Hyperspectral imaging using a linear variable filter (LVF) based ultra-compact camera

Thomas D. Rahmlow, Jr., William Cote and Robert Johnson, Jr.*

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Hyperspectral imaging using a linear variable filter (LVF) based ultra-compact camera

Thomas D. Rahmlow, Jr*., William Cote and Robert Johnson, Jr.

Omega Optical, Incorporated
Brattleboro, Vt. 05301

Abstract

Narrow bandwidth linear variable filters (NB-LVF) bring hyperspectral imaging to a wide range of applications in a compact, low weight, rigid structure. The center wavelengths of the narrow bandpass of a linear variable filter changes smoothly in one dimension and are constant in the orthogonal dimension along the surface of the filter. The filter, which is the size of the camera's detector, is placed directly ahead of the detector and successive frames are acquired as the camera skews or as the camera platform moves across a scene. The full width, half maximum bandwidth of the filter used is 0.8% of the center wavelength and the spectral range is 400 to 900 nm with a wavelength gradient of 50 nm/mm. Examples using the LVF camera for emission spectroscopy, absorption spectroscopy, machine vision, and industrial process control and hyperspectral imaging are presented.

Keywords: Optical filters, Linear Variable Filters (LVF), Hyperspectral Imaging

1.0 Introduction

A Linear Variable Filter (LVF) is a unique type of interference filter where spectral performance varies along one axis and is constant along the orthogonal axis. A LVF can be a narrow bandpass design providing spectral discrimination or a long pass design and used as an order sorting filter in a grating based spectrometer. In both cases, spectral performance shifts in a consistent manner as a function of spatial position on the filter. Filter bandwidth varies as a constant percentage of the center wavelength of the filter bandpass. While the concept of linear variable filters is not new[1,2], the current trend is to reduce the size of the filter to that of the imager's detector to allow placing the filter directly in front of the detector or at an intermediate focal plane creating a hyperspectral imager with moderate spectral resolution, but high spatial resolution[3,4,5].

The use of a filter to replace the grating or prism in an imaging system results in a significant reduction in weight, size and cost of the imager. High spatial resolution allows for discrimination of fine detail, texture [3]and resolution of a scene where different elements of the scene are finely dispersed such as monitoring mixed crops, healthy and unhealthy patches with a field, or veins of minerals exposed in river beads or geological strata[3,8].

The design of an imaging system using a linear variable filter requires attention to a number of unique details. The spectral resolution of an LVF camera is limited by the bandwidth of the filter, the operating F-number of the imaging system and the distance between the filter and the detector. Alignment of the filter to the detector array is important in extracting spectral information. The light source is a significant consideration when using the LVF camera. Fluorescent or LED lighting consists of strong spectral bands. Broadband solar or incandescent lighting is preferred.

In order to obtain a full spectrum of points in the image, motion between the imager and the scene is required. The camera can rotate acquiring images as a function of angle, the camera platform can move across the scene as in the example of mounting the camera on a drone or CubeSat, or elements within the scene can move across the field of regard as in the example of monitoring exhaust gasses and particulate from a jet engine.

In order to better understand the capabilities and potential of LVF cameras, we assembled and evaluated a simple camera design. We present our approach to LVF camera assembly and calibration as well as use as a field spectrometer and hyperspectral imager.

2.0 LVF Camera Design

Two monochrome cameras were modified by adding an LVF filter. In each case, the filter was attached to a mount designed to fit within the existing camera housing without any additional modifications to the housing. Both cameras came with an uncoated glass cover slip protecting the detector. The cover slip was not removed or modified. The filter is placed as close to the detector cover glass as possible. Both cameras use a USB 3.0 interface.

Figure 1: The LVF filter shown here was cut to 8 x 6 mm and installed in a FLIR (Point Grey) camera. This camera uses a 1.6 mega-pixel monochrome detector. This camera is very light weight and is suggested for drone applications.

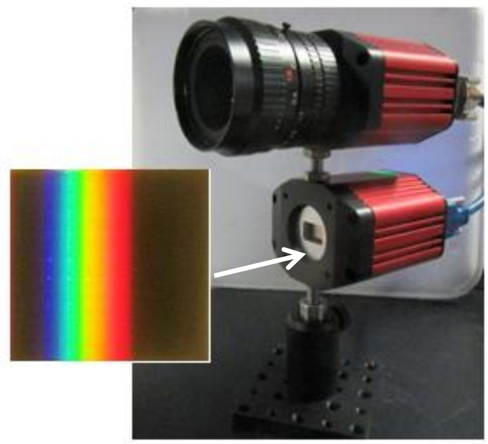


Figure 2: A second LVF filter cut to 15 x 11 mm was mounted on a holder and assembled into a ThorLabs CMOS 5 mega-pixel camera. Two cameras are used to acquire both RGB color and LVF monochrome frames. The high spatial resolution is suggested for applications where high spatial resolution is required.

The camera presented in figure 1 is a FLIR BFS-U3-16S2M-CS[9]. This is an ultra-light weight camera engine and was selected for potential drone applications. The detector is 1.6 mega-pixels with a format of 1480 x 1260. The LVF was cut to 8 x 6 mm and covers a spectral range of 380 nm. The camera presented in figure 2 is a Thorlabs compact scientific camera with a 5.01 mega-pixel detector[10]. This camera was selected for applications where high spatial resolution is required. The high spatial resolution allows for better determination of texture and detail in a cluttered field. The Thorlabs CMOS camera detector is 2448 x 2048 pixels. The LVF filter was cut to 15 mm x 11 mm and covers a spectral range of 500 to 910 nm. In both cases, the LVF filter used has a wavelength gradient of 50 nm/mm.

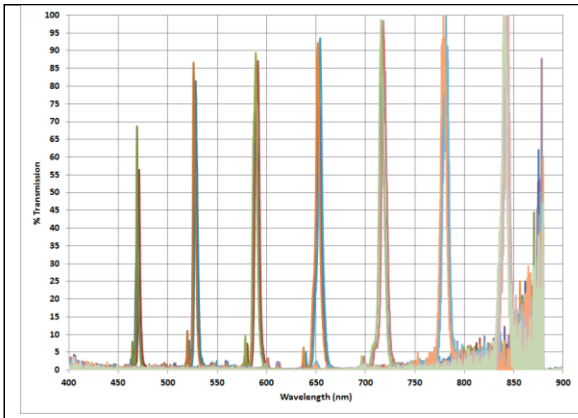


Figure 3: measured transmissions at various positions along the gradient axis of the LVF are overlaid. The bandwidth of the filter is constant percentage of the center wavelength.

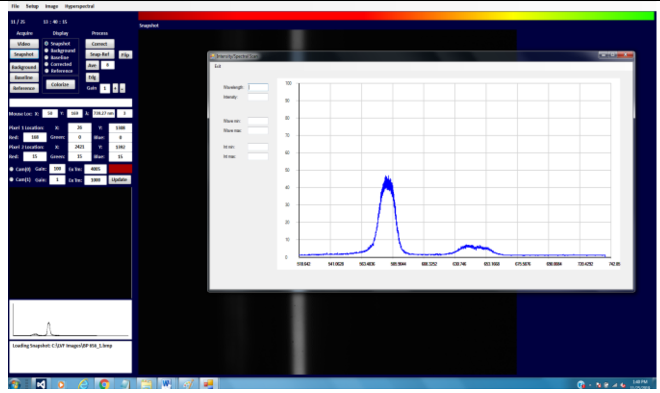


Figure 4: A concern in mounting the LVF filter is illustrated in this figure. Although the off-band rejection is greater than OD 4, off band 'leaks' can occur as a result of tilt between the LVF and the uncoated cover glass on the detector.

Figure 3 presents an overlay of spectral transmission at various spatial positions along the gradient axis of the filter. Measurements across the center, bottom quarter and upper quarter are overlaid at each spectral position and demonstrate good control of center wavelength along the constant wavelength axis. A characteristic of linear variable filters is that the filter bandwidth is a constant percentage of the center wavelength. This means that filter bandwidth varies along the gradient axis. The filters used for this demonstration have a bandwidth of 0.8% of the center wavelength. They are 4nm full width half maximum (FWHM) at 500 nm and 6.4 nm at 800 nm.

Care in mounting the LVF is required to avoid the occurrence of artifacts in off-band transmission. Figure 4 illustrates the creation of an apparent 'leak' in transmission despite the off-band rejection of the filter being greater that OD 4. In this case, the artifact is a reflection of the transmission band being reflected off the uncoated cover glass covering the camera's detector. Tilt between the filter and the cover glass results in the reflected beam 'walking' down the array. Adjusting the tilt, using an index matching oil or coating the cover glass with a broad band AR all help mitigate the problem .

3.0 Calibration and Alignment

Filter transmission is measured using the micrometer attachment shown in figure 5. The filter location is measured against a fiducial mark on the substrate or edge of the filter. The filter is positioned in the attachment just ahead of a 10 micron by 3 mm slit aperture. Transmission is measured across the center, upper and lower quadrants. Typical results for measurements made every 0.2 inches across the gradient axis are overlaid in figure 6. Off-band blocking measurements are made using a 500 µm aperture to insure an accurate measurement of optical density (OD). These measurements were made using an F/8 beam in a Cary 5000 spectrometer.

The LVF used covers a spectral range of 350 nm to 1000 nm across 13 mm with a spectral gradient of 50 nm/mm. The size of the camera's detector therefore determines the spectral range of the LVF camera. The spectral range of the 1.6 mp camera is 325 nm and the spectral range of the 5 mp camera is 450 nm. Spectral performance of the narrow passband is also strongly influenced by angle of incidence (AOI) of light at the filter[4]. Figure 7 presents modeled transmission for the LVF design at various F/# values.

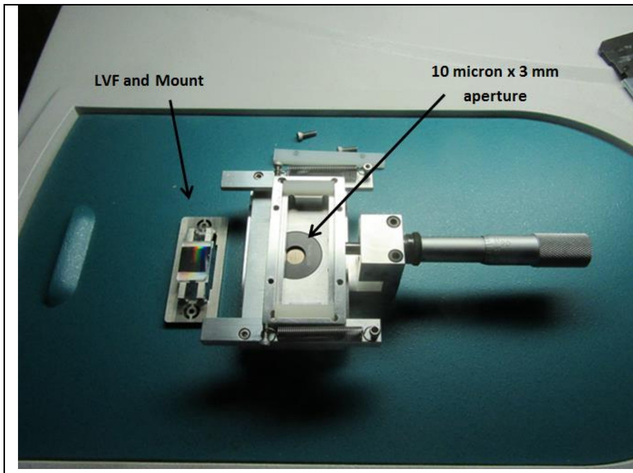


Figure 5: The LVF filter is mounted in a customized micrometer positioning sample attachment. The sample is placed up against a 10 µm by 3 mm slit.

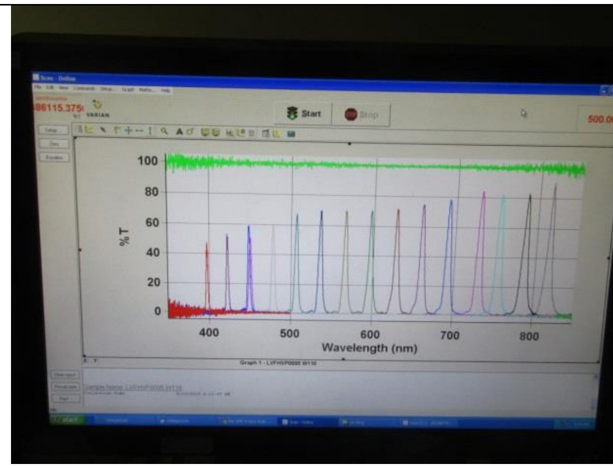
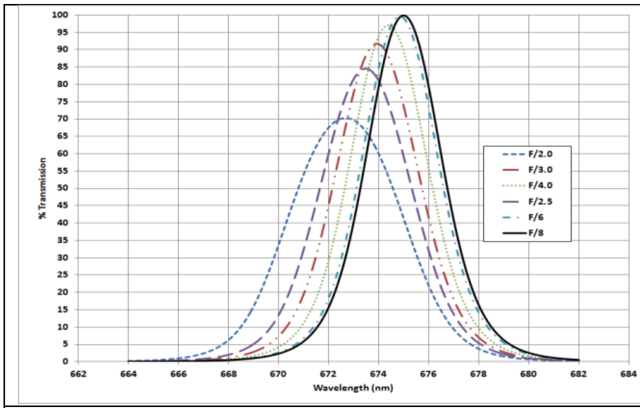


Figure 6: Final Scan Set – each measurement is offset 0.2 inches. The 10 µm slit is used to characterize spectral shape. Off-band blocking measurements are made using a 500 µm aperture.

The LVF needs to be aligned to the detector and there are two aspects to consider – orthogonality and wavelength calibration. Orthogonality is the rotation of the filter to insure that each column of the detector is aligned to the same center wavelength. The wavelength calibration is the mapping of the variable filter's center wavelength as a function of pixel row index.

Orthogonality is adjusted by illuminating the filter with a light source containing spectral lines. This could be a mercury source or something as simple as a florescent lamp. Figure 8 presents a frame taken using an overhead florescent light. The filter is rotated into a position where the lines are vertical. A narrow bandpass filter can also be used to align for orthogonality. This method works well using natural outdoor lighting.

The technique used to calibrate wavelength to pixel index is to place the camera and filter assembly in a spectrometer sample compartment and scan the spectrometer through a range of wavelengths. Figure 9 shows the LVF camera in the sample compartment of the Cary spectrometer. Pixel location of the center wavelength versus spectrometer wavelength is presented in figure 10. Figure 11 and 12 present the camera frames at 600 and 850 nm respectively.



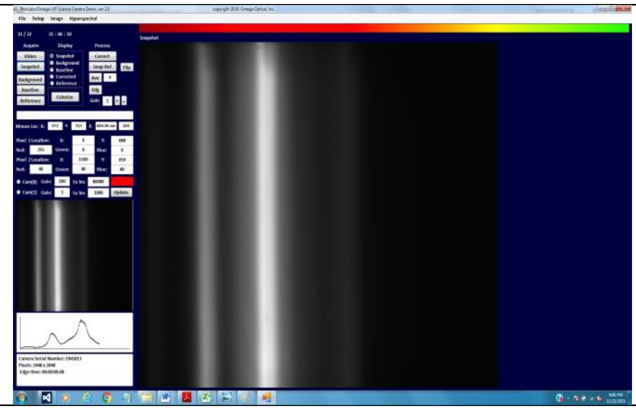
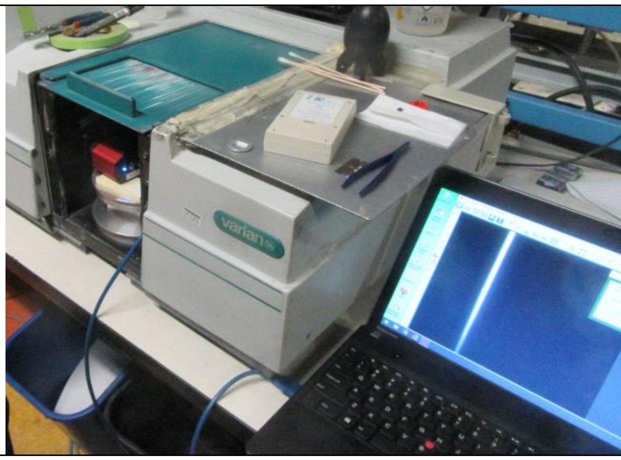


Figure 7: Filter performance is strongly influenced by F/# at the filter. This graph presents modeled transmission for the LVF filter at F/8, F/6, F/4, F/3, F/2.5 and F/2.

Figure 8: The filter mount allows a few degrees of rotation. This frame presents the LVF filter (no lens) imaging a florescent light spectrum. The filter is rotated to a position maximizing vertical alignment.



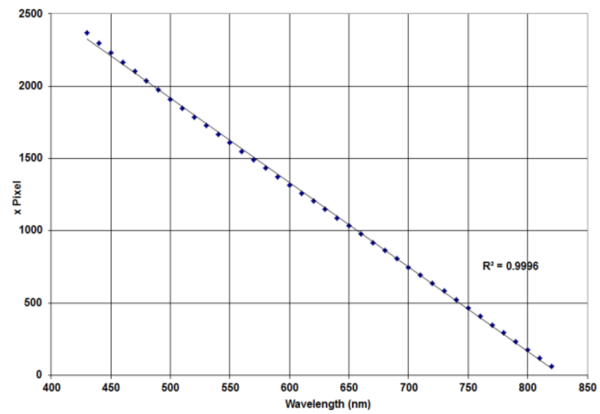


Figure 9: The LVF camera is calibrated for wavelength by placing the LVF camera, without a lens, in the sample compartment of a Varian CARY spectrometer.

Figure 10: Wavelength versus pixel location is recorded and a least square fit is generated. This is loaded into the camera software for calibration.

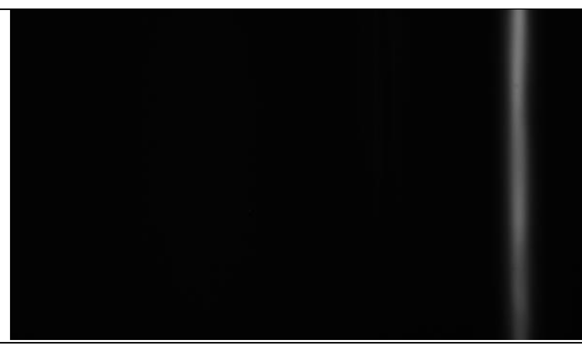


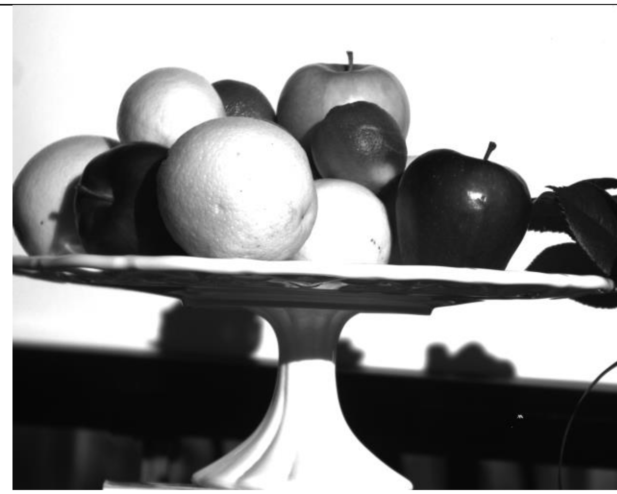
Figure 11: LVF Camera image in the Cary spectrometer at 600 nm.

Figure 12: LVF Camera image in the Cary spectrometer at 850 nm.

4.0 Applications

The LVF camera offers high 2 dimensional spatial resolution with moderate spectral resolution. Useful applications lie in the observation that the spectrum of many naturally occurring scenes of minerals or agricultural plots and are spectrally broad. The high spatial resolution allows for measurements of texture and fine detail. Mixed crops or regions of healthy versus infected plants can be discriminated.

Interpreting the images from an LVF camera can be challenging since the passband wavelength is changing spatially along the gradient axis but is constant along the orthogonal axis. Figures 14 through 16 compare filter Images using the Thorlabs CS505MU camera and different filters.

	
Figure 13: Color camera – no filter	**Figure 14: Black and white - uncoated glass**

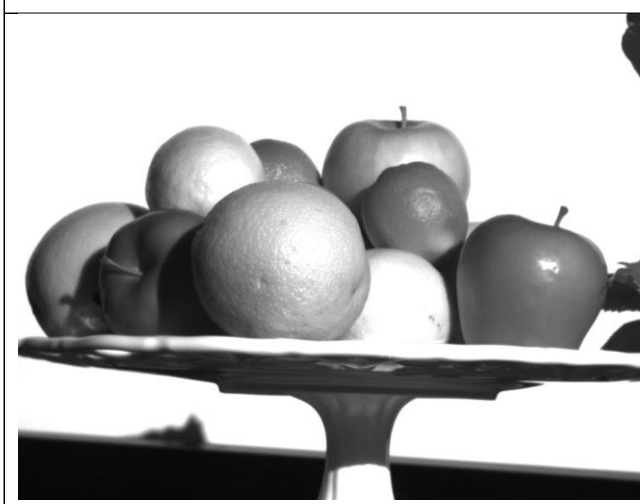



Figure 15: Fixed wavelength bandpass (610nm x10 nm bandpass filter	**Figure 16: LVF camera: note that longwave passbands are on the left – shortwave passbands are on the right.**

Figure 13 is a Bayer color image of a platter of fruit. Figure 14 is the scene photographed in monochrome with an uncoated glass substrate installed at the position of the linear variable filter. Figure 15 present the scene photographed using a narrowband width 610 nm bandpass filter. Figure 16 presents the scene in monochrome using the linear variable filter. Notice in particular the apples on the left and right sides of the platen. The apple on the right is very dark where the LVF center wavelength is blue and the apple on the left is bright in the red pass band region.

Application for the LVF camera can be divided into two classes depending on whether there is motion between the camera and the scene being viewed. If the camera and scene are held fixed, scanning across the frame in the direction of the LVF gradient results in a spectral scan similar to that of a single point spectrometer. Since the camera produces a 2 dimensional spectral scan, we term this mode of operation a field spectrometer. If the camera moves relative to the scene, a hyperspectral scan can be created at each point in the scene. Frames taken of the same point in the field but at different positions of the LVF bandpass allow for the creation of a spectrum of each point in the field. The spectral resolution of each point is a function of the number of overlapping but displaced frames as well as the bandwidth of the LVF passband and the performance of the optical system.

4.1 Field Spectrometer

Several examples of using the LVF camera are presented. Figures 17 and 18 present the transmission of narrow bandpass filter plates. The filter bandpass is 10 and 5 nm respectively. The camera is setup using a collimated light source and bandpass filters are inserted in the path between the source and LVF camera. The LVF camera offers a means of rapidly characterizing uniformity across the plates in the vertical direction.

Figure 17: 10 nm bandpass filter

Figure 18: 5 nm bandpass filter

Figures 19 and 20 present an example of emission spectroscopy. Figure 19 is a color photograph of the scene. Table salt (NaCl) is placed on an aluminum block and the salt is heated with a torch. Figure 20 is the same scene photographed using an LVF camera but the only region of the scene in the LVF frame is transmission at the sodium emission line wavelength.

Figures 21 and 22 present an example of using the LVF camera for product inspection. Figure 21 presents a color photograph of three beverage bottles take with a Bayer color camera. Figure 22 presents the same scene taken with an LVF camera. The black printing of the bottle on the left is clearly visible while the red is clearly visible on the right. A product inspection application where the bottles are on a conveyer and the bottles move past the LVF camera allows the monitoring of a number of spectral features including print quality and label integrity.

Figure 19: Bayer color photograph of NaCl on an aluminum block heated with a torch.

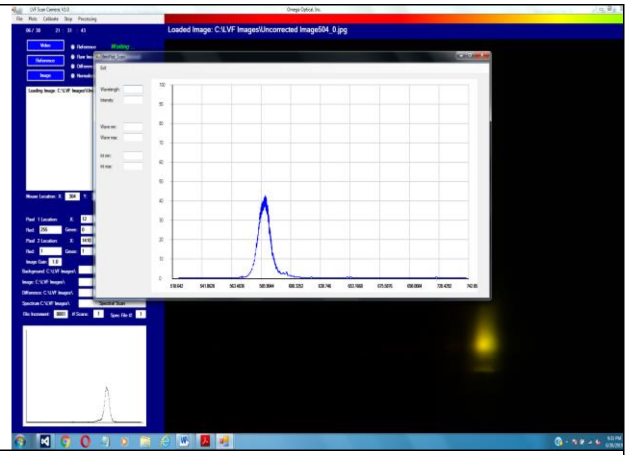


Figure 20: LVF camera scan of the same scene

Figure 21: Bayer color photograph of beverage bottles

Figure 22: LVF Camera (FLIR camera) photograph of same three bottles on left.

4.2 Spatial and Temporal Spectroscopy

Combining the high throughput of the filter with a high data rate digital camera allows the simultaneous capture of spectral, temporal and spatial data. To illustrate this, the LVF camera was taken to a fireworks display and the event was recorded with the camera running in video mode at 14 frames per second. An interesting set of frames is presented in figures 23 through 26. The frames are presented in false color using an algorithm to convert wavelength to perceived monitor color (RGB). The camera is a black and white camera and the false color is added so that it corresponds to the LVF filter wavelengths. The red passband is on the left side of the image with blue on the right. The camera is pointed towards the dust cloud (left by previous bursts) above the bomb burst. This particular burst is about halfway

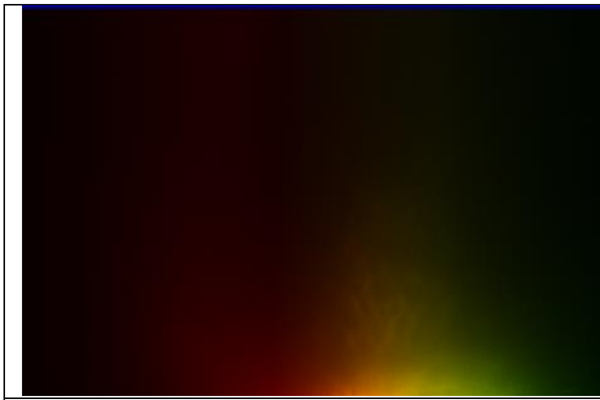


Figure 23: Characterization of fireworks: the camera is pointed above the blast at a region of smoke from previous blasts. The orange streaks are hypersonic particles from the blast as the compression wave has not yet entered the frame.

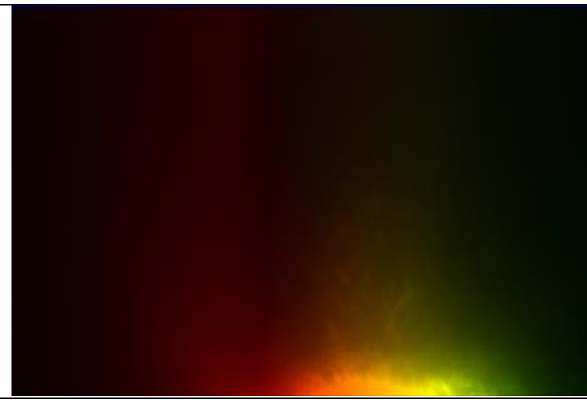


Figure 24: This frame is about 0.14 seconds later than the previous frame. High speed particles are present as is the appearance of the sonic compression wave. The sonic wave is compressing the dust cloud locally increasing the dust density and the reflection (apparent brightness) of the cloud.

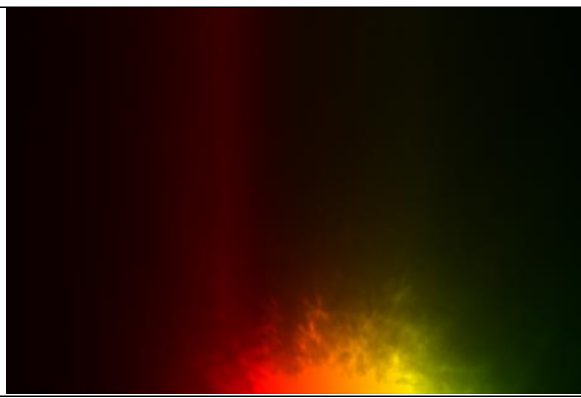


Figure 25: The compresion wave and sonic velocity particles are shown overlaid. The blast center is estimated to be about 140 feet below the bottom of frame.

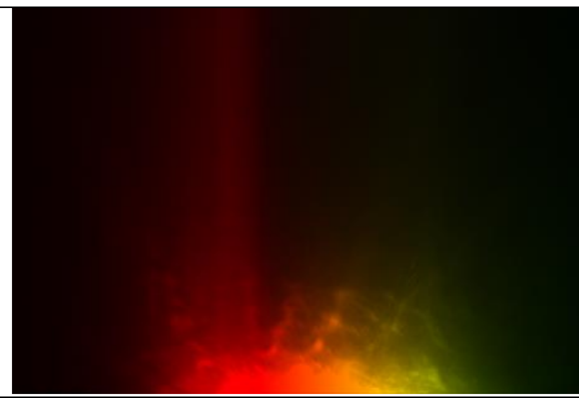


Figure 26: The compression wave has now moved into the field of view and nodes characteristic of wave interference patterns are seen. The red appears more intense. The nodes suggest coherent interference – possibly from sound emitted from opposing ends of the tube holding the charge.

through the fireworks event. The dust cloud acts a projection screen. The frames are taken at video speeds and are approximately 0.07 seconds apart in time. Figure 23 presents the light of the blast and trails of hypersonic particles. Figure 24 presents the appearance of the sonic wave from the bomb explosion at the bottom of the frame. Figures 25 and 26 present compression nodes of the sonic wave as it moves out from the bomb blast. The intensity of the red light increases in the later frames and the green is dying off more quickly that the red. Figure 27 presents scans through frames presented in figures 23, 25 and 26. These plots characterize the evolution of color in the first 0.5 seconds of the fireworks blast.

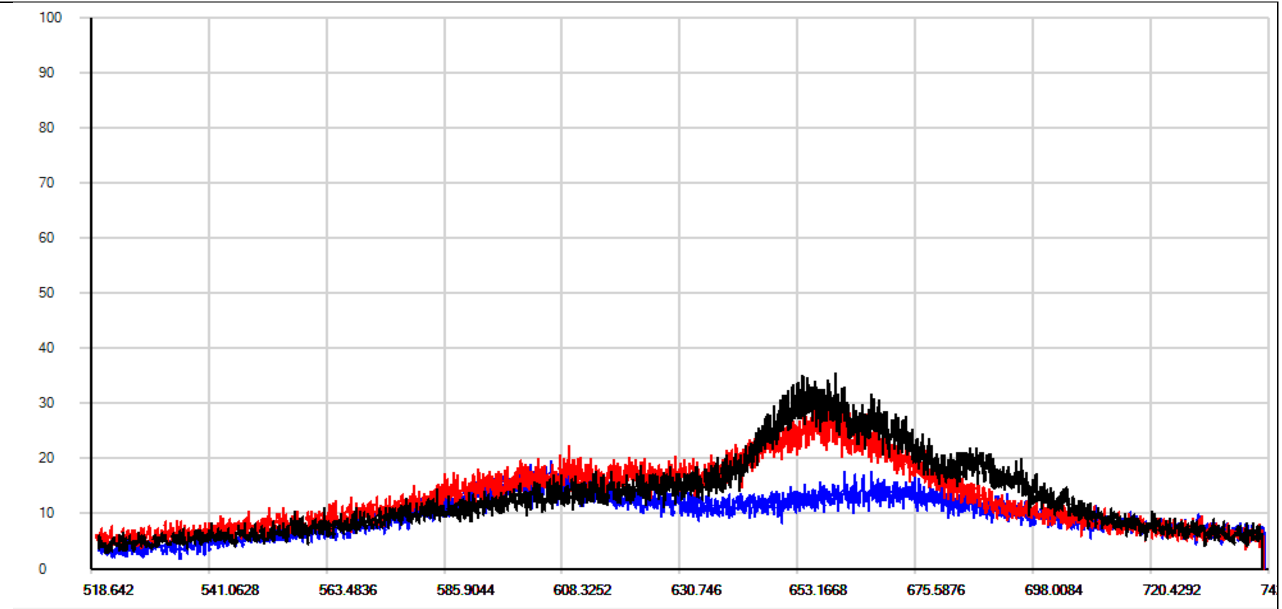


Figure 27: Spectral scan through the center of the previous frames showing a change in emission with time. The blue line is the first frame (figure 23), the red frame is figure 25 and the black frame is figure 26

4.3 Hyperspectral Imager

The NB-LVF camera can be used to create a hyperspectral dataset by collating images as the camera moves relative to the scene. This can be a result of using the camera in a push broom mode on a drone flying over an agricultural field or by rotating the camera on top a building and monitoring the emissions from smoke stacks across the city.

The process is demonstrated in three steps. The first step collects a series of frames at video rates. Each frame is correlated to the preceding frame and an x and y offset from the previous frame is calculated. A composite array is then assembled. Clicking on any point within the composite image then pulls up a spectral scan of that point.

The LVF camera does not generate a true hyperspectral data cube. The wavelengths in the spectrum correlate to the position of camera's LVF/pixel wavelength. A wavelength versus frame number is created for each pixel, but the spectral scan for each point will potentially contain a different number of points at different wavelength intervals from other points in the image. Nevertheless, the LVF camera images can be stitched together and each point can produce a unique spectrum allowing for identification or characterization of the object at that point.

The example presented in figure 28 illustrates the LVF filter used as a hyperspectral imager. The camera slowly rotates as it acquires 100 frames. The plot in the lower left displays the offset in x and y of each frame from the initial frame. The red line shows the displacement in X (rotation) and the black line shows the displacement in Y. The composite image shown in the expanded screen is the overlay of the 100 images corrected for the relative offsets of each image to each other. When clicking the mouse on any point in the expanded image, a spectral scan is generated and plotted on the graph in the bottom center of the screen.

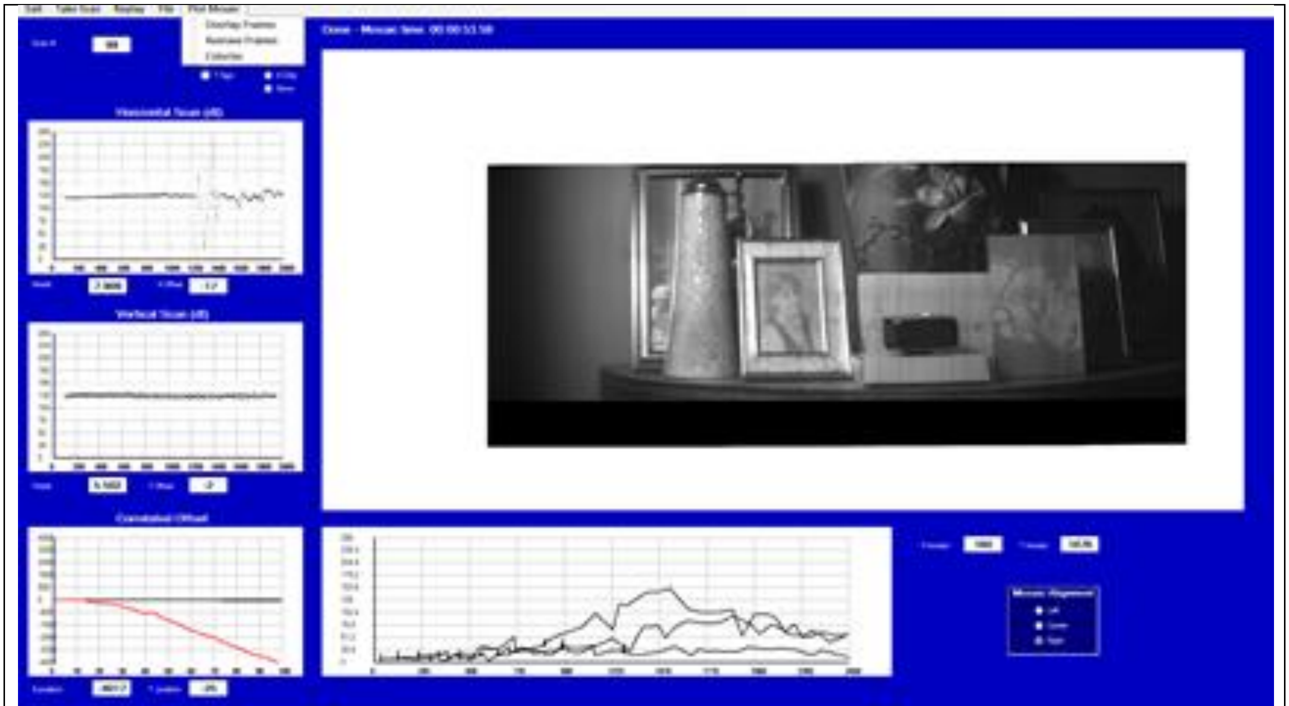


Figure 28: The LVF camera can be used as a cost, light weight hyperspectral imager. In this example, the camera is rotated 35^{o} while acquiring 100 frames. Each frame is correlated to the preceding frame and a composite image is generated. Clicking on any point in the composite image results in a display of the spectral signature of that point in the bottom center graph.

5.0 Conclusions

Using an NB-LVF camera, we can demonstrate a range of applications from industrial process control to the study of high speed transient events. Combining the high throughput of the linear bandpass filter with a high performance digital camera allows of simultaneous acquisition of spectral, spatial and temporal data. We installed the LVF in two camera types. The cameras were not modified in order to accommodate the LVF and we were able to demonstrate the LVF camera as a field spectrometer and as a hyperspectral imager. Nevertheless, optimizing the optical design would be expected to maximize performance.

6.0 References

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