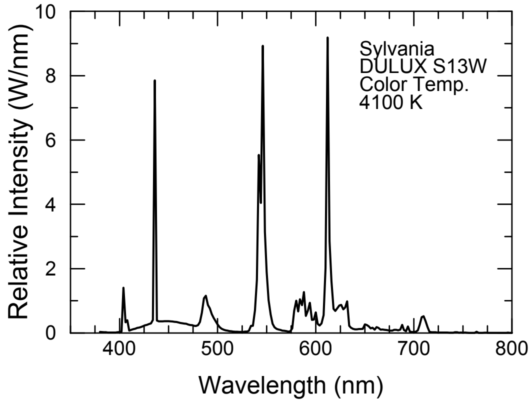

Figure 4. Light spectrum provided by Sylvania for their DULUX–S, CF 13 DX/841 fluorescent light.

Figure 4 is a reproduction of the fluorescent light spectrum provided by the manufacturer. Table 1 is the authors' attempt to quantify the wavelength and intensity of the spectral features for use as a calibration reference. Table 2 has been included as an aid to the reader in correlating the spectral wavelengths reported in this article with perceived color.

The slit was located in the vicinity of the source for several reasons. With the slit a long distance from the camera, it can be opened much wider than if it were near the camera. This makes it easier to adjust its width and to have separate test and calibration slits. If the slit were too near to the camera, it would not be possible to focus the camera on it as required, and only a small portion of the grating and camera lens would be

Table 2. Approximate Wavelengths Associated with Various Colors of Light.[6]

Perceived Color	Approximate Wavelengths (nm)
Red	700 to 610
Orange	610 to 590
Yellow	590 to 570
Green	570 to 490
Blue	490 to 450
Violet	450 to 400

used. Further, localized imperfections in the grating and lens could degrade spectrometer performance. Most importantly, with the slit attached to the holder of the test flame source, it is trivially easy to control its orientation so that light from the central portion of the flame is directed to the grating and camera.

To collect spectral data with usably accurate intensities, one must not over-load the charge coupled device (CCD) of the video camera with an over bright image. Apparent source brightness should be controlled by adjusting the test source slit width, the distance between the source and slit, the distance from the slit to the camera, or any combination of the three. Also the video camera's iris control should be set to manual and adjusted to control the apparent source brightness.

The resolution achieved by the video spectrometer is determined by the convolution of the slit width and the characteristics of the diffraction grating and video system. For any given camera, narrowing the slit and "zooming in" for a close-up view increases the resolution up to some value that is limited by the quality of the diffraction grating. The grating used in this case has a moderately high number of lines (530 lines per mm) but is quite inexpensive (< \$2).[8] The resolution achieved is more than adequate for use in pyrotechnics. As a test of the resolution, a neon discharge tube was used as the test source with a slit width of 1 mm. A spectral resolution of 2–3 nm at a wavelength of 600 nm was achieved, see Figure 5. (Note that the top portion of Figure 5 is an expanded view of the neon spectrum, accomplished by using the video camera's telephoto capability to zoom in on just the red portion of the neon spectrum.) This resolution is sufficient to allow the identification of rather narrowly spaced atomic lines, whereas most pyrotechnic spectral intensity will appear as much broader molecular bands. (For more information on spectral types and pyrotechnic spectra see Modules 6 and 7 of reference 1.)

Not shown in Figure 1 is a large screen video monitor connected to the video camcorder. While it is possible to set up and use the video spectrometer using only the small eyepiece monitor on the camera, it is much more convenient to have a large screen monitor that can be viewed throughout the work area. Although colored spectra are attractive, the intrinsic resolution of the chromance (color) signal is significantly less than that for the luminance (black and white intensity) signal. Accordingly, fine tuning the video spectrometer (and data processing) is facilitated by operating the video monitor in a black and white (gray scale) mode.

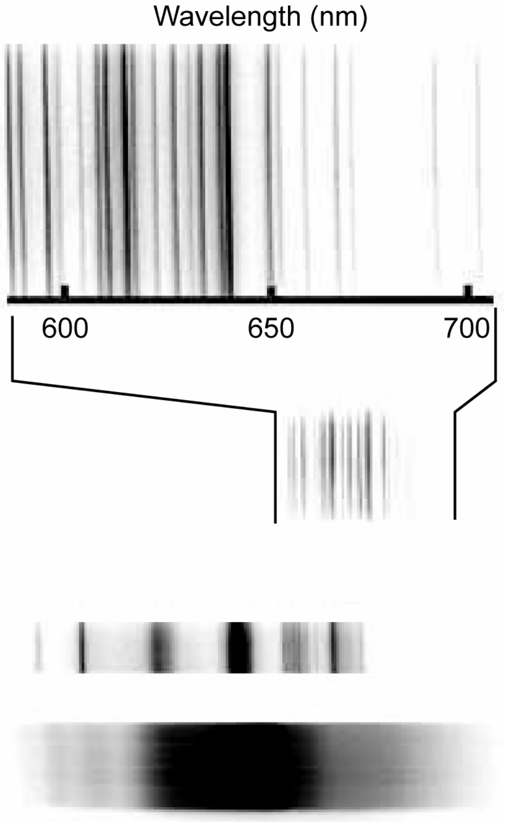

Figure 5. Upper: View with video camera "zoomed in" on the neon spectrum (1 mm slit width). Lower: The two calibration spectra (on the bottom) plus the neon spectrum (above).

Data Capture

Preparation for the collection of spectral data requires some adjustment of the instrument. First, set up the video camcorder with the diffraction grating in place and aim the camera directly at the light source slit(s). With the work area moderately dark and an operating light source located directly behind the slit, set the camera's focus control to manual and adjust the focus for a sharp image of the slit. Then aim the camera to the side (pan) just enough for the spectral image to become visible. At this time, using the wide angle / telephoto ("Zoom") control, adjust the size of the image so that the spectrum from the incandescent light nearly fills the width of the image area. (If a light source that produces reasonably narrow features is used, such as a fluorescent bulb, fine tune the camera's focus for the sharpest spectral image.) Finally, if the camera has an electronic iris control, set it to manual and adjust it such that the brightness of the image is not excessive. The light produced by pyrotechnic flames is quite bright, and it may be necessary to fine tune the iris adjustment or narrow the test source slit to keep the camcorder CCD from being overloaded. Also, the exposure should be set for 1/60 second (in the US); this will eliminate potential problems with flickering of the electric lamps.

The bulk data capture mechanism is the video recorder of the camcorder itself. As a test sample of pyrotechnic composition is burned, an essentially continuous collection of flame spectra (60 video fields per second), including any audio commentary by the experimenter, is preserved for later reproduction and processing. In addition, because the slit can be oriented along the length of the flame from its base to its tip, a series of spectra at varying distance along the flame are also recorded. This is potentially useful because of differences in the chemical species and temperatures present at various points in the flame.

As always it is necessary to follow all safety procedures, such as limiting the presence of combustible materials in the work area and employing air handling equipment to remove combustion products from the burning compositions.

Qualitative Data Processing

If only qualitative spectral information is needed, then simply playing back the recorded spectra may be sufficient, possibly using the pause capability of the recorder to hold the video image for more thorough examination. For this type of data interpretation, generally only approximate wavelengths are determined, and no correction is made for the sensitivity of the camera as a function of wavelength. Figure 6 presents two examples, a red and a blue color flame spectrum. (Note that calibration spectra have been removed from Figure 6 for simplicity of presentation, and a nanometer wavelength scale has been added.) The red flame spectrum is the same as that presented in Figure 3, and it obviously dominates in the longer wavelength (red) end of the spectrum. The color of the blue flame is not as pure. In the blue flame spectrum there are strong bands in the short wavelength (violet–blue) end of the visible spectrum. However, there are also strong bands near 500 nm (green) and even features near 600 nm (orange). These non-blue features in this blue flame act to seriously reduce the purity of its color.

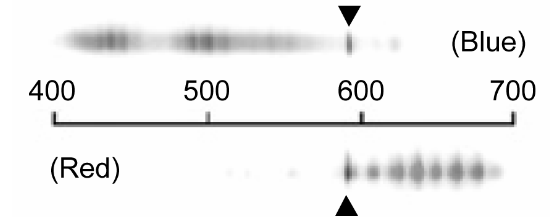

Figure 6. Examples of blue (above) and red (below) flame spectra, with the calibration spectra removed, a wavelength scale (in nm) added, and the Na-lines (589 nm) annotated (▲).

In Figure 6, the wavelength scale was established using the known spectral features from the fluorescent light, specifically the peaks at 436 and 612 nm. The accurate positioning of the wavelength scale was then accomplished using the very narrowly spaced sodium doublet lines (▲) at 589 nm, clearly visible in the test spectra. The sodium doublet lines are present in essentially all pyrotechnic flames due to trace amounts of sodium in the chemicals used.

An acceptable alternative wavelength calibration method is to use the prominent known spectral features present in the test spectra themselves. To facilitate use of this, Table 3 was complied. It lists the wavelengths and relative intensities of prominent features in pyrotechnic colored flame spectra.[9–11] In addition, many other spectral features are possible, most notably features from various oxides. However, in typically formulated colored flame compositions, they are relatively weak features.

Table 3. Identification of Some Major Spectral Features Grouped by Chemical Species and Band Group.

Source(a)	Wavelength (nm)(b)	Relative Intensity(c)
SrCl	689	< 1
	674–676(d)	5
	661–662(d)	10
	649	4
	636	10
	624	2
SrOH	608–611(d)	10
Sr(e)	461	10
CaCl	633–635(d)	1
	621–622(d)	10
	618–619(d)	10
	605–608(d)	1
	593	10
	581	4
CaOH	644	2
[Ref. 10]	622	10
	602	2
	554	5
Ca(e)	442–445(d)	10
Na	589	10
BaCl	532	3
	524	10
	521	1
	517	2
	514	10
	507	1
BaOH [Ref. 10]	513 488	10 8
CuCl(f,g)	538	2
	526	4
	515	2
	498	4
	488	8
	479	5
	451	1
	443	6
	435	9
	428	7
	421	4
CuOH	537	10
[Ref. 10]	530	9
	524	9
	505	6
	493	5
Cu(e)	522(d)	10

(a) Unless otherwise indicated, these data are taken from reference 9.

(b) Wavelengths are only reported to the nearest nm.

(c) The reported relative intensities are normalized to 10 for the strongest emission within a group of features from each chemical species. Different band groups for the same chemical species are separated by a single solid line in the table. Because intensities are normalized within each group and because the manner of excitation for the spectra in the literature is generally different than that for pyrotechnic flames, it cannot be assumed that the intensities listed in the table will be those observed in pyrotechnic flames.

(d) When two or more spectral features are within about 2 nm of each other, they are listed as a single feature showing a range of wavelengths and with the combined intensity of the features.

(e) Other weaker atomic lines occurring in the visible range are not reported.

(f) Pearse and Gaydon[9] report six groups of bands for CuCl; however, the bands in only three of the groups were seen in flame spectra examined for this article. Also they appear to have collectively normalized the intensities of the bands (i.e., the strongest band in each group is not set to 10).

(g) Shimizu[11] reports a total of 31 bands for CuCl; only the 10 strongest of those correspond to wavelengths reported by Pearse and Gaydon.

Figure 7 is a comparison of the spectra of two burning orange stars. The lower spectrum is from a standard formulation based on a calcium salt, and the upper spectrum is from a formulation producing a visibly more attractive orange flame. In the lower spectrum, the emission bands observed are those characteristic of calcium monochloride, a band from calcium monohydroxide and the sodium doublet lines at 589 nm. The same features are present in the upper spectrum; however, also visible are three features near 520 nm, which are the strongest bands from barium monochloride. Obviously then, the improvement in the orange color was accomplished by using a small amount of a barium salt to shift the composite calcium color point from reddish orange to orange. (A similar approach is described in reference 12; a discussion of color mixing and composite colors is discussed in Module 6 of reference 1.)

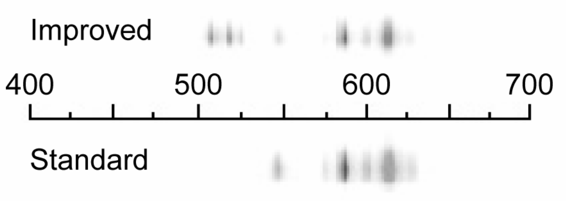

Figure 7. Comparison of spectra from two orange stars. The upper spectrum has green bands to improve the orange color.

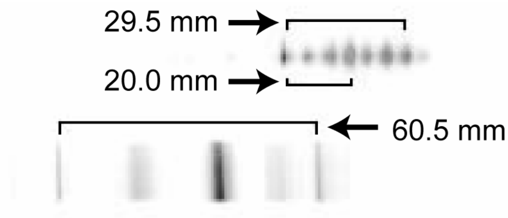

Figure 8. Example of approximate method for determining unknown wavelengths.

Semi Quantitative Data Processing

If more quantitative spectral information is desired, one can capture the video data using a personal computer. The spectra for this article were collected with the inexpensive (but quite effective) Snappy® software / hardware system.[13] Computer capture allows for the production of hard copy printouts of the spectral images, such as those presented in this paper. Also disk files of the video images can be created for use in data processing or for archival purposes.

To identify unknown spectral features, fairly precise identification of their wavelengths is helpful. Because the relationship between wavelength and screen location is essentially linear, only two spectral features of known wavelength are needed to establish a scale factor (the wavelength in nm per millimeter separation on the printout). The peaks at 436 and 612 nm in the fluorescent calibration spectrum are convenient for this purpose. By simply measuring the physical distance in millimeters between the two features on a paper printout of the spectrum and dividing (612 – 436 =) 176 nm by the measured physical distance, one establishes the scale factor in nm per mm. This same scale factor applies to all spectra recorded, providing no changes are made to the camera setup. The most convenient method to locate oneself on the test spectrum is to use the sodium doublet lines at 589 nm. If the physical distance from the sodium lines to an unknown feature in the test spectrum is measured, its corresponding wavelength can be determined by simply multiplying the distance just measured by the scale factor and adding to or subtracting from 589 nm, depending on whether the unknown feature lies to the higher or lower wavelength side of the sodium lines.

This type of approximate wavelength calibration is illustrated in Figure 8. In this case, from the full size printout of the spectra, the distance between the 436 and 612 nm features in the fluorescent light spectrum was measured as approximately 60.5 mm. Thus the scale factor is 2.91 nm/mm (176 × 60.5). In the test spectrum, the distances from the sodium doublet line to two of the features are 29.5 and 20.0 mm. Thus they correspond to wavelength displacements of 86 nm (2.91 × 29.5) and 58 nm from the 589 nm sodium doublet, or wavelengths of approximately 674 nm (86 + 589) and 647 nm. From Table 3, it is fairly obvious that these must be the SrCl bands listed as 674 – 676 and 649 nm. As a practical matter, this method only allows identification of wavelengths to within a few nanometers. This is due to difficulty in visually determining the points of peak intensity for the features seen on the spectrum printout.

Adobe PhotoShop®[14] is a popular digital image processing program. Although not its normal function, it offers the ability to produce intensity data from the spectra captured on a personal computer. One uses the “color-picker” (densitometer) intensity function, found on the “Info Pallet”, on the spectral areas of interest to generate intensity versus image position data. This position data can then be used to determine screen position (wavelengths) more accurately. The procedure used is the same as suggested above; however, instead of making physical measurements with a ruler, the locations of screen pixels corresponding to the highest intensity for spectral features are used. In addition, although labor intensive, it is possible to use the Adobe intensity function to produce an intensity versus wavelength graph of the spectrum. Starting on one side of the screen image, intensity readings are recorded manually

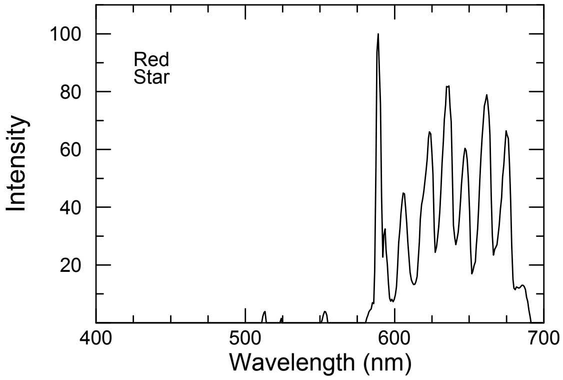

Figure 9. Example of the spectrum from a red test star.

as one moves from pixel to pixel across the image. Then these data are plotted to produce a graph of intensity (density) versus screen location. By knowing the wavelengths of at least two features in the spectrum, one can convert the screen locations to wavelengths. In a trial of this method it took about 30 minutes to produce and graph the data from a single spectrum.

Un-Scan-It Gel®[15] is a software package intended for computerized density scanning of gel electrophoresis plates. However, it works wonderfully to digitize video spectrometer data captured on a personal computer. It also allows intensity calibration of the image, plotting the results, integrating peak (band) intensities, and dividing the length of the flame into multiple separate spectra. With Un-Scan-It, the time to produce an intensity versus screen position graph

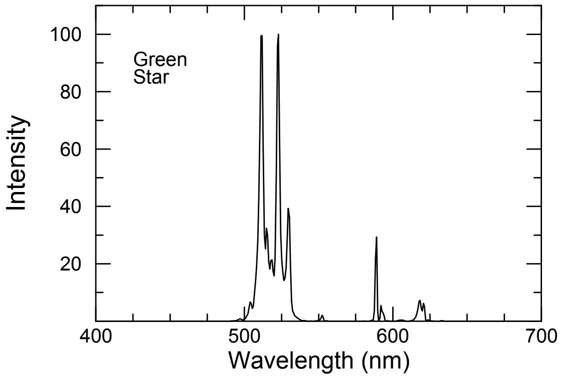

Figure 11. Example of the spectrum from a green test star.

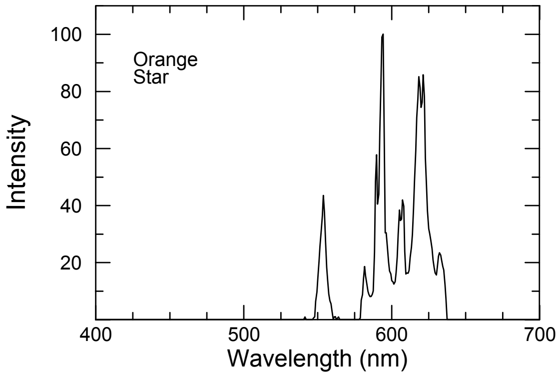

Figure 10. Example of the spectrum from an orange test star.

and store the data is about one minute. Snappy and Un-Scan-It were used to produce the graphs in the remainder of this paper, including a series of example color flame spectra. The test stars[16] used to produce these spectra are based on ammonium perchlorate, hydroxy-terminated polybutadiene (HTPB), and a color agent. The spectra are presented in Figures 9 through 12 with their peak intensities normalized to 100.

As an example of the utility of having the spectral data in graphical form, consider Figure 13. This presents two similar appearing green flame spectra. These spectra were produced as a test of the hypothesis that replacing some of the ammonium perchlorate with potassium perchlorate would improve the green flame color. Both formulations used the same chemical color agent, barium nitrate; however, the new (im-

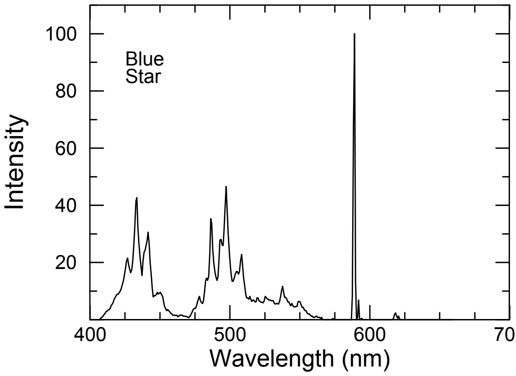

Figure 12. Example of the spectrum from a blue test star.

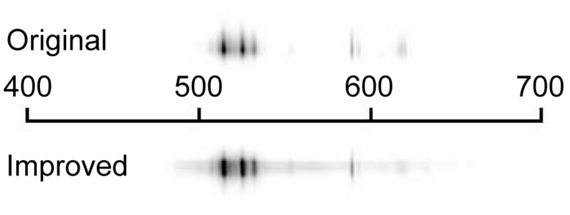

Figure 13. Comparison of the spectra from two green star formulations. The upper one appeared noticeably more yellow.

proved) formulation was prepared a couple of years after the first. The improvement to the color was obvious, as perceived by a panel of viewers; the original formulation appeared noticeably more yellow. In Figure 13, the most obvious difference seen in the "Improved" spectrum is the presence of a weak continuum for the "Improved" formulation. The reason for this is not entirely clear, but presumably it is a result of the incandescence of liquid potassium chloride particles in the flame or from potassium ion recombination (see Modules 6 and 7 of reference 1). Regardless of its source, the presence of the continuous emissions could only act to reduce flame color purity, contrary to what was observed. The second most obvious difference in the improved formulation is the increased intensity of the green bands (from BaCl, see Table 3). This is presumably the result of an increase in flame temperature. However, these greater intensities should only cause an increase in brightness and not an improvement in color, unless there is a perceived increase in the green intensities relative to interfering features (i.e., the line from sodium and bands from CaCl).

Figure 14 presents graphs of the spectra from Figure 13. The presence of the continuum and the increase in intensity noticed in Figure 13 are confirmed. Table 4 is a listing of intensities of key spectral features. The presence of the continuum and the increase in intensity are confirmed. However, notice in the improved star formulation that the normalized intensity of the sodium doublet is reduced by about 5%, and the calcium monochloride bands are reduced by about 50% as compared with the original formulation.

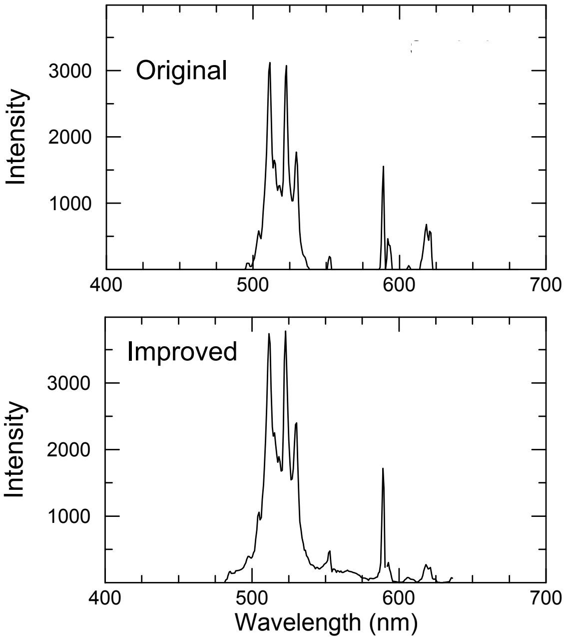

Figure 14. The two green spectra as in Figure 13, but rendered as graphs.

Thus spectral analysis suggests that it is unlikely the visible improvement in flame color is the result of substituting potassium perchlorate for some of the ammonium perchlorate as hypothesized. It is more likely that, over the two year time span, chemicals from different lots (or suppliers) were being used and the different lots had differing amounts of interfering chemicals.

Table 4. Intensity of Key Spectral Features Seen in Figure 13.

Wavelength (nm)	Intensity (x 1/1000)		Normalized Intensity		Identification of Source	Perceived Color
	Original	Improved	Original	Improved		
507–532	61.2	98.3	≡ 100	≡ 100	BaCl	Green
589	3.7	5.6	6.0	5.7	Na	Yellow
593	1.5	1.3	2.5	1.3	CaCl	Orange
618–622	4.5	3.4	7.4	3.5	CaCl	Red

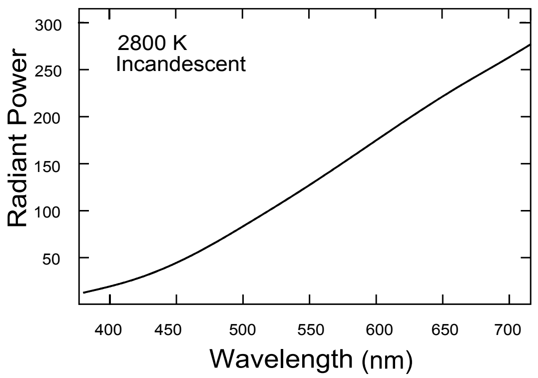

Figure 15. Spectral energy curve of typical 2800 K tungsten lamp.

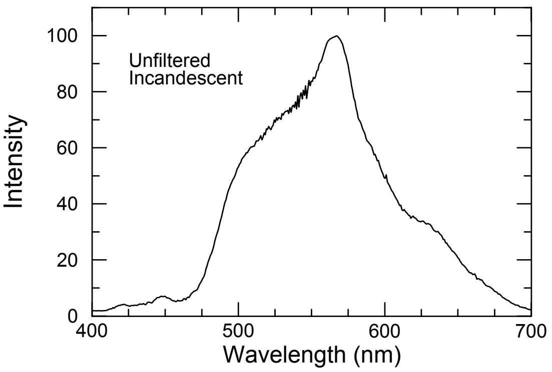

Figure 16. The observed spectrum of the incandescent calibration light source.

Quantitative Data Processing

The relative intensity data such as demonstrated in the green example can be very useful. However, when reasonably-accurate, absolute-intensity results are needed, an intensity calibration is necessary. The need for this calibration is a result of the way in which the camcorder prepares its composite color image. Internal light filters differentiate between the three primary video colors. These filters, in combination with an internal infrared filter and the wavelength dependent sensitivity of the CCD, produce a wide deviation from constant light sensitivity across the color spectrum.

The needed calibration information might be acquired using the fluorescent light source and the spectral data provided by the lamp's manufacturer. However, there are not many useful spectral features in the light output, and there is no guarantee that each bulb produces spectra identical to that reported by the manufacturer. A somewhat better alternative is to use the spectrum from an incandescent bulb as shown in Figure 2. (Obviously, still better would be to use a black body source or a spectrally calibrated lamp.)

A 60 W tungsten filament is expected to produce a color temperature of approximately 2800 K.[17] Figure 15 is a graph of radiant power as a function of wavelength for a color temperature of 2800 K.[18] However, the spectrum recorded with the video spectrometer, Figure 16, is grossly different than that of Figure 15. Originally it had been hoped that the two spectra would be similar enough that the needed correction would simply require applying a set of wavelength-dependent correction factors. However, the magnitude of the correction required in the region from 650 to 700 nm is too extreme for this method. The grayscale image captured using Snappy is only 8-bit data (intensities ranging from 0 to 255). With correction factors exceeding 50 being needed, the resulting intervals between successive values would be unacceptably large. Accordingly, another method was sought.

A more constant sensitivity as a function of wavelength would be obtained with a black and white video camera. However, that would be an additional purchase for many potential researchers and would probably require the use of a separate video recorder. Another alternative would be to use a still camera and black and white film. But for a short duration light source, only a few spectral images could be recorded, and because of the flame's flickering (movement behind the slit) they might not be typical of what is being produced. Another drawback of using film is the time delay in developing it, thus making set up and adjustment more difficult than with the video camera.

A coarse initial correction for intensity was attempted using externally mounted light filters. A pair of rose colored filters (GamColor[19] polyester color filters #105 and #130) reduced the sensitivity in the green region and improved the observed continuous spectrum sufficiently to allow final correction using reasonably small numerical calibration factors. Figure 17 is the

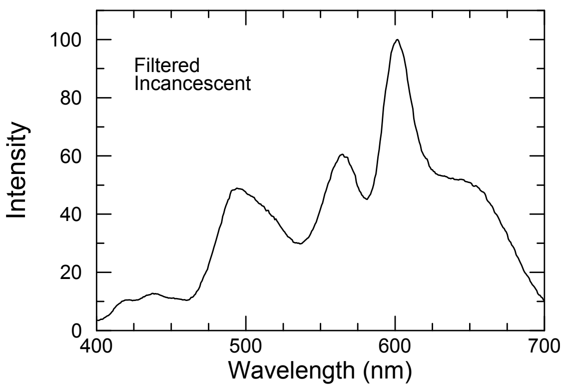

Figure 17. The filtered spectrum of the incandescent calibration light source.

filtered continuous spectrum. Figure 18 is a graph of the intensity calibration factors which successfully reproduce the 2800 K spectrum (Figure 15).

As of this writing, no studies have been conducted using intensity-corrected spectra. However, studies to measure the temperature of glitter spritzel (dross particles) and flash temperatures may be initiated soon. For that work, fairly accurate spectral intensities will be needed.

Conclusion

Although still in an early stage of development, the video spectrometer has already proven useful. For example, a recent gathering of flame color researchers were able to conclude that many of the problems preventing the better colored flame formulations from producing high purity colors, stem from impurities in the chemicals used. (Most notably the presence of sodium and calcium caused problems.)

Probably the most significant advantage of a video spectrometer in studying flame color formulations is its relatively low cost, assuming a camcorder and personal computer are already available. Also, its ability to continuously record very short duration spectra is ideal for pyrotechnic flames. Finally, the ability to look simultaneously at various points along the length of a flame is a feature generally absent from even high quality commercial spectrometers.

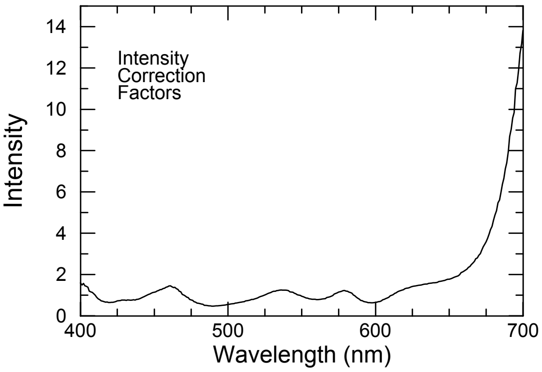

Figure 18. Intensity calibration factors for the filtered spectra.

Clearly further improvements can be made in the hardware and operation of the video spectrometer. This work is shared in the hope that others would find the video spectrometer useful and would further develop the instrument.

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