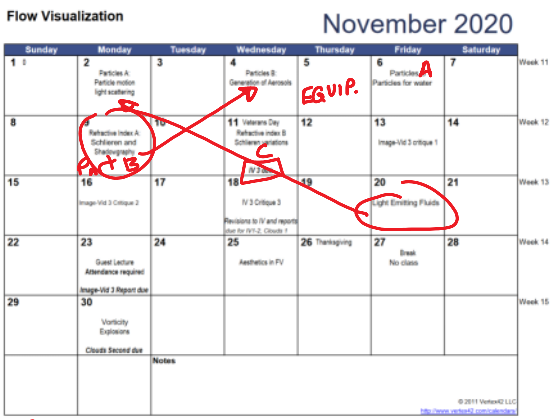
21.IndexOfRefraction

Wednesday, November 4, 2020 7:50 AM

Index of refraction techniques:
- Caustics
- Shadowgraphy
- Schlieren
- Background-oriented schlieren (BOS)



Flow Visualization — November 2020

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	
1	2 Particles A: Particle motion light scattering	3	4 Particles B: Generation of Aerosols	5	6 Particles C: Particles for water	7	Week 11
8	9 Refractive Index A: Schlieren and Shadowgraphy	10	11 Veterans Day Refractive index B Schlieren variations IV 3 due	12	13 Image-Vid 3 critique 1	14	Week 12
15	16 Image-Vid 3 Critique 2	17	18 IV 3 Critique 3 Revisions to IV and reports due for IV1-2, Clouds 1	19	20 Light Emitting Fluids	21	Week 13
22	23 Guest Lecture Attendance required Image-Vid 3 Report due	24	25 Aesthetics in FV	26 Thanksgiving	27 Break No class	28	Week 14
29	30 Vorticity Explosions Clouds Second due						Week 15
		Notes					

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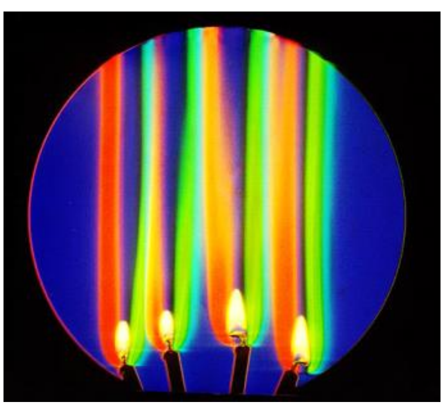
2 Strobes
Triggers Nikon Canon
Backdrop
Umbrella
Black light
CW work | video
2 LED Panel

Index of refraction techniques

Requires no seed. Can visualize differences and gradients in temperature and chemical concentration,
as both change the index of refraction of the media.
Examples first, then techniques discussed in detail: schlieren and shadowgraphy

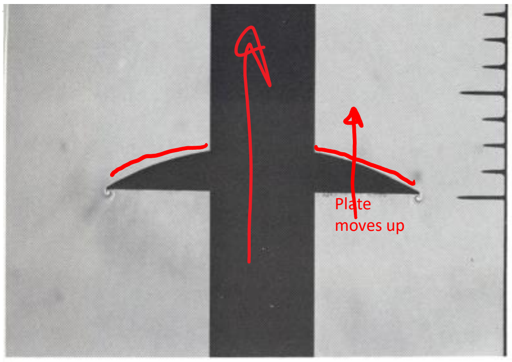
Color schlieren



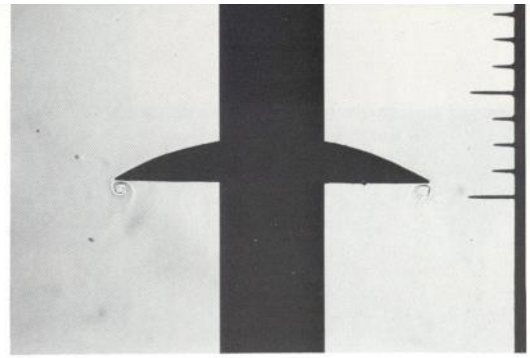
Pasted from <http://www.compadre.org/informal/images/features/schlierenlarge-11-29-06.jpg>

Andrew DAVIDHAZY (retired now),
RIT = Rochester Institute of Technology,
offers engineering and BS through PhD in
Imaging Science.

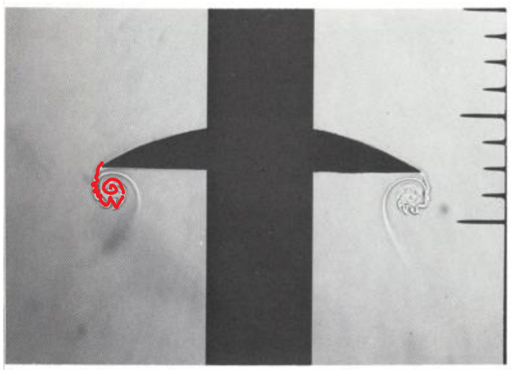
SHADOWGRAPH



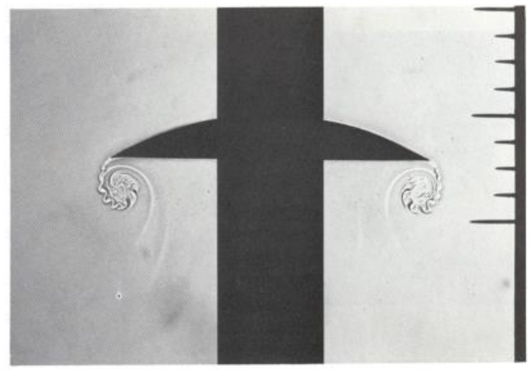
$t = 1.05$ ms, $v = 5.5$ ft/s



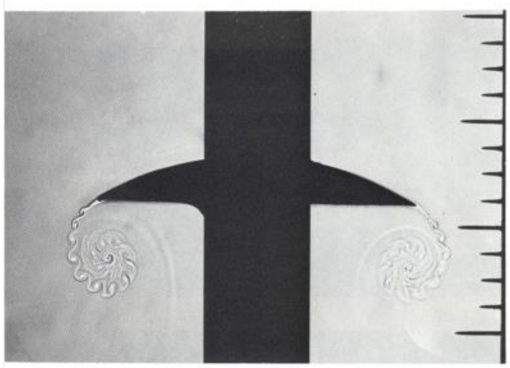
$t = 2.14$ ms, $v = 11.1$ ft/s



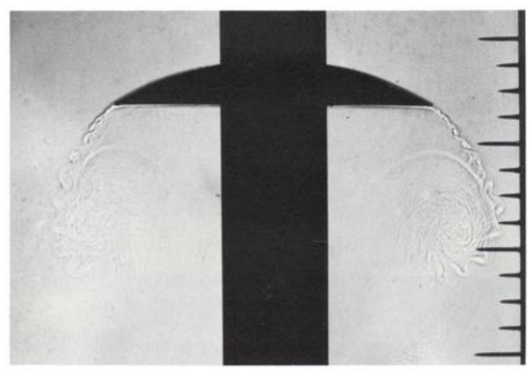
$t = 3.22$ ms, $v = 16.9$ ft/s



$t = 4.30$ ms, $v = 21.0$ ft/s

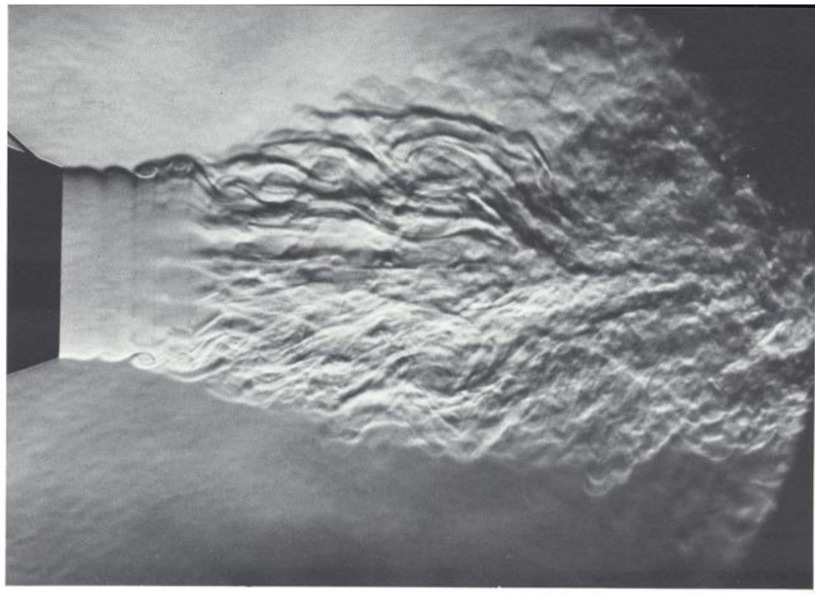


$t = 6.53$ ms, $v = 24.0$ ft/s

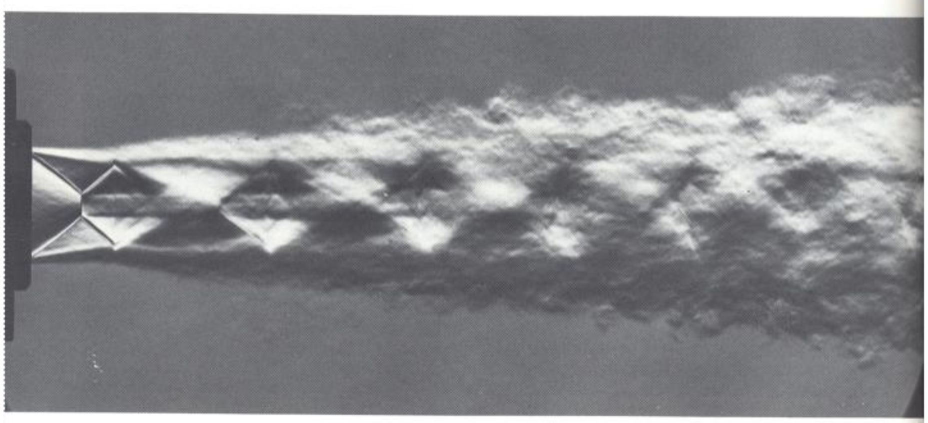


$t = 10.66$ ms, $v = 24.0$ ft/s

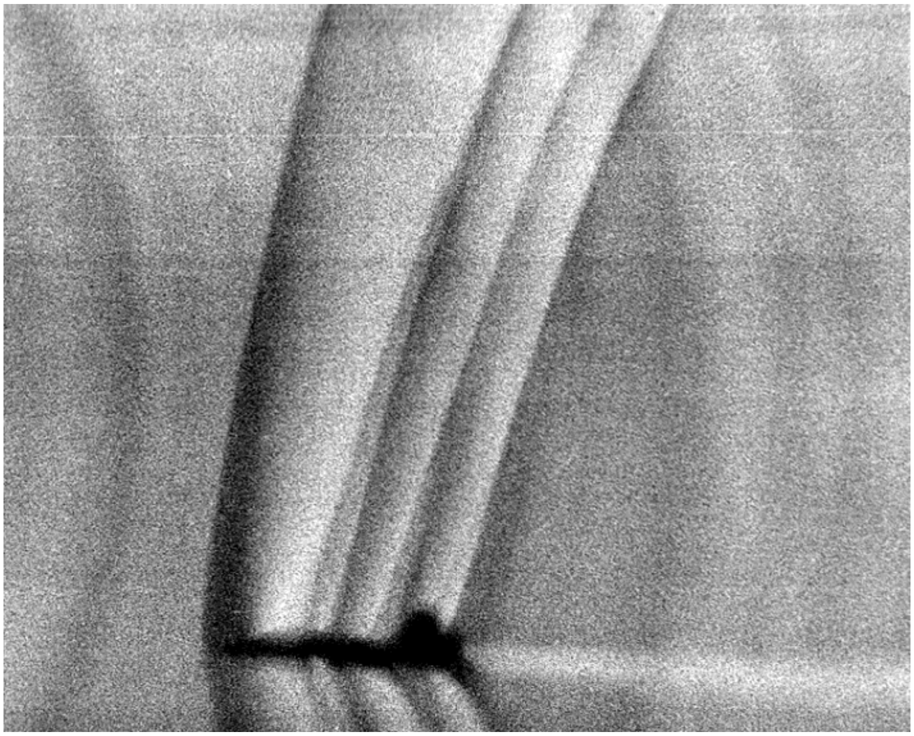
81. Growth of vortices on an accelerated plate. Spark shadowgraphs show the history of a 3-inch-square plate in air, accelerated from rest to 24 ft/s. The sharp edge of the plate is initially opposite the first of a series of pins spaced ¼ inch apart. The motion is actually vertical, and the flow is visualized by painting a narrow band of benzene across the center of the balsa-wood plate, so that when the plate accelerates benzene vapor is drawn into the vortex sheet. The difference in density between the vapor and the air makes the paths of their boundaries visible. Care was taken to ensure that the undulations observed in the vortex sheet were not caused by vibrations of the model. *Pierce 1961* hair dryer



167. Subsonic jet becoming turbulent. A jet of air from a nozzle of 5-cm diameter flows into ambient air at a speed of 12 m/s. The laminar interface becomes unstable as in figure 102, and the entire jet eventually becomes turbulent. *Bradshaw, Ferriss & Johnson 1964*



168. Supersonic jet becoming turbulent. At a Mach number of 1.8 a slightly over-expanded round jet of air adjusts to the ambient air through a succession of oblique and normal shock waves. The diamond-shaped pattern persists after the jet is turbulent. *Oertel 1975*



Pasted from <http://commons.wikimedia.org/wiki/File:Schlieren_photograph_of_T-38_shock_waves.jpg>

Mach 1.1, full size T-38 in flight, 1993. L. Weinstein, NASA
example of Background Oriented Schlieren (BOS). Correlate patterned background from image to get schlieren

http://fuckyeahfluiddynamics.tumblr.com/post/47622561173/this-high-speed-video-shows-schlieren-photography

CO_2 bottle rocket video. Shows Mach diamonds and expansion fans.

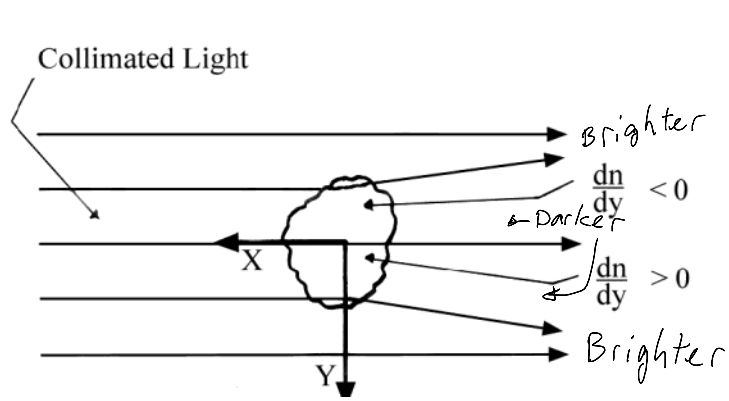
How it works:

http://www.npr.org/2014/04/09/300563606/what-does-sound-look-like
Michael Hargather, New Mexico Tech

speed of light

$$\eta = \frac{c_{vacuum}}{c_{medium}} = \text{eetah} = n$$ = index of refraction

Light is deflected towards more dense medium



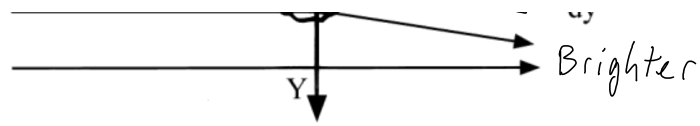


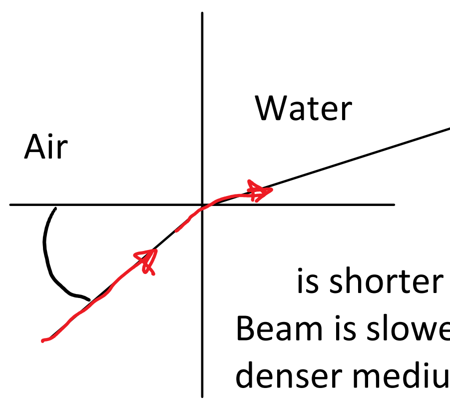
Figure 1. Disturbance in Collimated Beam

Shadowgraphy:

constructive and destructive interference from disturbed parallel light

$$\frac{1}{\eta}\frac{\partial \eta}{\partial y} = \frac{\partial^2 y}{\partial x^2}$$

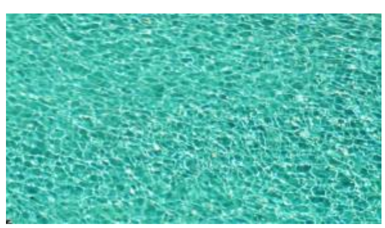
curve of disturbed line

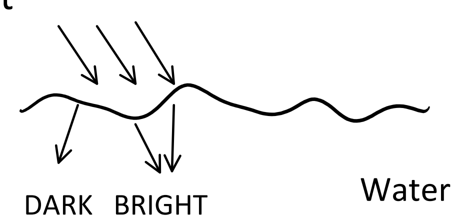


is shorter

Beam is slowed, turns into, i.e towards the denser medium

like a caustic sunlight





http://www.shutterstock.com/video/clip-3174052-stock-footage-dappled-pool-water-ripple-background-swimming-pool-water-abstract-background-with-seamless-loop.html

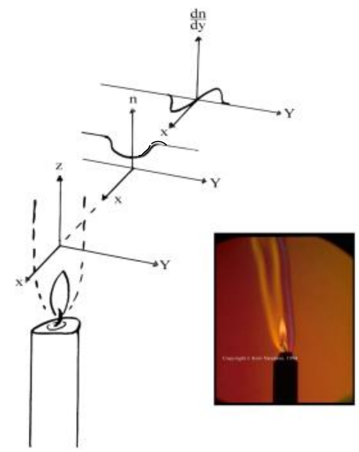


Figure 2. The Refractive Index Gradient Above a Candle

http://web.mit.edu/Edgerton/www/schlieren5.html

schlieren is just a German noun, not somebody's name.

Shadowgraphy:

constructive and destructive interference from disturbed parallel light

schlieren:

Selectively remove constructive or destructive interference from disturbed parallel light.
Higher contrast, controlled sensitivity to ? gradient directions

Dark field

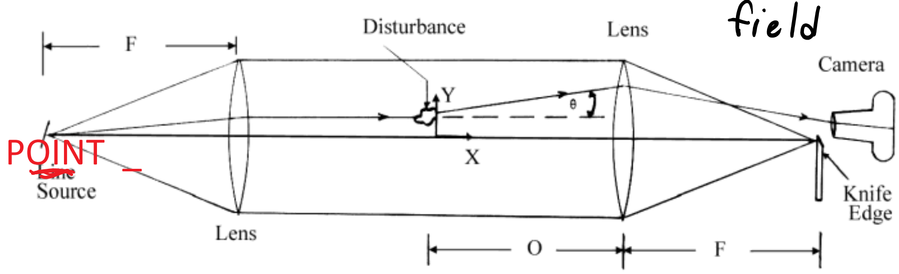
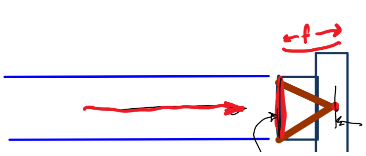


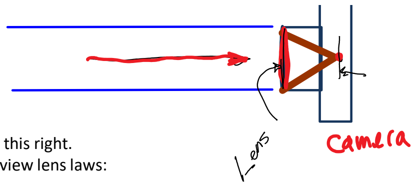
Figure 3. Schlieren System with a Small Disturbance

Minute paper: What would camera or your eyes see looking straight at parallel light, with the camera lens focused at infinity?
Hint: what light sources do you know that emit parallel light? What do they look like? Sun, starlight
Hint 2: what does the lens law say about light entering parallel to the optical axis?

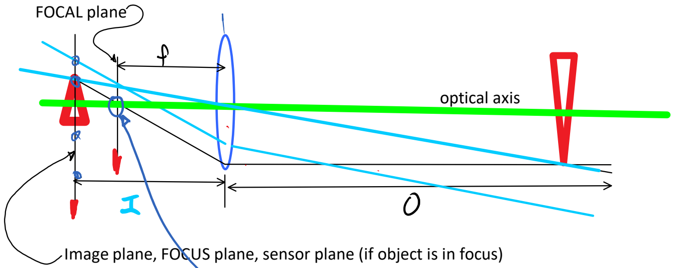
73% A) Point of light
27% B) Uniform brightness
C) Something else....

Stars: the light is parallel, and they look like points of light in a dark field.





1/2 got this right.
Let's review lens laws:



Lens Laws

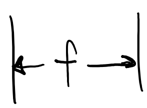
1) light through center of lens is undeflected
2) light parallel to axis goes through focal *point* ≠ focus point
3) all light entering lens at a given direction ends up at the same point in the *focal* plane (**not** *focus* plane)

Focus equation

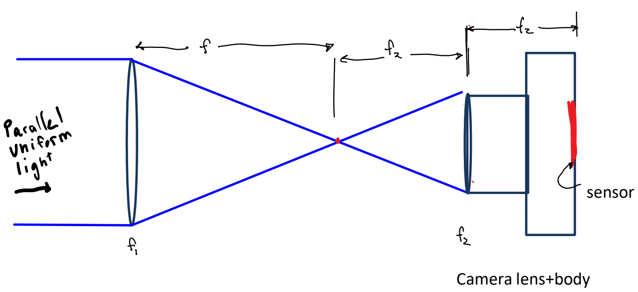
$$\frac{1}{f} = \frac{1}{O} + \frac{1}{I}$$

f = focal length
O = dist. Lens → object
I = dist. Lens → image (Sensor)

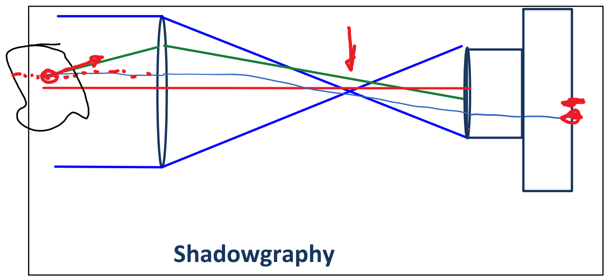
Minute paper, groups: 1) Where is lens relative to sensor when focus is at infinity?

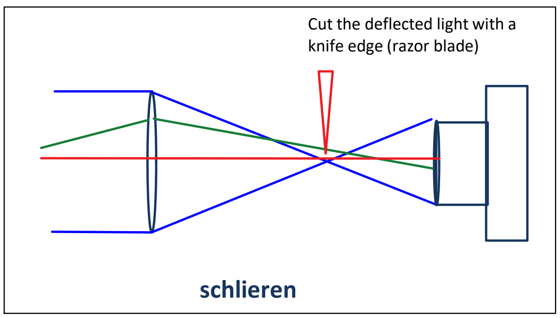


Back to schlieren and shadowgraphy: What does the camera see in this case? No disturbance, no knife edge



Now, deflect some of those light rays. Would add light in some areas, reduce it on others.





Bright field

By Foucault, 1859

schlieren: German noun, Not a name

Shadowgraph Equation

Shadowgraph, sensitive to 2nd derivative of η

$$\frac{\Delta I}{I} = l \int_{z_1}^{z_2} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)(\ln \eta)\, dz$$

Relative light intensity at exit. Light propagates in Z direction

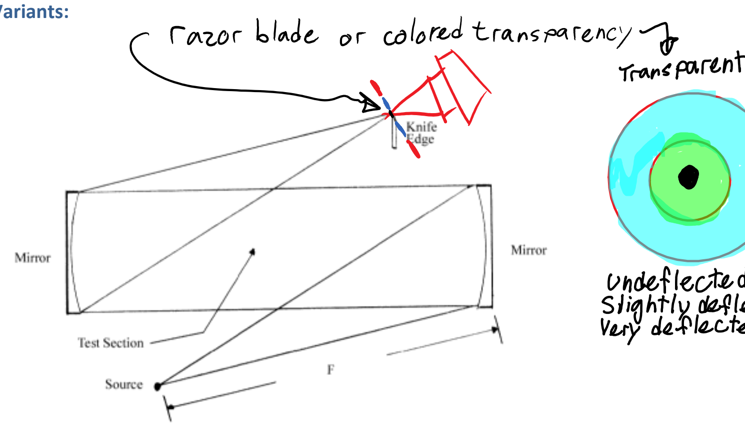
Integrated along line of sight. Drawback for looking at 3-d phenomena

Ref:

1. Wolgang Merzkirch, *Flow Visualization, Second Edition*, 2nd ed. (Academic Press, 1987).

Similar math for schlieren, is sensitive to first derivative; to gradients in temperature.
Has higher contrast, visibility; deflected light is not adding to or confusing light field.

Variants:



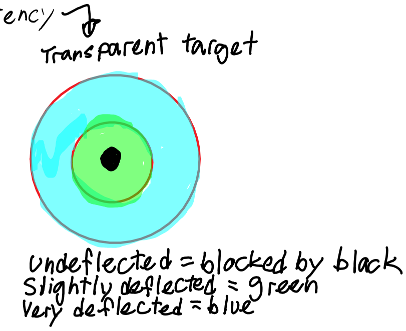
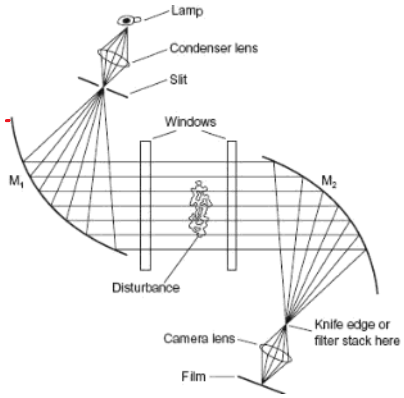


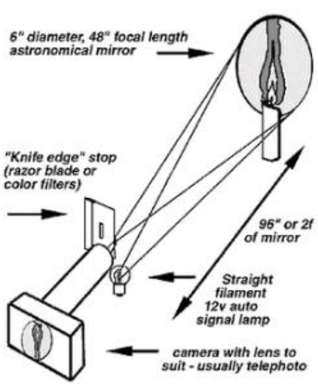
Figure 7. Mirror System

Z fold with mirrors; saves space, cost. Want space between mirrors to be 3 x f

Either spherical or parabolic mirrors work.

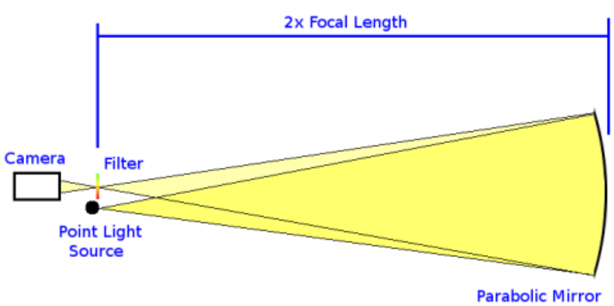


Pasted from <http://2.bp.blogspot.com/_JUESvkRXuK0/SQZ0JdkMBAI/AAAAAAAABPk/OGvKULVzNJ4/s320/schlieren.gif>



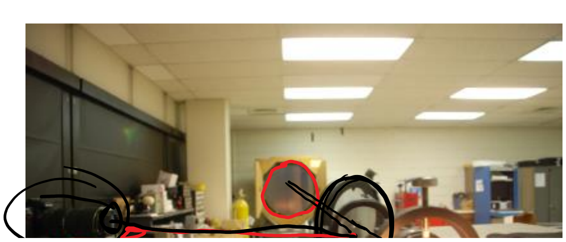
Single mirror system

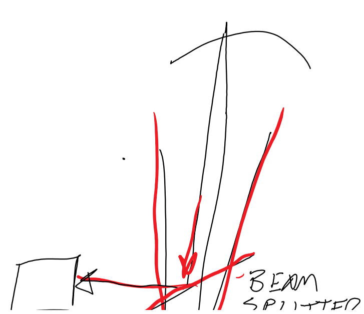
Pasted from <http://www.ian.org/Schlieren/SchlierenDiagram.png>

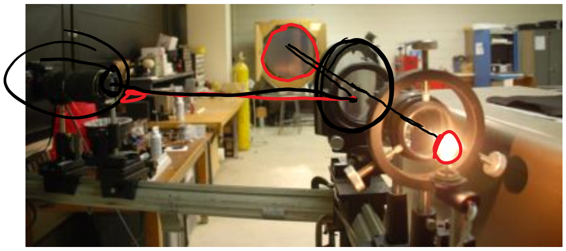


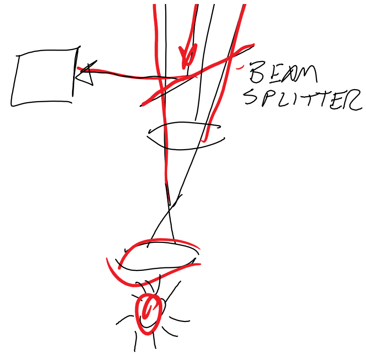
Emissions from Musicians project uses this method.
https://vimeo.com/showcase/7707430

https://m.youtube.com/watch?v=BPwdlEgLn5Q Smarter Every Day; high speed video of shock waves from bullets









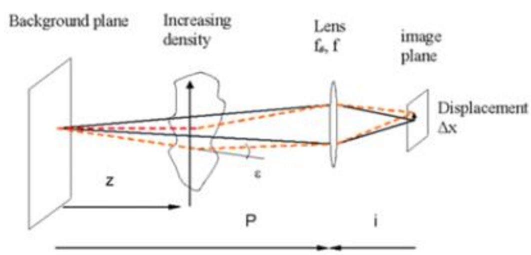
Gas Dynamics lab at Penn State University
Prof. Gary Settles, author of

Schlieren & Shadowgraph Techniques, Corrected. (Springer, 2001).

<file://C:\Users\hertzber\Documents\01CLASSES\FlowVis\MiscImages\Settles\SchlierenVisit\DSC_0324.AVI> My visit in March 2011

BOS = Background Oriented Schlieren

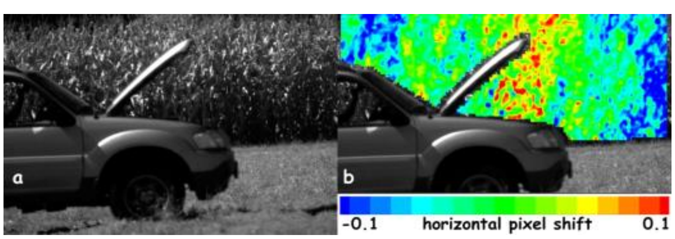
Uses patterned background instead of mirror, any random lighting. View of background will be distorted by η field. Take two images and do cross correlation, like PIV.



http://www.dlr.de/as/en/desktopdefault.aspx/tabid-183/251_read-2726/

http://www.mne.psu.edu/psgdl/Res-Optical.html
The thermal plume generated from a hot truck engine is visualized against a background of corn. The (a) original image is compared to one recorded 7 ms later to determine the (b) horizontal pixel shift. The contour plot of horizontal pixel shift in a BOS image is optically equivalent to a vertical knife-edge cutoff in traditional schlieren.

Pasted from <http://www.mne.psu.edu/psgdl/Res-Optical.html>

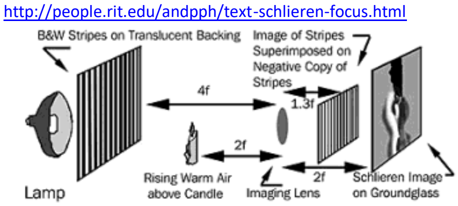


Hargather, Michael, and Gary S. Settles. "BACKGROUND-ORIENTED SCHLIEREN VISUALIZATI ON OF HEATING AND VENTILATION FLOWS: HVAC-BOS. Paper 266." In *ISFV14 - 14th International Symposium on Flow Visualization*, 1–8. EXCO Daegu, Korea, 2010.
Hargather, Michael John, and Gary S. Settles. "Natural-background-oriented Schlieren Imaging." *Experiments in Fluids* 48, no. 1 (January 1, 2010): 59–68. doi:10.1007/s00348-009-0709-3.

Software for this is ~ $10,000 from LaVision.

Focusing schlieren

http://people.rit.edu/andpph/text-schlieren-focus.html



https://www.youtube.com/watch?v=DYx2xLLrUyg ice cube in a fishtank, by Spectabit:
http://www.spectabit.com/index.php/product-types

Now, an even simpler method, using an encoded light field:

Light Field Back-
ground Oriented Schlieren Photography (LFBOS)

http://www.cs.ubc.ca/nest/imager/tr/2011/LFBOS/

Klemkowsky, Jenna N., Timothy W. Fahringer, Christopher J. Clifford, Brett F. Bathel, and Brian S. Thurow. "Plenoptic Background Oriented Schlieren Imaging." *Measurement Science and Technology* 28, no. 9 (2017): 095404. https://doi.org/10.1088/1361-6501/aa7f3d.
In Zotero library.

We have two sets of 4" diameter mirrors; would love to see 3D stereoscopic schlieren.