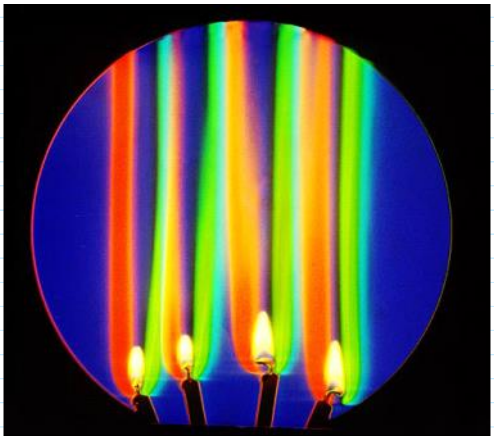
17.IndexOfRefraction

Monday, November 5, 2018 7:50 AM

## 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

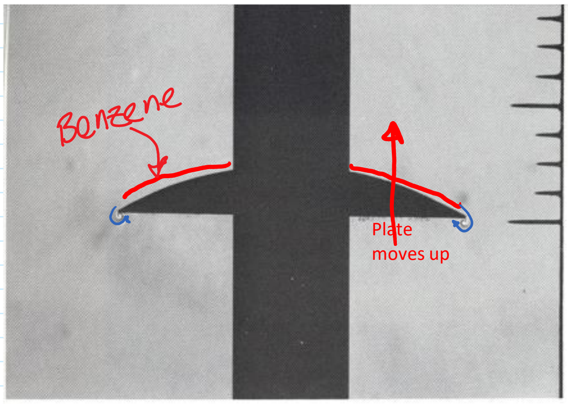
### Color schlieren



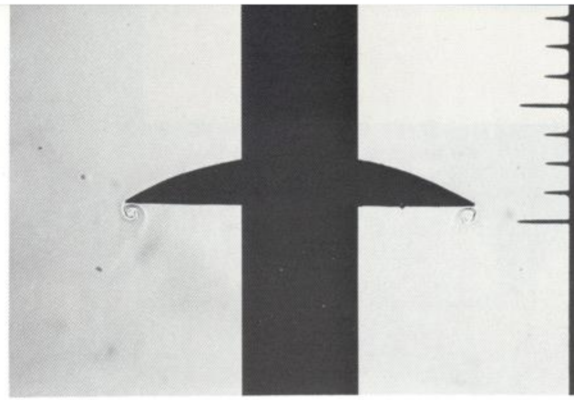
Pasted from <http://www.compadre.org/informal/images/features/schlierenlarge-11-29-06.jpg>

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

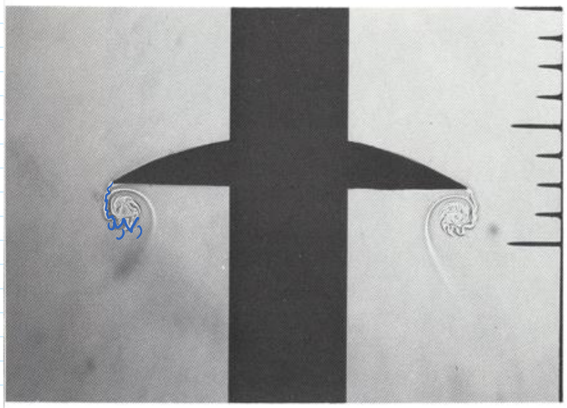
SHADOWGRAPH



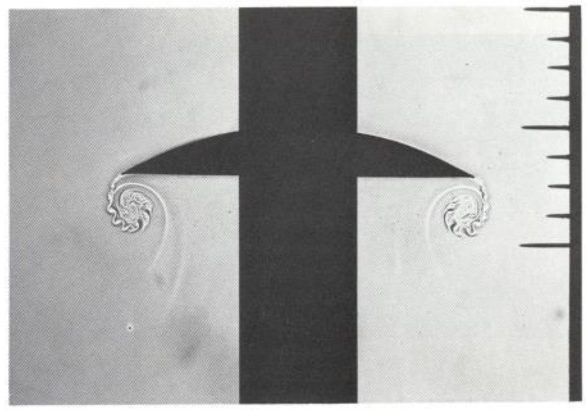

$t=1.05$ ms, $v=5.5$ ft/s



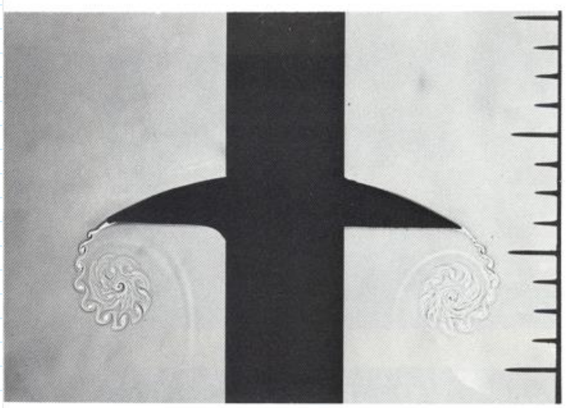
$t=2.14$ ms, $v=11.1$ ft/s



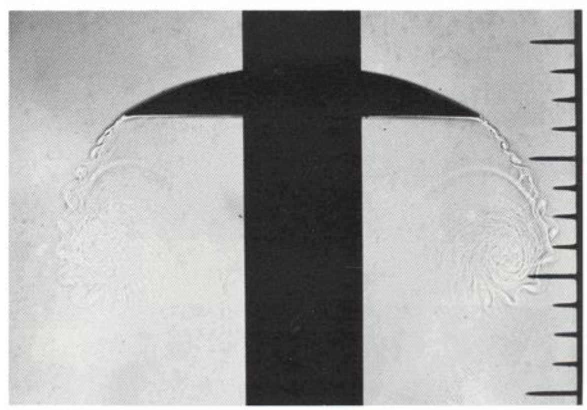
$t=3.22$ ms, $v=16.9$ ft/s



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

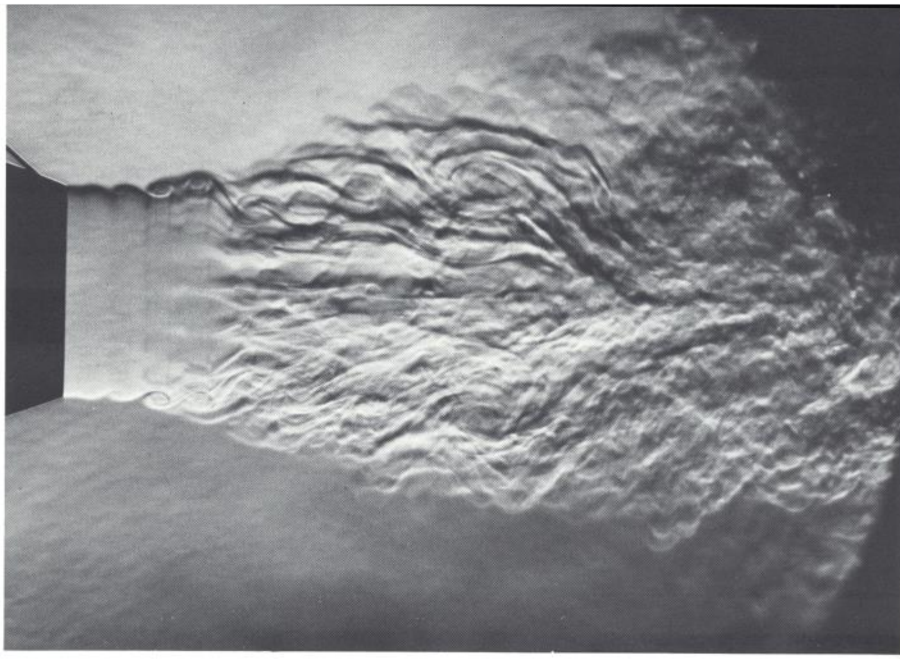


$t=6.53$ ms, $v=24.0$ ft/s

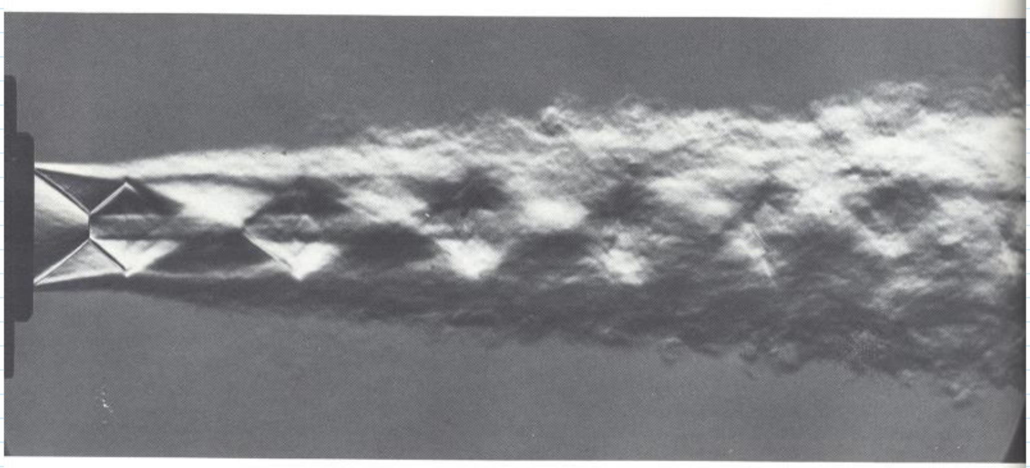


$t=10.66$ ms, $v=24.0$ ft/s

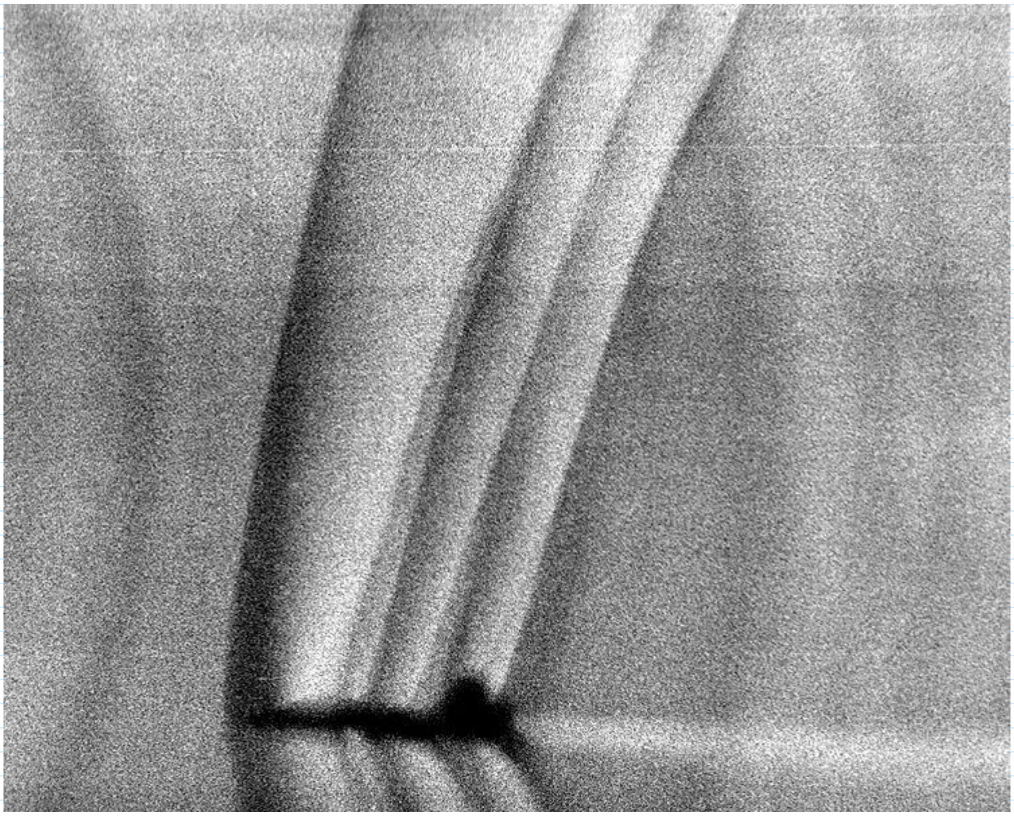
**81. Growth of vortices on an accelerated plate.** Spark shadowgraphs show the history of a 3-inch-square plate in air, accelerated from rest to 24 ft/s. The sharp edge of the plate is initially opposite the first of a series of pins spaced ¼ inch apart. The motion is actually vertical, and the flow 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*



**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

$$\eta = \frac{c_{VACUUM}}{c_{MEDIUM}}$$ eetah

n = index of refraction

Light is deflected towards more dense medium

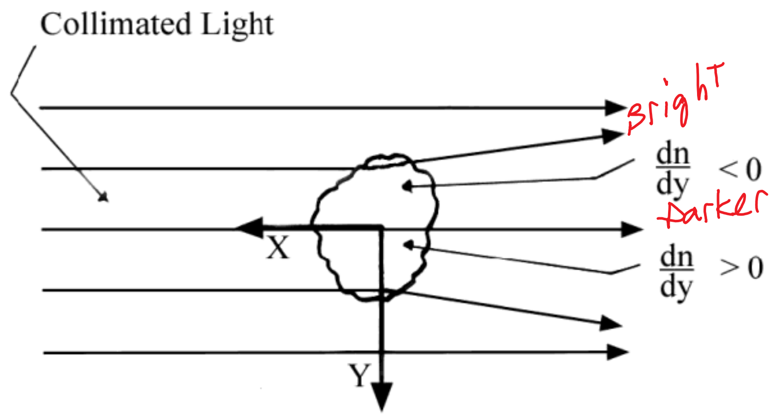



Figure 1. Disturbance in Collimated Beam

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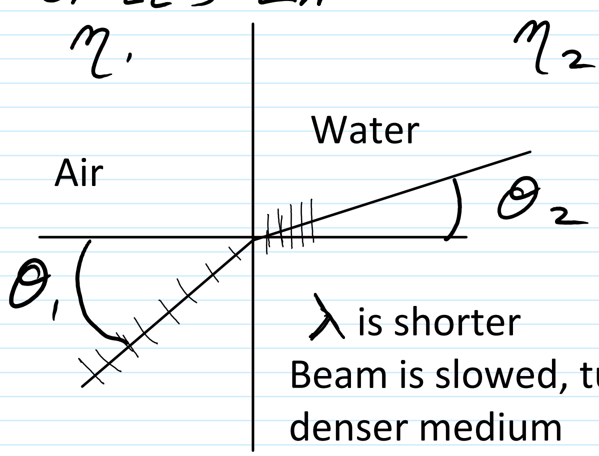
## Shadowgraphy:

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 $= y(x)$

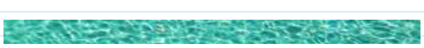
SNELL'S LAW

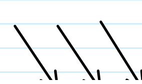



$\lambda$ is shorter

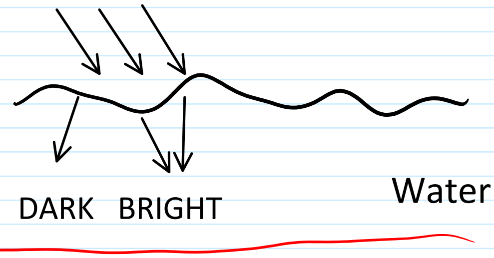
Beam is slowed, turns into, i.e towards the denser medium

like a caustic sunlight





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

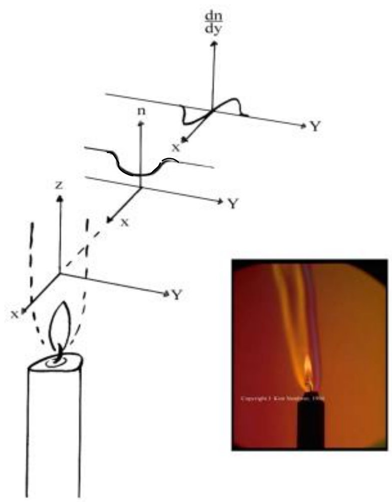



Figure 2. The Refractive Index Gradient Above a Candle

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

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

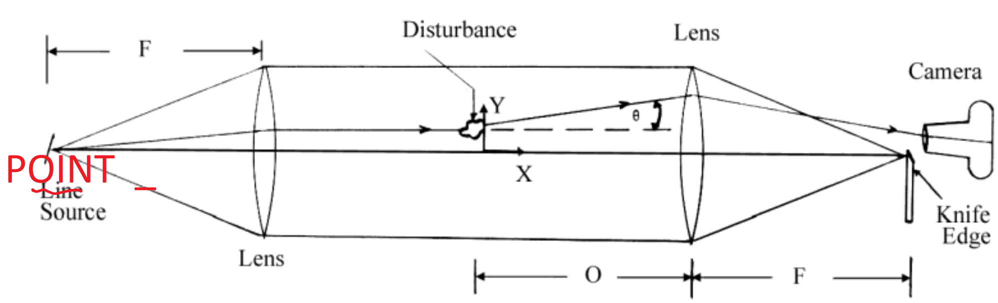


Figure 3. Schlieren System with a Small Disturbance

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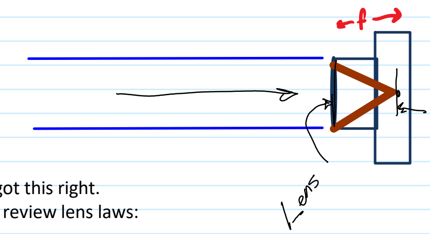
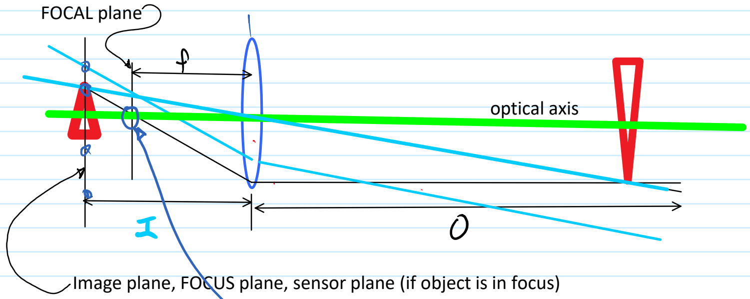
Minute paper: What would camera see looking at parallel light, camera lens focused at infinity?
Hint: what light sources do you know that emit parallel light? What do they look like?




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)

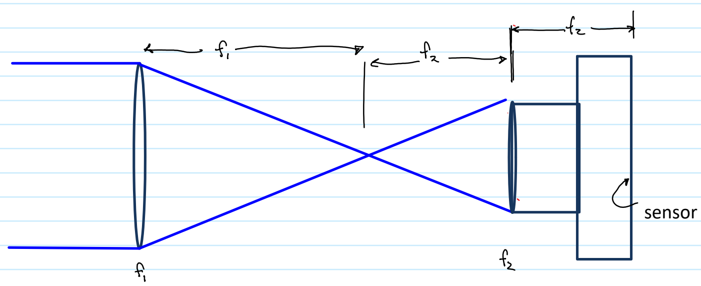
Focus equation

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

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

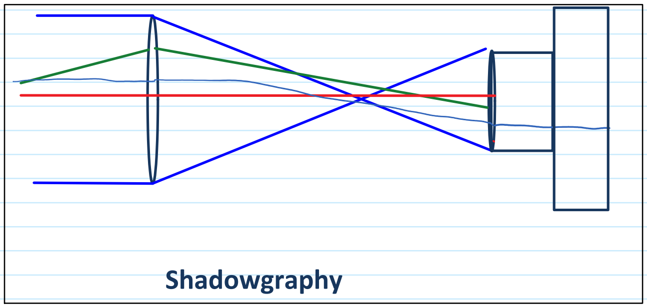
Minute paper, groups: 1) Where is lens relative to sensor when focus is at infinity?

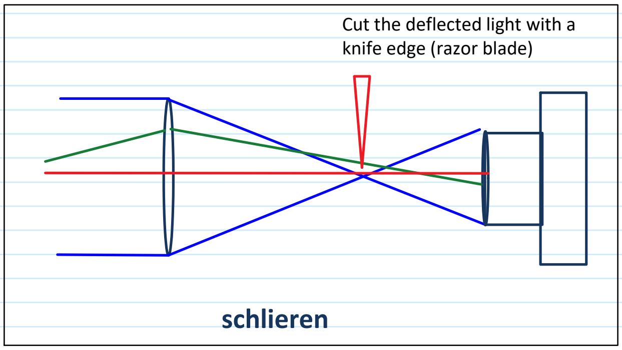
Back to schlieren and shadowgraphy: What does the camera see in this case? No disturbance, no knife edge




Camera lens+body

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




By Foucault, 1859

schlieren: German noun, Not a name

### Shadowgraphy Equation

Shadowgraph, sensitive to 2nd derivative of $\eta$

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

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:

razor blade or colored transparency

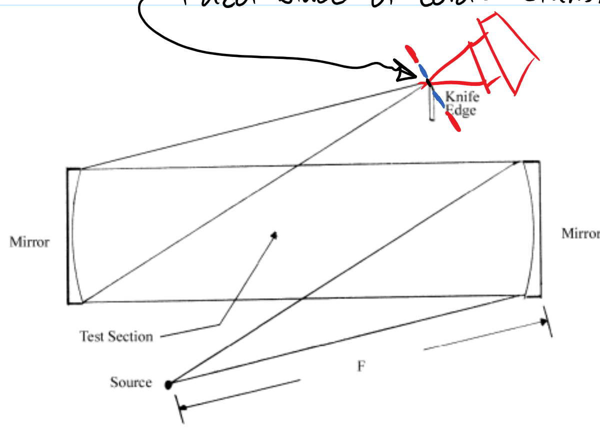



Figure 7. Mirror System

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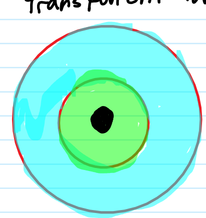
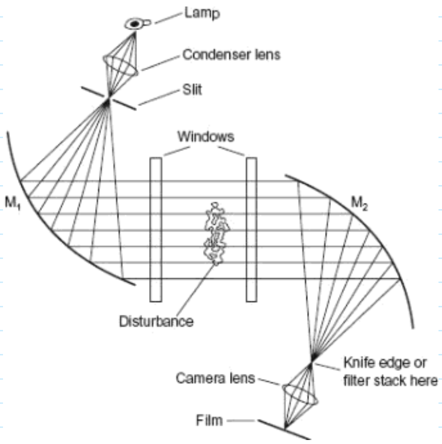
Transparent target



undeflected = blocked by black
Slightly deflected = green
Very deflected = blue

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>