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NATURAL-BACKGROUND-ORIENTED SCHLIEREN IMAGING

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ABSTRACT : *The background-oriented schlieren (BOS) flow visualization method has the potential for large-scale flow imaging outside the laboratory by using natural backgrounds instead of the artificial patterns normally used indoors. The natural surroundings of an outdoor test site can sometimes be used as such a background, subject to criteria of fine scale, randomness and contrast that are developed here. Some natural backgrounds are more appropriate than others for a given application. Backgrounds used here to visualize both high- and low-speed schlieren disturbances include a sunlit cornfield and a backlit grove of trees. The distances from the test object to the camera and to the background must be chosen to provide adequate sensitivity and reasonably-sharp focus. A digital camera with high pixel resolution is needed, and a high-speed imaging capability is required for all but quasi-steady phenomena observed in very calm weather. Image post-processing methods are considered for both qualitative and quantitative BOS. It is found that high sensitivity and a broad measuring range are in conflict here, much as they are in traditional schlieren instruments. Applications of natural-BOS include explosive characterization, firearms and artillery testing, chemical and natural-gas leak detection, and related phenomena.*

1 Introduction

The use of traditional schlieren visualization methods is frequently limited by the small size and indoor location of the typical optical components employed. These limitations not only restrict the potential field-of-view of an experiment, but also prohibit the study of large equipment or phenomena that cannot typically fit into the laboratory. The background-oriented schlieren method, however, has the potential to alleviate such limitations by allowing experiments outdoors.

Background-oriented schlieren (BOS) is the modern name for Hubert Schardin's simple background-distortion schlieren method of 1942 [1, 2]. This technique allows refractive objects to be visualized by their distortion of a patterned background. The background distortion is directly related to the strength of the schlieren object as well as the optics and physical geometry of the experiment [2]. By comparing two images of the background, one with the schlieren object and one without, the density gradients within the schlieren object can be determined from the apparent shift in the background pattern [3]. Digital image pairs are typically analyzed through either image-reconstruction algorithms [3, 4] or particle image velocimetry (PIV) software [5] to determine the pixel shift caused by the schlieren object, thus the density gradients within the field of view.

Most often this approach uses modest laboratory-scale backgrounds of random dot patterns [4]. Richard and Raffel extended the approach to using white paint splatter on concrete and a grassy field as backgrounds to visualize compressible vortices from helicopter rotors [5]. They were the first to use “natural” BOS backgrounds, but they did not explore this topic in general.

Settles [6, 2] reviewed outdoor schlieren and shadowgraph imaging in detail. Outdoor schlieren observation by background distortion was examined in particular, and several examples were given (blast wave seen against clouds, jet aircraft shock waves and exhaust seen against a background tree-line or the sun, etc.). It was also shown that BOS is actually Schardin’s [1] canonical schlieren method #1. Readers are encouraged to see the pre-BOS historical survey in [6], which is omitted here due to space limits.

The present research explores the suitability of natural backgrounds for BOS visualization. Several natural backgrounds are used to visualize both high- and low-speed phenomena. A simple new approach is also found to process BOS image pairs in order to reveal pixel intensity changes qualitatively. Ultimately, these backgrounds and techniques are critiqued for their ability to render BOS visualizations and suggestions for the ideal natural background are presented.

2 Experimental Setup

2.1 BOS Sensitivity

Schardin’s [1, 2] schlieren method #1, being typical of BOS illumination, is illustrated in Fig. 1. Here, for simplicity, a single light-dark background boundary is shown. Point p in the schlieren object S refracts light through angle ε. This causes an apparent background shift or distortion of a point on the optical axis to a point at p´´. This shift is recorded by the camera.

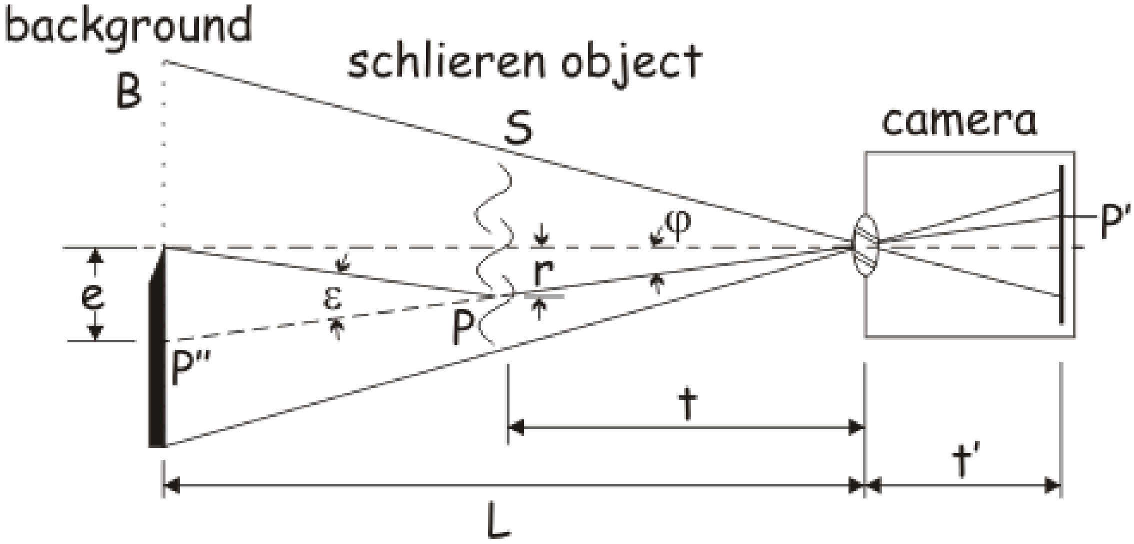

Fig. 1. Schardin’s schlieren method #1, the typical optical arrangement for BOS imaging.

The sensitivity of this system, i.e. the smallest density gradient that can be detected, is a function of the optical geometry shown in Fig. 1, the camera capability, and the strength of the schlieren object. For a given schlieren object, BOS sensitivity is influenced by the distance of the background to the object, L-t, and the distance L from the background to the camera [2, 4, 6, 7]. Camera lens focal length and pixel size also affect the ability to detect small disturbances [7]. In general, a distant background, imaged with a long-focal-length lens by a camera of high resolution (many small pixels), results in the greatest sensitivity. This is constrained, however, by depth-of-field, since maintaining both the background and schlieren object in reasonable focus is important for good photography. For the present work, the required sensitivity was established by choosing a suitable distance L-t, then t was chosen for acceptable depth-of-field. This procedure usually places the schlieren object about halfway between the camera and the background.

2.2 Background Selection

In the laboratory, random dot patterns can be easily generated and used as BOS backgrounds. A random dot pattern is ideal, providing high contrast and unique features from which image correlation algorithms can easily determine pixel shifts. In the field, though, creating such large artificial backgrounds is impractical. Instead, a natural background that exhibits the characteristics of a random dot pattern is desired: high contrast and random fine-scale structure.

The required background quality is also directly related to the object being visualized. For high-speed events, such as explosions, high background contrast is required to allow fast framing rates and brief shutter speeds. The needed contrast level also depends upon the analysis method or software to be used in processing the images. Background feature size limitations arise from the required schlieren resolution, and depend upon field-of-view, schlieren object strength, and image processing method. The background features must be large enough in the recorded images to allow the detection of pixel shifts. They must also be unique if image processing is to determine locations and their distortions accurately. Finally, background features need to be distributed uniformly; as demonstrated below, regions of low contrast or overlarge features results in the loss of data.

Two primary backgrounds are used here, the edge of a cornfield and a small grove of trees. The corn row used here was approximately 3 m high and was illuminated directly by the sun. This produced detailed highlights and shadows having a unique semi-random pattern. The grove of trees was approximately 30 m deep, allowing sufficient tree density while permitting sunlight trans-illumination from behind. On a winter afternoon in Central Pennsylvania the bare tree branches and trunks before the bright sky provided a high-contrast background with ample random detail. Various other natural backgrounds could also meet the above criteria, but are not explored here. A man-made background (corrugated steel silo) was also used in some of our early experiments.

2.3 Camera Properties

Our principal camera is a high-speed digital black-and-white Photron APX-RS. For low-speed thermal plume imaging, this camera records images up to 3000 frames per second (fps) with a 1024x1024 pixel resolution. High-speed images of gunshots and explosions were recorded at 15,000 fps with a pixel resolution of 1024x192. The shutter speed was independently set in each case based on the ambient light conditions, but was at most 10 µs for the high-speed-imaging case. Even for low-speed events, using a high-speed camera was found beneficial in reducing errors due to background motion caused by the wind, etc.

The camera was fitted with a Nikon 80-200 mm variable zoom lens. The f/stop was adjusted to allow both the background and schlieren object to be more-or-less simultaneously in focus. However, for all present BOS experiments the background was sharply focused while the subject was sometimes allowed to be slightly out-of-focus. Note that this conflicts with the philosophy espoused in [6], where a sharply-focused subject and a fuzzy background were used.

A Nikon D80 digital SLR camera was also used for the low-speed applications. This camera provided superior pixel resolution, thus potentially-higher BOS sensitivity than the Photron APX-RS. It was triggered remotely to avoid camera motion between images, which were typically separated by about 1 s. This consumer-grade digital camera was simple and portable for outdoor BOS experiments, but was limited to imaging low-speed events.

3 Experimental Results

3.1 Thermal Plume from a Hand-Held Propane Torch

A commercial Bernz-o-Matic^{TM} propane torch flame was used as our first schlieren object to evaluate different background and image-processing options. The torch flame creates a strong local density gradient and a well-defined thermal plume of at least 1 m extent.

The first experiment performed with this torch used a corrugated steel silo as the background. With direct sunlight illumination this silo approximates the type of grid commonly used for the background-grid-distortion schlieren imaging that was classified by Schardin [1, 2] as his “schlieren method #2.” Fig. 2 shows three approaches to the visualization of the hot torch plume. The raw image, Fig. 2a, was taken with the Nikon D80 camera using distances t and L-t both approximately 13 m. The torch plume can be seen as it distorts the boundaries of the corrugations. The pixel intensity change between the raw image and a tare image with no torch present is used to visualize the plume in Fig. 2b. The pixel shifts between the raw and tare images are then calculated using commercial software to create Fig. 2c.

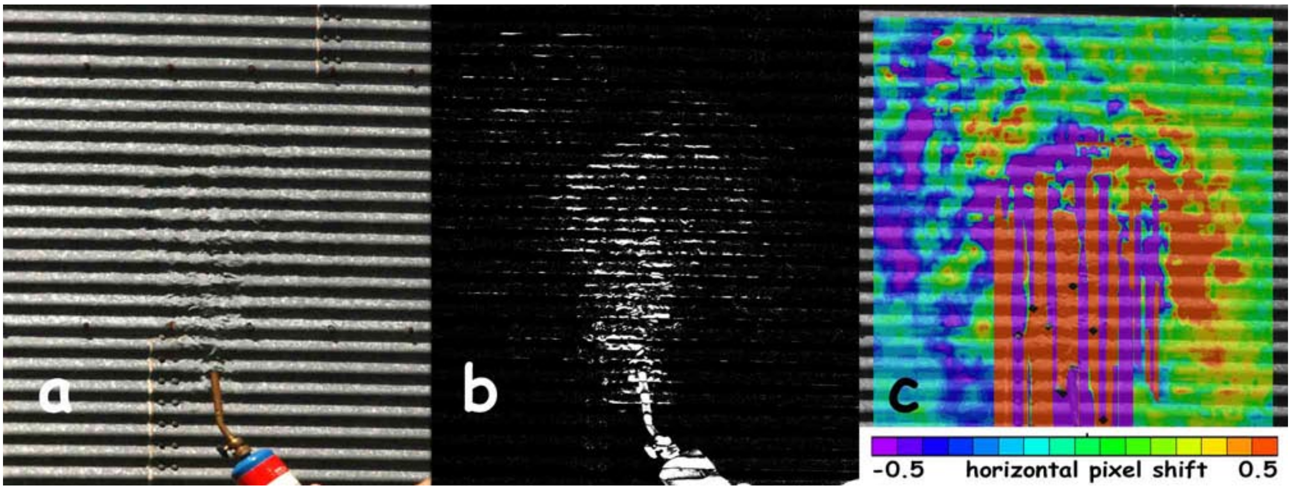

Fig. 2. Bernz-o-Matic^{TM} propane torch visualized against a corrugated silo background. The raw image (a) is compared to a tare image to determine the pixel intensity change (b) and the pixel shift (c).

Fig. 2b reveals the torch plume better than does the raw image a. The image processing highlights locations where the pixel value has changed, i.e. where a schlieren disturbance exists, and the distracting background grid pattern is largely removed. Quantitatively, the intensity of each pixel in the processed image, denoted “new,” is determined from the pixel intensities in the “hot” and “cold” (raw and tare) images according to Eqn. 1. The resulting processed image, Fig. 2b, shows only some residue of the corrugation pattern. The nearly-black background now makes it more difficult to detect small changes in the pixel intensity, however. The weak pixel-shifted bands also show some noise thought to be due to sunlight illumination changes between images.

$$new(i,j)=\frac{\left(hot(i,j)-cold(i,j)\right)^2}{\frac{hot(i,j)+cold(i,j)}{2}+1} \qquad (1)$$

Fig. 2c was created using Vic-2D® software from Correlated Solutions, Inc. The software determines the pixel shift at each pixel location by matching patterns in the surrounding pixels. It is not intentionally designed for the BOS application, but it was nonetheless found useful for determining shifts as small as 0.05 pixel between images. This sub-pixel resolution fails, however, when large vertical and horizontal shifts occur simultaneously, as in the center of Fig. 2c. Vertical stripes or "drop-outs" then occur. We are told that Correlated Solutions, Inc. is working on a solution to this problem that will make the Vic-2D® software more suitable for BOS imaging.

Overall, the corrugated steel succeeds conditionally as a BOS background even though it lacks the desired fine-scale random features. While they are not naturally occurring, corrugated buildings can nonetheless serve as useful backgrounds for large-scale outdoor BOS imaging. Still, our search for true natural BOS backgrounds continues.

The grove of trees described in Sec. 2.2 was tried next. With our high-speed camera positioned approximately 40 m in front of the treeline, the propane torch plume was again visualized. Fig. 3 shows the original image and field of view (a), along with three BOS images of the torch plume processed according to Eqn. 1, and having time separations between images of 0.667 ms (b), 2 ms (c), and 10 ms (d).

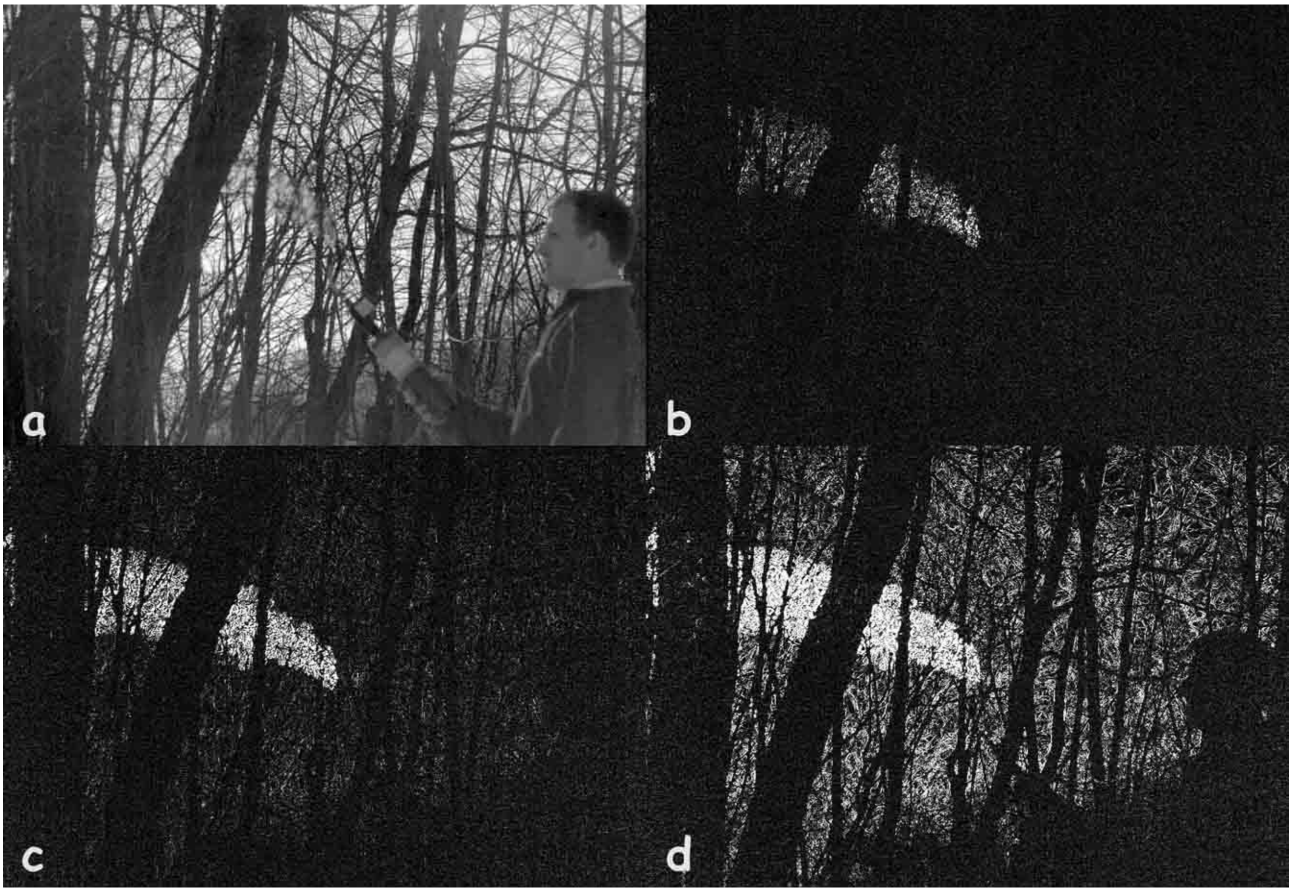

Fig. 3 Images showing torch plume visualized against a background of trees trans-illuminated by the afternoon sunlight. The original image (a) is compared to images taken 0.667 ms (b), 2 ms (c), and 10 ms (d) later.

In this case a tare image is not used; rather two subsequent images from the high-speed camera sequence are compared by the image analysis. This highlights the unsteady nature of the torch plume. Figs. 3b-d clearly show a light breeze carrying the torch plume right-to-left across each frame. Short time differences between these processed image pairs, e.g. Fig. 3b, help to limit background variations caused primarily by the wind shifting the trees. A longer time delay between images also improves the plume visibility, which is linked to the timescale of the plume motion, but brings up the background noise as well, e.g. Fig. 3d. In that the plume is mixing with surrounding cold air, its refractions decrease with downstream distance and thus become less visible. Within limits, larger time delays between frames help maintain the plume visibility and better reveal its entire extent. Slower phenomena are also more easily visualized with larger time steps between the processed images. However, the ~ 1 s delay inherent in Nikon SLR camera images is too long to avoid excessive background motion, except perhaps in the case of a perfectly calm wind.

This natural tree background is more appropriate for present purposes than the corrugated steel used earlier because it has finer detail and more pattern randomness. Areas in the background of the original image, Fig. 3a, having many thin branches at odd angles, reveal the plume well. The thicker tree trunks, however, cause a local loss of data due to the inability to determine pixel shifts in regions of featureless black background. With increased illumination of the trunks themselves, yielding textured surfaces, data might be obtained in these regions. This was not feasible, though, in the present series of experiments.

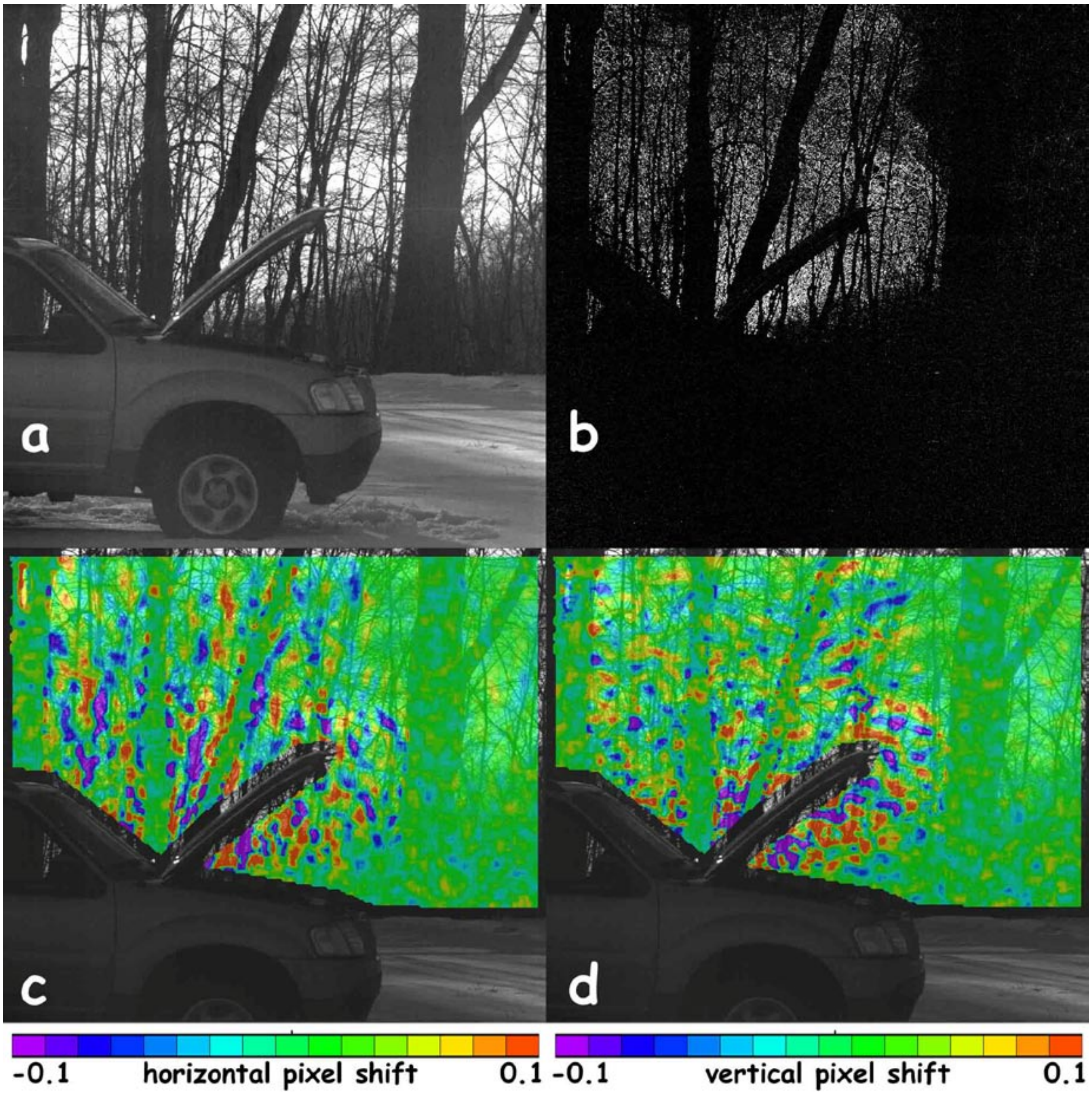

Fig. 4. BOS images showing the thermal plume of a hot truck visualized against a background of trees. The original image (a) is compared with an image taken 100ms later to determine the percent pixel intensity change (b) and the horizontal (c) and vertical (d) pixel shifts.

3.2 Thermal Plume from a Hot Automobile Engine

The tree background was also tried for the natural BOS visualization of a weaker thermal disturbance, the thermal plume rising from a hot automobile engine. Fig. 4 shows the same tree-line background as before, but now with a truck at operating temperature with hood open in the schlieren-object position (20 m in front of the tree-line). The original image, Fig. 2a, is compared with an image obtained 100 ms later in Fig. 2b, where Eqn. 1 has once again been used. The overall shape of the thermal plume rising from beneath the hood, and from the truck in general, is revealed. The same two images were also compared using the Vic-2D® software in Figs. 4c and 4d.

Based on Fig. 4, the weak truck plume is difficult to visualize with the present background and sensitivity level. The Vic-2D® software also reveals the gross outline of the plume without showing any coherent plume structure. Both horizontal (c) and vertical (d) pixel shifts are shown, though little difference can be seen between them. In general, the pixel shift direction should be selected in the same manner as one would choose a horizontal or vertical knife-edge orientation in conventional schlieren imaging [2]. The Vic-2D® software is most effective where unique background features are present, but also fails across the largest tree trunks. This weak-plume visualization could be improved with more sensitivity and a better tree-line background, but the latter was not attempted here.

Instead, the sun-illuminated cornfield described earlier was found to be a more appropriate background for this schlieren object. In bright sunlight the corn provides a near-random natural pattern of light and dark patches that is ideal for BOS. The height of the corn, approximately 3 m, limits the vertical field-of-view but the horizontal field-of-view can be many meters long. For visualizing the truck plume, the camera was positioned at approximately L = 75 m from the corn-row background and the truck was again located approximately halfway between the two. Note that this almost doubles the tree-line BOS sensitivity, based on the geometrical optics of Fig. 2.

Fig. 5 shows the truck and the corn background in the original image (a), and the pixel shift (b) between that image and one recorded 7 ms later, as determined by the Vic-2D® software. Now the thermal plume is clearly seen rising from the engine compartment. Other thermal plumes also rise from the truck aft of the engine compartment. This increased sensitivity, relative to that of Fig. 4, reveals more physics of the flow and is ascribed to doubling L-t and a better natural background.

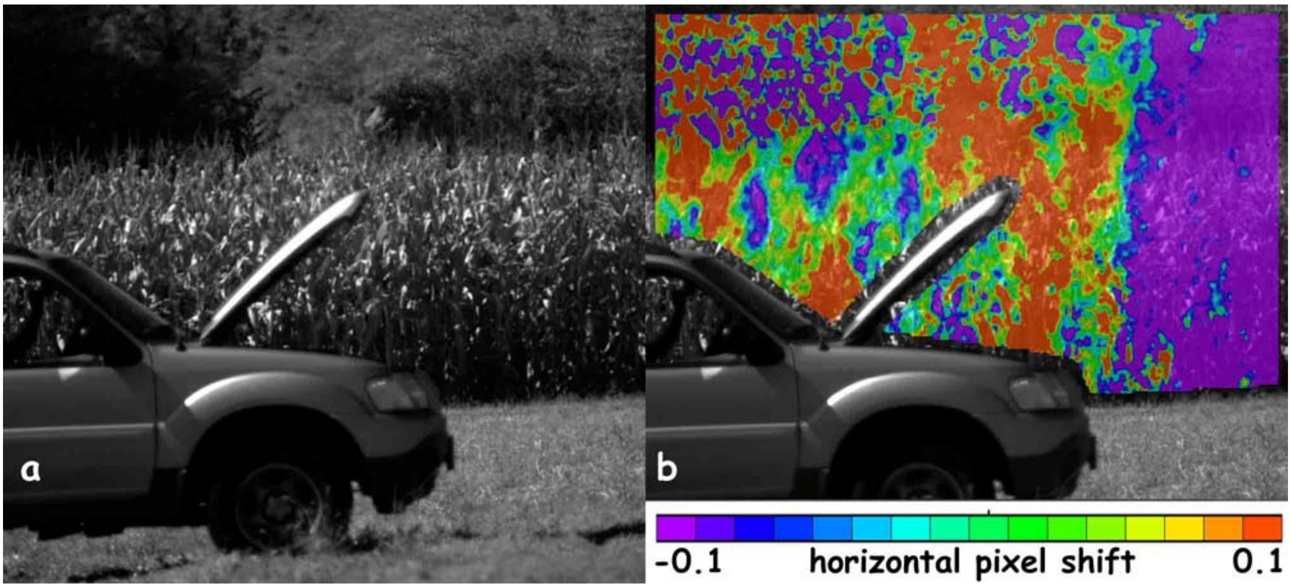

Fig. 5 Image showing a hot truck engine plume visualized against a background of corn. The original image (a) is compared to one recorded 7ms later to determine the horizontal pixel shift (b).

While Fig. 5b shows the thermal plume distinctly against the corn background, above the corn it is limited by the poor quality of the background there. The top left corner of the background in Fig. 5a is dark and featureless, thus providing only weak disjointed correlations. The remainder of the background above the corn has some texture and provides a different sensitivity level, since the distance L-t from background to schlieren object is increased there.

In order to visualize this weak plume by BOS, an ideal background and high sensitivity are called for. The cornfield background used here is near-ideal because of its high contrast and randomly-detailed texture. Even so, additional sensitivity obtained by increasing the distance L-t between Figs. 4 and 5 visibly improves the visualization.

3.3 Shock Waves in the Discharge of a .30-06 Rifle

A high-powered.30-06 rifle is next used to explore the potential for high-speed visualization of shock waves using the BOS technique with natural backgrounds. This rifle discharge has been previously visualized using the Penn State Gas Dynamics Lab's Full-Scale Schlieren system [8]. The goal of the present work is to reproduce this visualization with a cornfield background.

The cornfield was again illuminated by direct sunlight and the camera was placed at approximately L = 25 m from the corn row with the subject located midway between the two. The corn was selected here for its near-ideal background properties, even though the large refractive disturbance of the muzzle blast was not expected to require ultimate schlieren sensitivity. The camera shutter speed setting was 10μs, the fastest speed available while still maintaining sufficient exposure of the subject and background, and images were obtained at 15,000 fps.

Fig. 6a shows an image recorded approximately 0.67ms after the bullet emerges from the gun barrel. This image is compared with a "tare" image taken immediately before the bullet emerges from the barrel in Fig. 6b, where the intensity differencing scheme of Eqn. 1 is once again applied. The horizontal pixel shift between the two images, computed by the Vic-2D® software, is shown in Fig. 6c. Finally, a Full-Scale Schlieren System image of the .30-06 rifle discharge [8, 9] is shown in Fig. 6d for comparison.

Given only the image in Fig. 6a, the eye can discern little more than some muzzle flash and distortion. The pixel-intensity-difference image, Fig. 6b, shows the spherical muzzle-blast shock wave, the emerging propellant gases and the bullet, but fails to clearly show the oblique shock waves streaming back from the bullet. The high background noise level characteristic of such images sets a limit on the visible detail. The pixel shift image, Fig. 6c, reveals the muzzle blast well, but is not sensitive enough to capture either the bullet or its oblique shocks. It does, however, yield pixel-shift direction information in color that is lacking in Fig. 6b. The Vic-2D® software once again has trouble with the muzzle blast due to significant pixel shifts in multiple directions, preventing it from correlating some locations and leading to the banding or "drop-outs" in Fig. 6c.

In all these images some shock wave blurring (at least several mm) occurs due to the 10μs shutter speed used here. Better illumination or a faster camera lens, by providing a shorter exposure, would allow sharper BOS images without requiring a significant sensitivity increase.

Finally, it is obvious that none of the natural BOS images can compete with Fig. 6d in terms of resolution, sensitivity, or visual appeal. Note, however, that this Full-Scale Schlieren image was taken in a large indoor facility that was developed over a period of several years with the expenditure of considerable time, effort and money [2, 8-10], whereas Figs. 6a-c were shot during an excursion to a country cornfield on a sunny afternoon.

3.4 Shock Waves from an Explosion

Since the cornfield background has proven the most successful so far, we stay with it for a final example of natural BOS imaging using a 1-gram charge of triacetone triperoxide (TATP), a primary

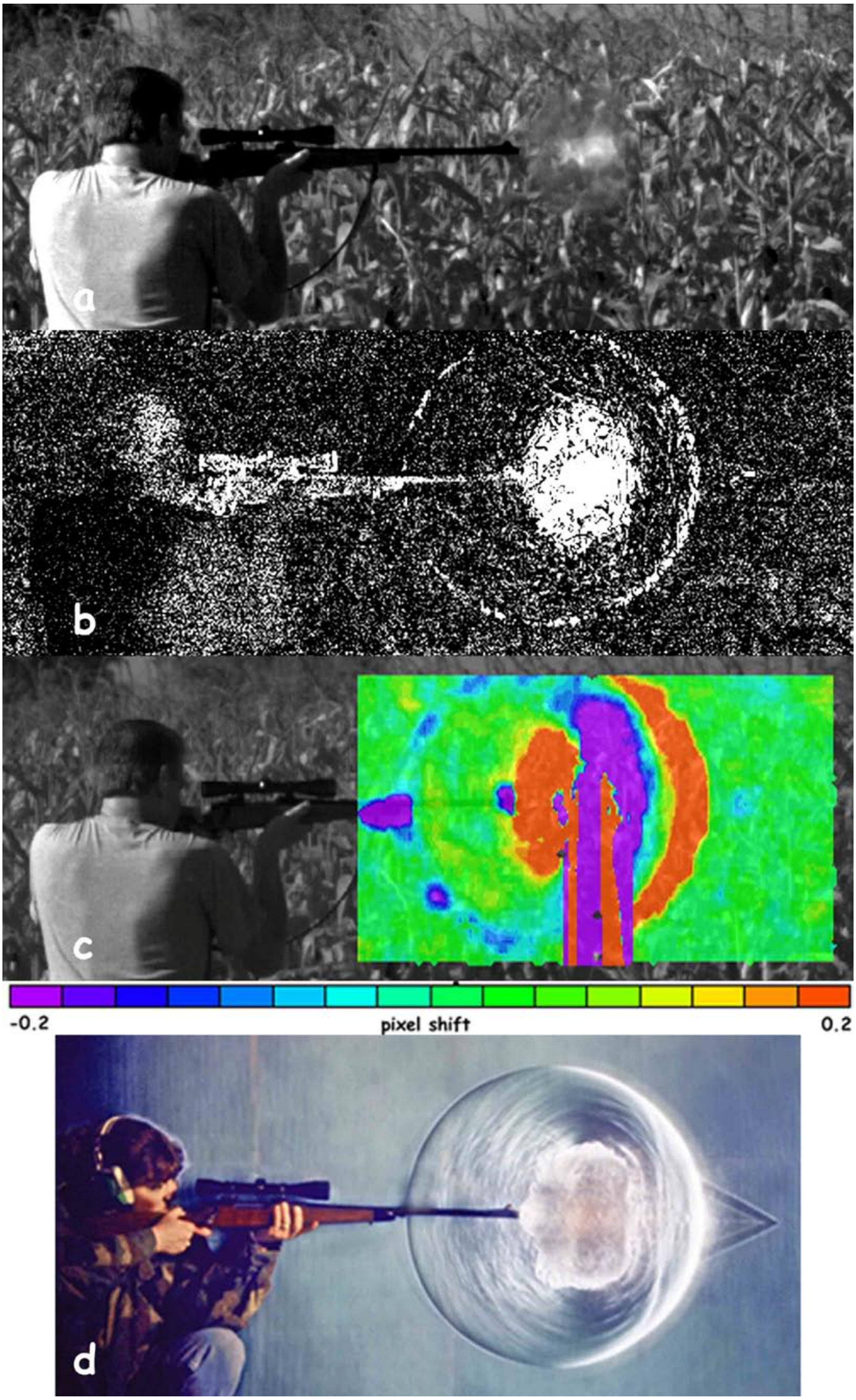

Fig. 6. High –speed images of a .30-06 rifle discharge showing the muzzle blast and supersonic bullet. A raw image (a) is compared with a tare image to find the pixel intensity change (b) and the horizontal pixel shift (c). The BOS images (b) and (c) show different views of the gunshot also imaged using the PSGDL Full-Scale Schlieren system (d) [8, 9].

explosive. This charge was exploded and imaged using the same camera settings and physical distances as in the previous section, so the schlieren sensitivity remains unchanged. The explosive charge was suspended on a wooden stake in the field of view, as can be seen in Fig. 7a.

The intensity images in Fig. 7b-d show the shock wave propagating out from the explosion center. These images also show disturbances caused by the gaseous fireball of the explosion. This technique could be used to track the spherical shock wave propagation away from the explosion center in order to characterize the explosive yield, as was previously done by shadowgraphy [11]. The same characterization process could then be applied to field tests of large explosive charges that cannot be safely tested in the laboratory, but can be exploded at an outdoor range with an appropriate natural background for BOS imaging.

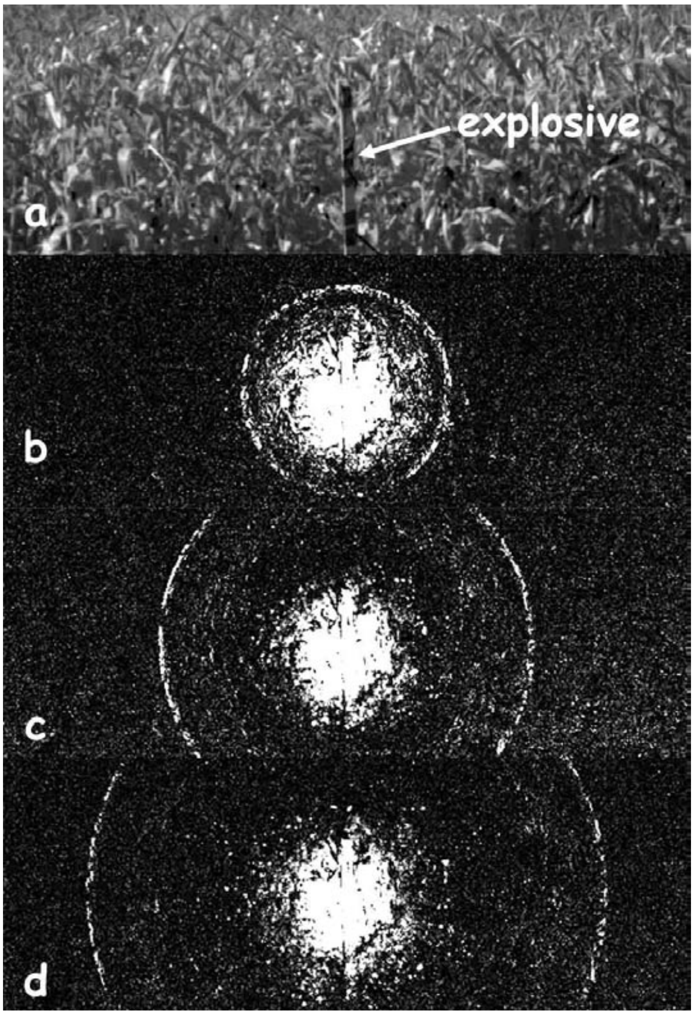

Fig. 7. Images of a 1-gram TATP explosion showing shock propagation. Pixel-intensity-difference images are obtained from reference frame (a) and later images at times of 0.67 ms (b), 1.33 ms (c), and 2.0 ms (d) after the explosion.

4 Conclusions

Background-distortion schlieren is not a new idea, having doubtless been observed outdoors long before it was described by Hooke, Mach, and Schardin [2]. The relatively-new background-oriented schlieren (BOS) visualization method likewise has the potential for flow visualization outside the laboratory using natural backgrounds. The natural surroundings of an outdoor test site, for example, can be used as a background against which to examine pixel shifts caused by schlieren effects produced during the testing. By taking advantage of such natural backgrounds, some of the size and cost limitations of BOS imaging can be overcome.

The choice of a natural background, however, requires one to consider both the nature of the phenomenon to be visualized and the requirements of the image processing method to be used in data reduction. For typical BOS image processing, an ideal background consists of small, high-contrast, randomly-distributed features. The desired background feature size is directly related to the schlieren object distortion strength, since schlieren distortions should be about the same size as the background features. Of the two natural backgrounds used here, appropriate feature size was demonstrated by a cornfield while a backlit tree grove caused data loss in some locations where there were thick tree trunks.

Effective BOS visualization outdoors also requires an optical setup, though a simplistic one, that is chosen to effectively visualize the disturbance of interest. For weak disturbances, a long object-to-background distance is needed for schlieren sensitivity. This usually implies a long camera-to-object distance as well, in order to maintain sharp focus of both the object and the background. Selecting an appropriate camera and lens combination is also important: we found that a long-focal-length lens and a digital camera with large pixel resolution provided the maximum BOS sensitivity once the object-to-background distance was set.

A typical BOS experimental setup is constrained by the required field-of-view and the illumination requirements of the available camera. With fixed camera resolution, the camera-to-background distance is first determined in order to obtain an appropriate pixel shift against the desired background. The schlieren object is then located in the field of view at approximately the halfway point between the camera and background in order to maximize sensitivity while maintaining sharp focus.

Following the experiment, the resulting images are processed to highlight pixel changes between image pairs caused by the schlieren object. The choice of image processing technique dependents on the desired result, and can be the most involved part of the process if quantitative pixel-shift data are desired. A simple pixel-intensity-differencing algorithm was shown effective here for qualitative natural-BOS imaging. Commercial digital-image correlation software was also applied to measure sub-pixel shifts quantitatively. This approach failed when the background distortion exceeded a certain threshold, demonstrating that BOS, like traditional schlieren, suffers a compromise between high sensitivity and a broad measuring range [2].

High-speed outdoor BOS imaging imposes further constraints: Digital cameras like the one used here lose pixel resolution by segmenting the sensor array as the frame rate increases. Further, the need for short exposure times at high frame rates demands strong illumination and high background contrast. In reality, image underexposure becomes likely at high frame rates; it occurred in the present experiments, but was correctable after the test by image post-processing.

The natural-BOS results obtained here do not have the fine, almost-artistic quality attainable in laboratory schlieren images. On the other hand, no refined optics are required beyond the camera and its lens, and a large field-of-view is had without needing a Palomar-scale parabolic mirror. In the spirit of Hooke, Mach, and Schardin, the present approach takes advantage of backgrounds and illumination already supplied by nature.

Overall, natural-background-oriented schlieren imaging can be used in a variety of outdoor applications where the typical methods of optical flow visualization cannot be applied. It mainly requires sufficient physical space, camera resolution and speed, and proper image-processing routines. Applications that have yet to be tried include full-scale explosives field testing, external artillery ballistics, and chemical and natural-gas leak detection [12, 13], to name a few. Other potential natural and quasi-natural backgrounds, yet to be tested, include striated canyon walls and cliffs, the mottled background of the desert, and stucco and split-face masonry walls in oblique sunlight.

References

[1] Schardin H, 1942. "Die Schlierenverfahren und ihre Anwendungen," *Ergebnisse der Exakten Naturwissenschaften*, Vol. 20, pp 303-439, 1942.

[2] Settles GS. *Schlieren and shadowgraph techniques: Visualizing phenomena in transparent media*, Springer-Verlag, 2001.

[3] Venkatakrishnan L and Meier GEA. Density measurements using the background oriented schlieren technique. *Experiments in Fluids*, Vol. 37 No. 2, pp 237-247, 2004.

[4] Meier GEA. Computerized background-oriented schlieren. *Experiments in Fluids*, Vol. 33, No. 1, pp 181-187, 2002.

[5] Richard H and Raffel M. Principle and applications of the background oriented schlieren (BOS) method. *Measurement Science & Technology*, Vol. 12, No. 9, pp 1576-1585, 2001.

[6] Settles GS. Schlieren and shadowgraph imaging in the great outdoors. *Proc. 2nd Pacific Symposium on Flow Visualization & Image Processing*, PSFVIP-2, Honolulu, ed. Mochizuki S. Paper PF302, 1999.

[7] Goldhahn E and Seume J., 2007. The background oriented schlieren technique: Sensitivity, accuracy, resolution and application to a three-dimensional density field. *Experiments in Fluids*, Vol. 43 No. 2-3, pp 241-249, 2007.

[8] Settles GS and Dodson LJ. Full-scale schlieren visualization of supersonic bullet and muzzle blast from firing a .30-06 rifle. *Journal of Visualization*, Vol. 8, No. 1, p 6, 2005.

[9] Settles GS. High-speed imaging of shock waves, explosions and gunshots. *American Scientist* Vol. 94, No. 1, pp 22-31, 2006.

[10] Settles GS. The Penn State full-scale schlieren system. *Proc. 11th International Symposium on Flow Visualization*. eds. Mueller TJ and I Grant, Notre Dame University, Paper 76, 2004.

[11] Hargather MJ and Settles GS. Optical measurement and scaling of blasts from gram-range explosive charges. Shock Waves, Vol. 17, No. 4, pp 215-223, 2007.

[12] Peale RE and Summers PL. Zebra schlieren optics for leak detection. *Applied Optics*, Vol. 35, No. 22, pp 4518-4521, 1996.

[13] Settles GS. Imaging gas leaks by using schlieren optics. *Pipeline and Gas Journal*, Vol. 226, No. 9, pp 28-30, 1999.