# BACKGROUND-ORIENTED SCHLIEREN VISUALIZATION OF HEATING AND VENTILATION FLOWS: HVAC-BOS

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KEYWORDS:
**Main subject(s):** *heating, ventilation, air conditioning, flow visualization*
**Fluid:** *air*
**Visualization method(s):** *background-oriented schlieren*

ABSTRACT : *There is an important need for simple methods to visualize and measure whole-field airflow patterns in the heating, ventilation, and air-conditioning (HVAC) field. We propose background-oriented schlieren (BOS) as such a method. The equipment required is simple, portable, and readily available, the most-expensive item being image-processing software. In this regard BOS supersedes previous lens-and-grid schlieren techniques that require large fixed installations. A custom random-dot background pattern is used, and imaging is done by a consumer-grade digital single-lens-reflex (SLR) camera. Examples are shown of visualized airjets and plumes from heating vents and registers, a space-heater and a teakettle. BOS images of candle plumes are also used to explore several different visualization approaches, equipment arrangements, and image color scales. While current results are purely-qualitative visualizations, quantitative temperature measurements can also be made in certain cases where the flow is approximately two-dimensional. Finally, BOS lends itself well to certain HVAC chores such as the diagnosis of commercial kitchen ventilation (CKV) airflows.*

## 1 Introduction

In 2007 M. Sandberg published a review entitled "Whole-field measuring methods in ventilated rooms" [1]. He surveyed particle-image-velocimetry (PIV), particle streak velocimetry, tomography of smoke plumes, IR imaging, and large-field schlieren imaging, although the schlieren references he cited are from the period before background-oriented schlieren (BOS) became readily available.

The most successful method surveyed by Sandberg was a simple and ingenious use of ordinary window-screen stretched across a room. Temperature variations imposed upon the window-screen by the airflow were observed using an infrared (IR) camera [2]. However, this approach is intrusive to the room airflow and has other problems, such as radiation between the screen and the walls, no frequency response, and the need for an expensive camera. Here we suggest a different approach: background-oriented schlieren for the non-intrusive imaging of ventilation airflows.

The BOS technique was introduced almost simultaneously by Meier [3] and by Dalziel et al., who called it "synthetic schlieren" [4]. In its simplest form it consists merely of a randomly-speckled background and a camera. High-resolution images are made of the background by the camera with and without refractive disturbances between the two. Post-processing of image pairs using PIV or digital image correlation (DIC) software then reveals small distortions of the background due to refraction.

Of course, these authors were not the first to discover the background-distortion effect of transparent refractive media. That was published by Hooke in 1665 [5], who saw the convection currents about hot objects in air by the distortion of a background, such as a tree. More recently Schardin [6] established this as a rudimentary *schlieren technique*, albeit one without the explicit knife-edge cutoff that is traditionally required [7, 8]. Schardin photographed glass objects against a background grid pattern, then removed the background photographically to reveal the schlieren image. Thus Hooke and Schardin were the true inventors of BOS/synthetic schlieren, except that they lacked the crucial *software*. Neither the camera nor the background is essentially new in BOS, but the addition of modern digital image processing makes a new and valuable flow visualization technique.

## 2 Experimental setup

Schardin's [6] schlieren method #1, being typical of BOS illumination, is illustrated in Fig. 1. Here, for simplicity, a single light-dark boundary is shown in the background. Point *p* in the schlieren object *S* refracts light through angle $\varepsilon$. This causes an apparent background distortion or shift of a point on the optical axis to a point at $p''$. This shift is recorded by the camera.

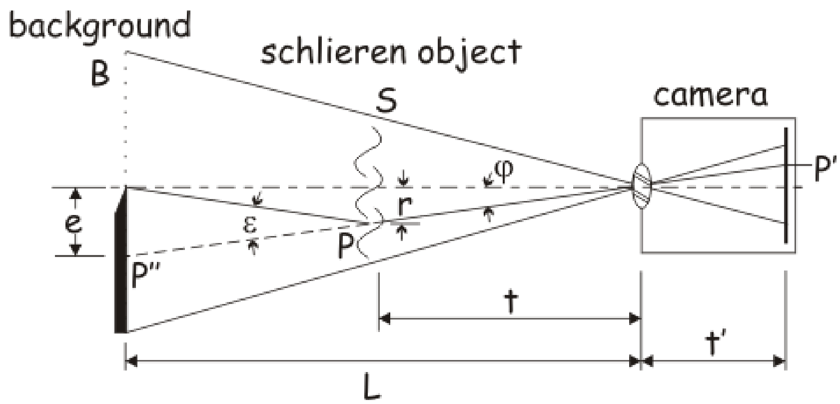


Fig. 1. Schardin's schlieren method #1, the typical optical arrangement for BOS imaging.

The sensitivity of this system, i.e. the smallest density gradient in *S* 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 from the object, *L-t*, and the distance *L* from the background to the camera. Camera lens focal length and pixel size also affect the ability to detect small disturbances. In general, a distant background, imaged with a long-focal-length lens by a camera of high resolution, 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 the success of the BOS processing and for good photography. In the present work, the required sensitivity was established by choosing a suitable distance *L-t* within the constraints of a given room, and then *t* was chosen for acceptable depth-of-field. This procedure usually places the schlieren object about halfway between the camera and the background.

The background for BOS imaging is composed of random patterns on a scale that can be clearly and uniquely imaged by the camera, which is focused upon it [9]. By incorporating different-scale "noise" into the background pattern, we have found that results are qualitatively better than those from a purely-random pattern (Fig. 2). The incorporation of these different background scales facilitates the simultaneous imaging of a wide range of schlieren disturbance scales, *e.g.* different turbulent structure sizes, and allows the background to be used for a range of distances *L*. These qualitative observations are similar to those seen in related fields where random patterns are used to resolve image details or pixel deformations [10, 11].

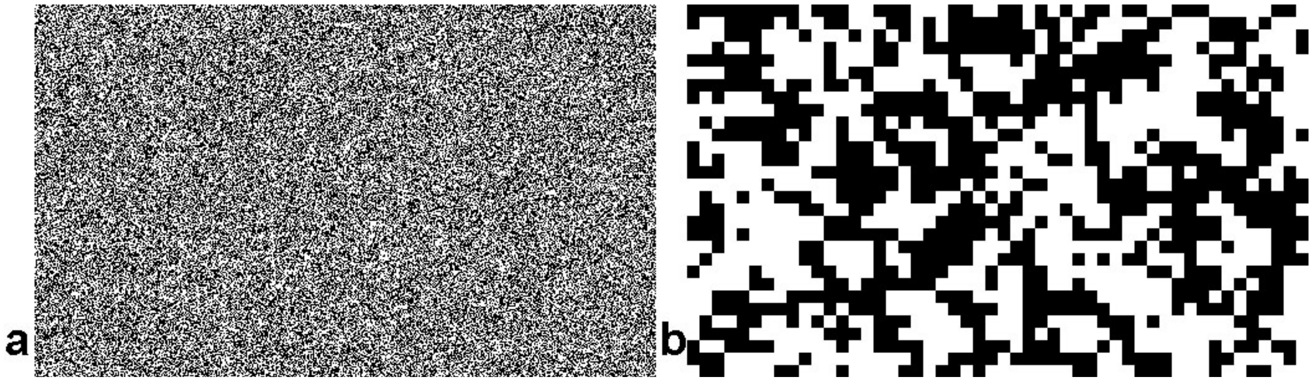


Fig. 2. (a) A random dot pattern created using the MATLAB command *rand* and then thresholded using *im2bw* creates a simple background with a fine-scale structure. This background works well so long as the individual pixels can be resolved by the camera. (b) A pattern with 10-, 20-, and 30-pixel “structures” created with MATLAB can be useful for imaging a range of phenomena. Small disturbances will not be observed if the pixel shift does not cross a light-dark boundary, while large disturbances can become difficult to process with random background “a” due to significant pixel shifts. Ultimately the background pattern should be “tuned” to the phenomenon under study for best results. Both backgrounds shown here are monochromatic in order to maximize the contrast of pixel shifts and to improve processing with PIV and DIC software.

To perform the BOS visualization, two images of the background behind the flowfield of interest are recorded using a digital camera. It is important to minimize camera motion and shutter jitter, and to avoid any changes in field-of-view or lens zoom between images. A consumer-grade Nikon D90 single-lens-reflex (SLR) camera with an 18-135mm zoom lens and 12.3 megapixel resolution was used for the majority of present images, although similar cameras by other manufacturers would serve as well. A modern digital SLR camera is preferred here because it provides high pixel resolution (thus high sensitivity), ease of use, portability, and a modest cost of less than $1000. A Photron SA-1 high-speed digital video camera was also used in the case of Figs. 3c-d to show the importance of time resolution, but this expensive camera is not generally required for HVAC-BOS, and has lower pixel resolution and limited portability compared to an SLR camera.

The two digital images that form a BOS image pair have a time delay between them and shifts of the background pattern resulting from refractions in the flowfield. They must be computer-processed to yield a schlieren-like result. Commercially-available PIV or DIC software packages are useful for this purpose, although in principle a custom-written algorithm would also suffice. Compared to other BOS costs, the commercial software is expensive: typically more than $10,000. However, PIV software is already available in many labs these days. “Vic 2D” software, from Correlated Solutions, Inc., was used here. The software measures the pixel shift between BOS frames. At a given location the shift is directly related to the spatial refractive index field and can be used to obtain quantitative information [12], although the results presented here are purely qualitative visualizations.

## 3 Experimental results: Image processing and setup-geometry influences

### 3.1 BOS image-pair processing

Traditional BOS imaging compares a background image taken with a refractive flowfield disturbance to a “tare” image taken with no flow present. Processing this image pair reveals the refractive-index-gradient field that was present at the instant of the flowfield image. The software output typically provides a measure of either horizontal or vertical pixel shifts between the images. As shown in Fig. 3, by contour-plotting the horizontal pixel shift a BOS image appears that is optically similar to a traditional vertical-knife-edge schlieren image, although in this case with reduced sensitivity.

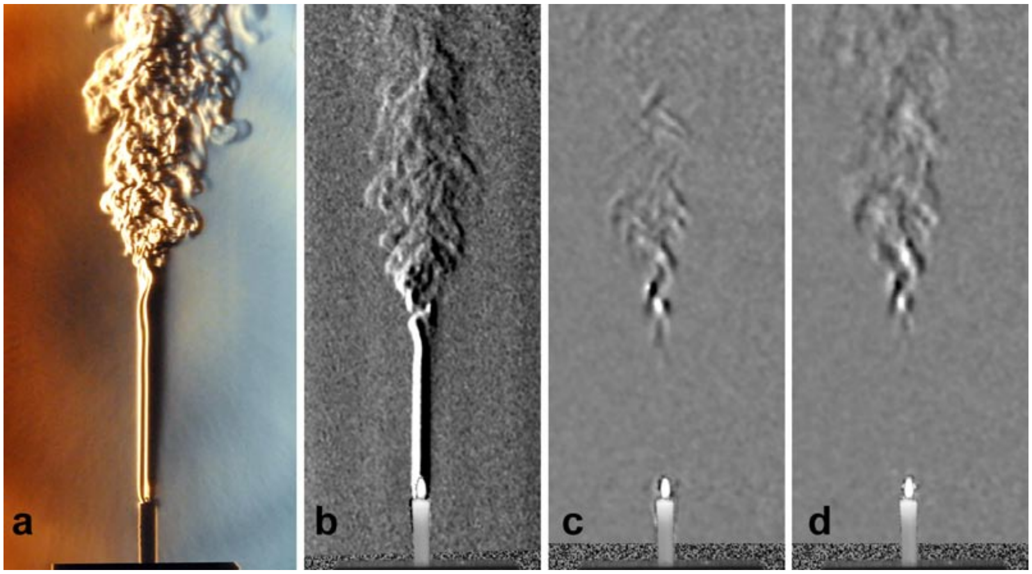


Fig. 3. Schlieren images of a candle plume by different visualization techniques, showing the natural laminar-to-turbulent transition that occurs in quiet room air. (a) Traditional schlieren image from the PSU 1m-aperture double-pass system [7]. (b) BOS image processed from a flowfield image and a tare image. (c) BOS image processed from two flowfield images separated by 0.02 second. (d) BOS image processed from two flowfield images separated by 0.1 second.

A new method of processing BOS images is presented in Figs. 3c-d: no tare image is used, but instead two flowfield images are processed relative to one other. This procedure reveals only the changes in the refractive flowfield between the two images. Fig. 3c and Fig. 3d both use the same base image but compare it to images recorded 0.02 and 0.1 second later. The laminar region of the candle plume is not revealed because its refraction does not change between images of the BOS pair. The turbulent part of the plume is visible, however, due to advection of turbulent eddies in the interim. This technique can thus reveal the time-history of refractive disturbances in turbulent flows or flows that are otherwise unsteady. It is also convenient for HVAC flowfields where turbulent flow is the norm, but where the flow may not be easily shut off in order to take a tare image.

### 3.2 Sensitivity changes due to BOS setup geometry

As discussed in Sec. 2, the sensitivity of the BOS technique is directly related to the experimental setup geometry, especially the distance from the schlieren object to the background. Fig. 4 shows three BOS images of a hot teakettle with increasing camera-to-subject distance $t$ and fixed camera-to-background distance $L$ = 4.7m. Fig. 4b represents the "recommended" setup with the teakettle located halfway between the background and the camera. Overall the subject is in reasonable focus while the background is sharply focused so that pixel shifts are accurately resolved. Although Fig. 4b shows the highest BOS sensitivity and resolution available in this example, it does not rival that of the traditional mirror-schlieren image in Fig. 4a. As the subject approaches the background ($t \rightarrow L$), much of the flowfield detail disappears as pixel shifts are reduced toward the ambient noise level of the system.

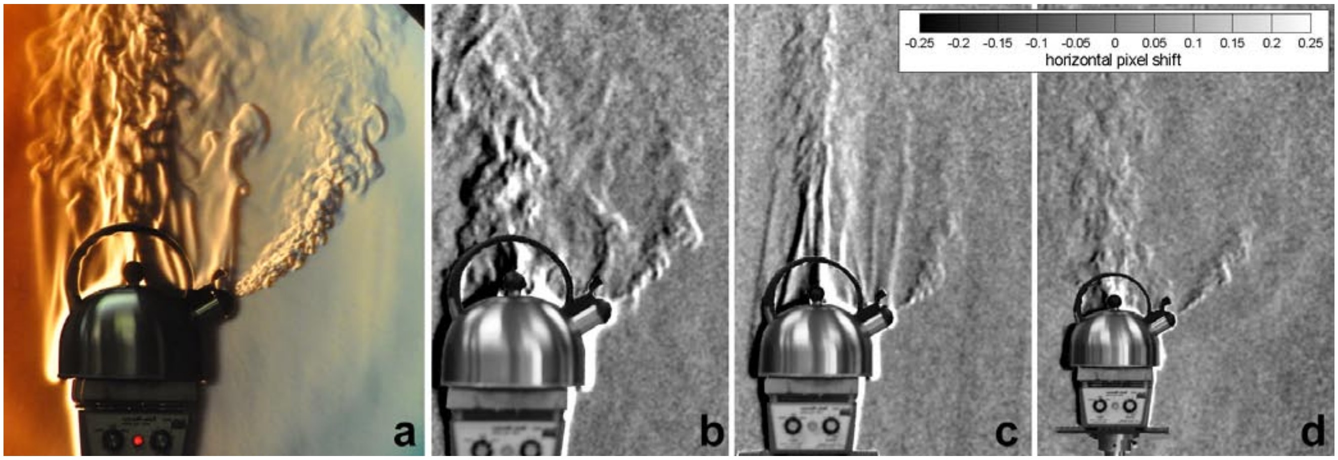


Fig. 4. Images of a hot teakettle just prior to boiling. (a) Traditional mirror-schlieren image. (b-d) BOS images illustrating decreasing schlieren sensitivity with decreasing subject-to-background distance: (b) t/L=0.5, (c) t/L=0.6, (d) t/L=0.75. L = 4.7m for this image series. Since image-correlation processing is irrelevant for opaque objects in the field-of-view, we have overlaid the front-lit image of the teakettle in frames b-d for clarity.

### 3.3 BOS Image presentation

The proper presentation of BOS results can be thwarted if default values, especially color contour maps, of the commercial image-processing software are accepted uncritically. The trained eye expects a schlieren image to appear in highlights and shadows upon a gray or neutral background. Different color schemes, such as the ubiquitous spectrum, can result in un-schlieren-like BOS images like the one illustrated in Fig. 5b, which lacks contrast. On the other hand a simple grayscale BOS image, like those shown in Figs. 3 and 4, can be post-processed by popular software such as Adobe Photoshop to produce a variety of effects, including colorization. Fig. 5 shows the results of different contour-map choices for rendering the horizontal pixel shifts of the candle-plume image from Fig. 3b.

## 4 Experimental results: HVAC applications and practical considerations

A representative set of HVAC scenarios was visualized within a residential home and an office building using the BOS techniques described above. The first scenario, a ceiling-mounted hot-air diffuser vent, is shown in Fig. 6. To image this vent the camera and background were raised to the ceiling and positioned so that the vent was halfway between them. Then the overall distance *L* was maximized within the available room size, thus maximizing sensitivity. Tare images were recorded before the heat was turned on, then several flow images were recorded with hot air being exhausted at approximately10ºC above ambient.

Fig. 6b was obtained from processing one flowfield image with one tare image, and reveals a high turbulent “noise” level. To improve the visualization and reduce the noise, a MATLAB script was used to average 5 tare images and 5 flowfield images. These two averaged images were then processed as a BOS pair, resulting in Fig. 6c. Through this averaging process the turbulence noise is suppressed and the mean vent flowfield becomes qualitatively more visible.

The same averaging technique was applied to the visualization of flow from the floor-level forced-air grille shown in Fig. 7. The hot-air jet exiting the grille attaches to the floor via the Coanda effect, forming a wall jet across the field of view. The vertical BOS pixel shift is used here (horizontal-knife-edge-schlieren equivalent) to best visualize the refractive-index gradients that are expected to be vertically oriented.

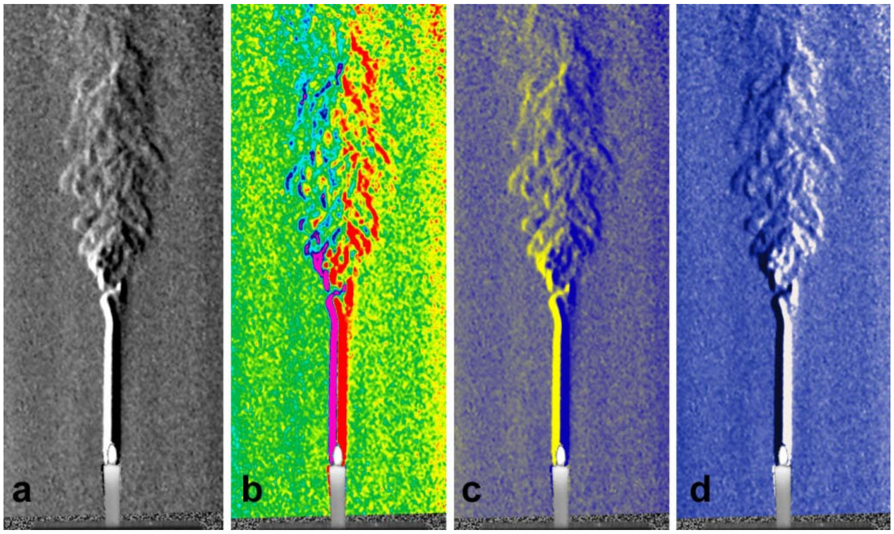


Fig. 5. BOS images of a candle plume (from Fig. 3b) with different color scales for the contour plotting of the horizontal pixel shift, all yielding a vertical-knife-edge-schlieren equivalent. (a) grayscale, (b) "spectrum," the typical default map in commercial PIV/DIC software, which produces an un-schlieren-like image. (c-d) Adobe Photoshop is used to create color gradient maps with which to colorize the original grayscale image, *e.g.* (c) yellow-to-blue and (d) deep-blue-to-white, which reverses the contrast of the original grayscale image.

Fig. 8 shows BOS images of (a) a passive wall-mounted heating register and (b-c) a fan-driven portable space heater. In Fig. 8a the overall pixel shift is significantly larger than other cases shown here because the hot-air plume is more than 20ºC hotter than the ambient air. Figs. 8b-c show a good example of a commercial product with a design flaw that is easily detected by schlieren visualization: the one- and two-sided exhaust control settings of the heater produce virtually-identical flowfields.

## 5 Conclusions

The background oriented schlieren technique, BOS, allows the visualization of a range of HVAC scenarios where traditional schlieren optics cannot be practically implemented. It is easily portable, durable, and inexpensive, it can image large fields-of-view without mirrors or other glass optical elements, and it can be applied in close quarters as well as in large interior spaces for the visualization of HVAC flowfields.

Effective BOS image capturing, processing, and post-processing are required to produce high-quality schlieren-like visualizations of HVAC flowfields. The image capture process can be effectively performed with a consumer-grade digital SLR camera that is rigidly tripod-mounted, level with the main flowfield, and focused upon a suitable background with the schlieren object of interest halfway between. Digital processing of BOS images can be enhanced by first averaging several flowfield and several tare images to reduce turbulence "noise" and camera-motion effects. A BOS flow-on image can be processed relative to a tare image or to another flowfield image in order to reveal either the total flowfield or the time-rate-of-change of the refractive-index field. Image post-processing with a grayscale contour map or a color gradient map yields schlieren-like visualizations and promotes enhanced visibility of flow features.

A few representative examples of HVAC airflows imaged by the BOS technique are shown here. Much broader applications are possible, including the diagnosis of airflow patterns in new buildings, checking the proper function of air-handling equipment, and the determination of effluent capture and containment in overhead hoods for commercial kitchen ventilation (CKV). Earlier large-scale fixed schlieren systems of the lens-and-grid type [7, 13] may be superceded by this simpler BOS approach.

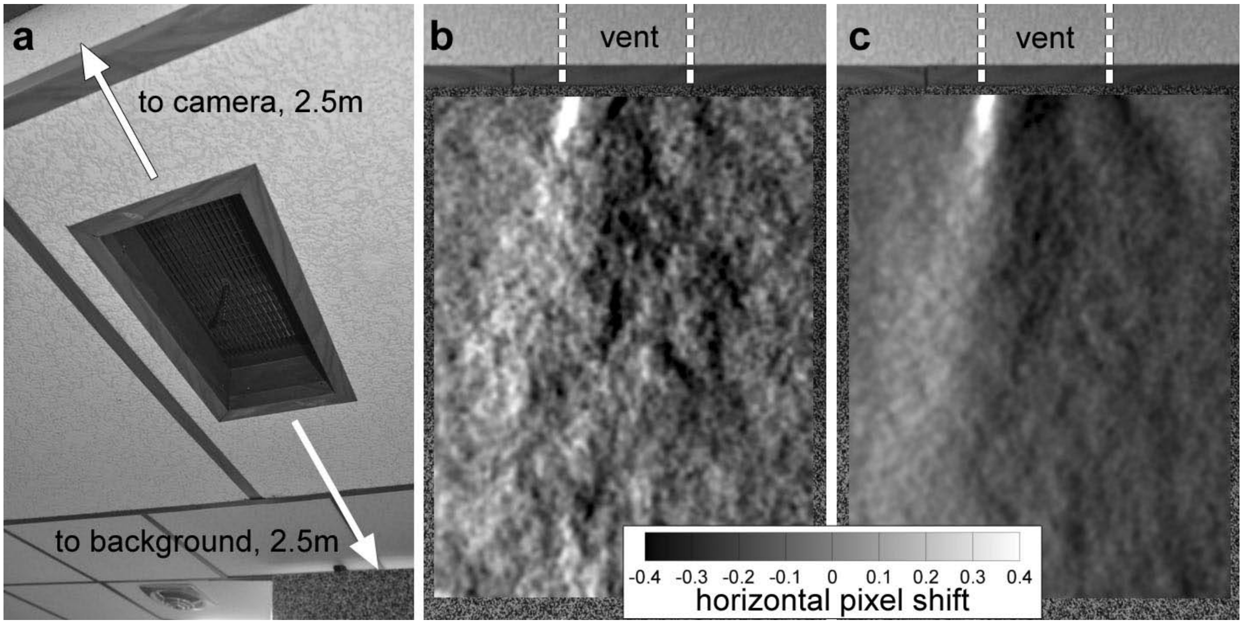


Fig. 6. (a) A ceiling-mounted residential hot-air vent is imaged using the BOS technique. (b) Processing a flowfield image with a tare image can yield a "noisy" result due to turbulence and/or slight camera shifts from shutter jitter. (c) Averaged flowfield and tare images are processed as a BOS pair to better visualize the mean flowfield despite the background noise.

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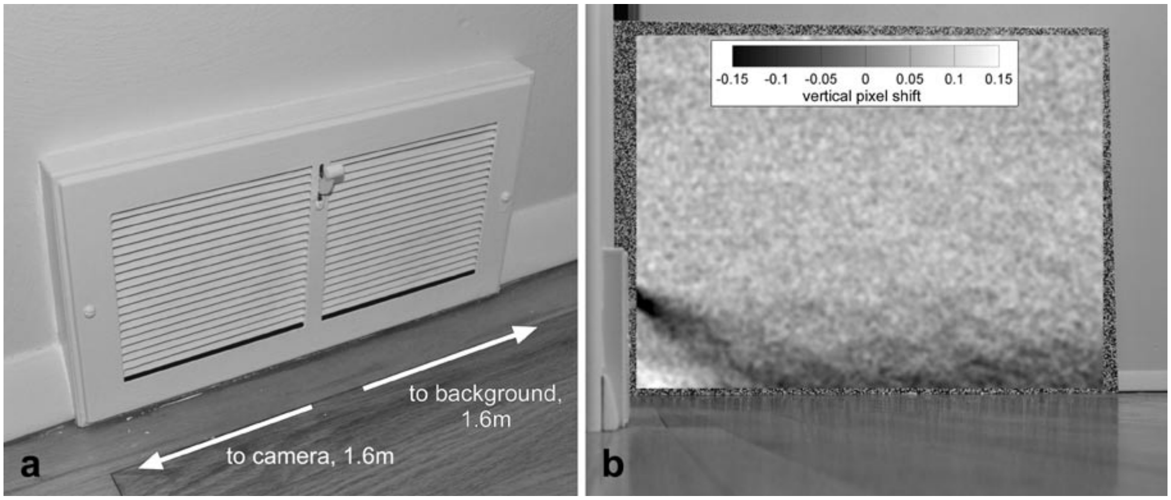


Fig. 7 (a) A floor-level forced-air grille flowfield is visualized with the BOS technique (b) using average flowfield and tare images. This grille creates an attached hot-air jet which moves across the floor. Note that the hot-air temperature difference above ambient is the same here as in Fig. 6, but the BOS sensitivity is less due to a shorter camera-to-background distance.

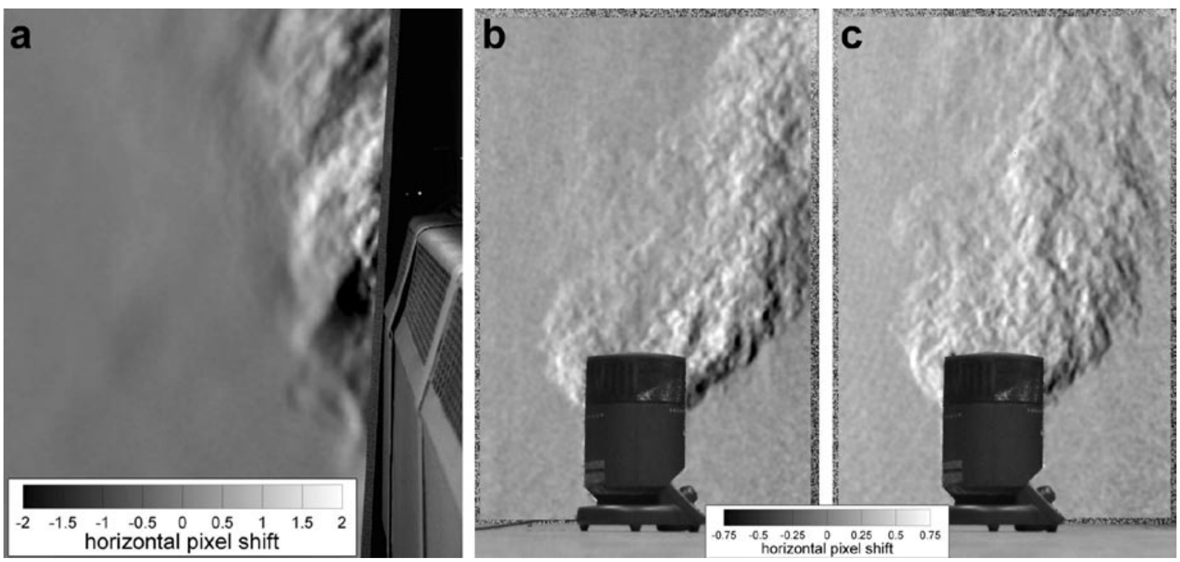


Fig. 8. BOS images of (a) a wall-mounted passive heating register and (b-c) a portable fan-driven space heater. The space heater has two options for fan output: (b) one sided and (c) two-sided. The airflow output control, however, involves only a simple flap that fails to properly divert the flow.

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