



FLOW VISUALIZATION

An introduction – II

Dario Ambrosini

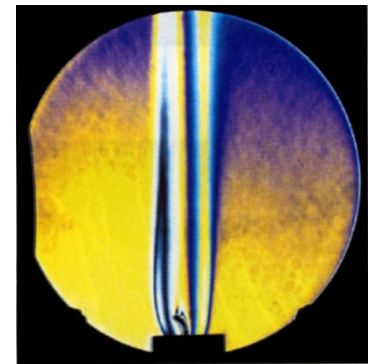
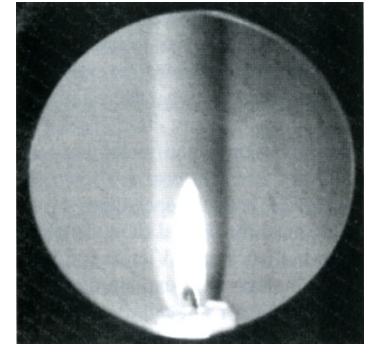
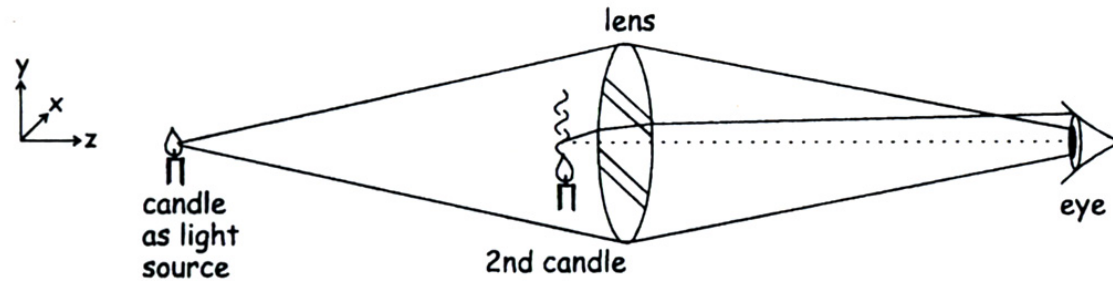
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The first optical pyrometer (from *Heat and Temperature Measurement*, by R. L Weber, 1950)

Schlieren



Hooke's original scheme, image from a modern reenactment and comparison with an actual image (Courtesy G.S. Settles, Penn State University).

Schlieren is generally traced to Foucault (1859) and Toepler (1864). Only recently has Rienitz* showed that schlieren could have been used by Robert Hooke as early as 1672.

*J. Rienitz, *Nature*, 254: 293-295 (1975); *Endeavour*, 21: 77-81 (1997).

Basic idea:

- light “deflected down” is removed

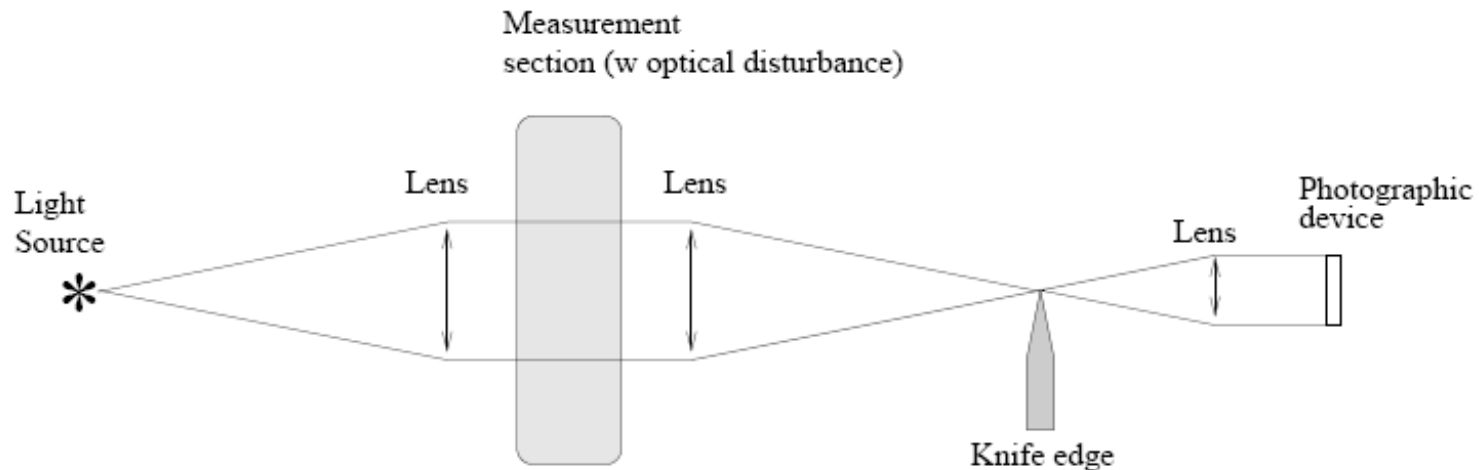


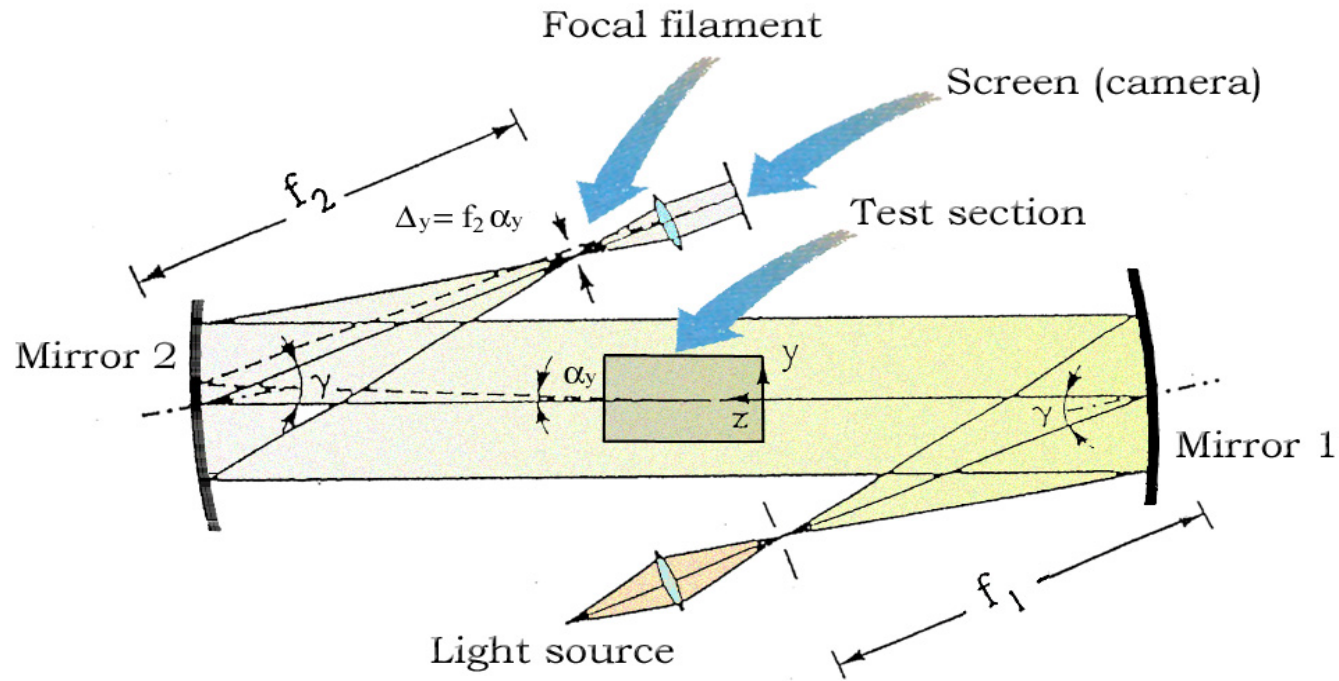
Black regions

- light “deflected up” is transmitted



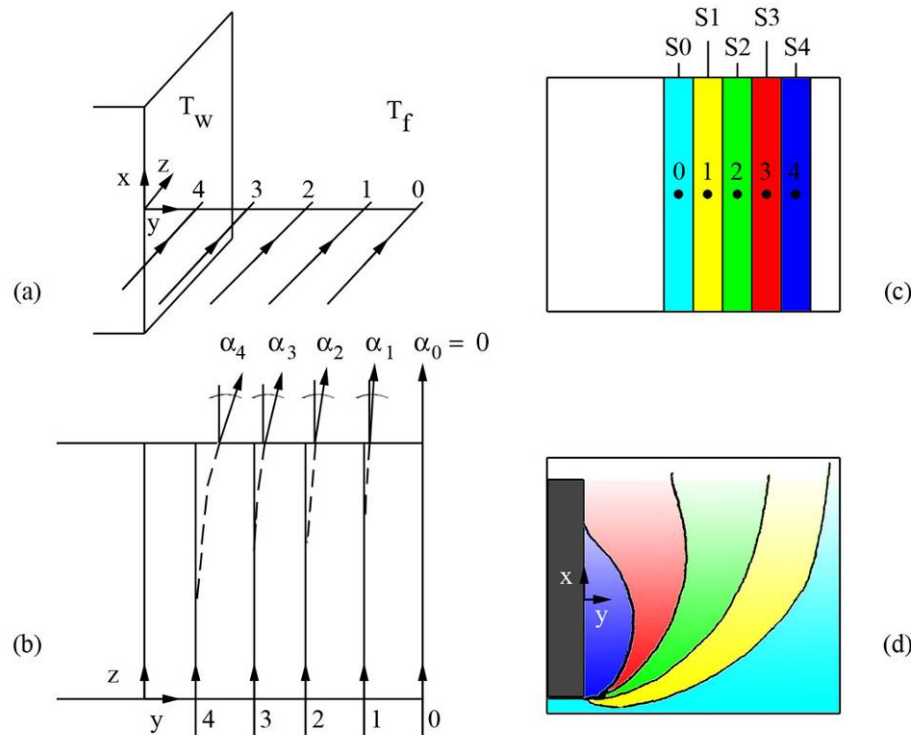
White regions





Classical Z-type Schlieren system: A non-coherent light beam from a vertical slit source, collimated by the concave mirror M1, passes through the test section. A second concave mirror M2, is then used to project a real image of the slit source in the focal plane and a real image of the test section onto a screen or camera. Owing to the inhomogeneities of the fluid refractive index around the heated plate, the light rays undergo angular deflections.

Colour Schlieren

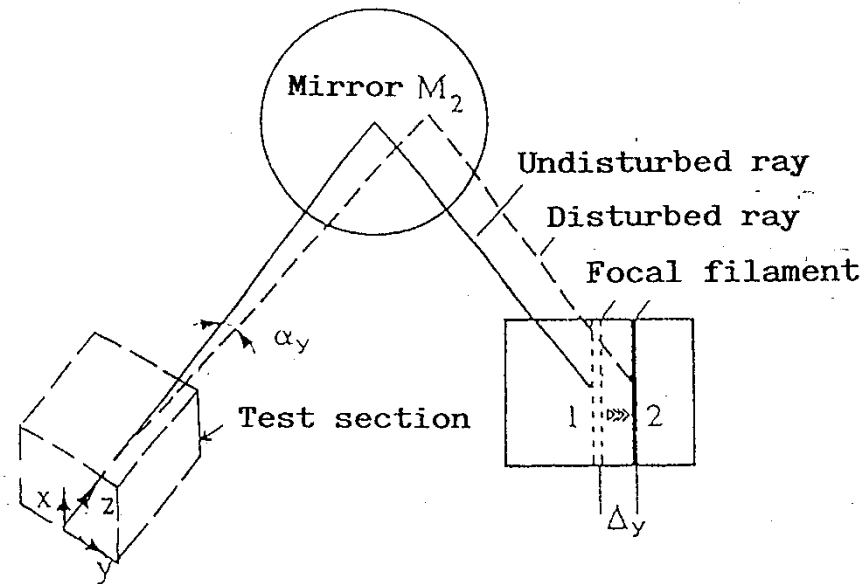


It is obtained by placing a colored filter (thin transparent colored strips) in the focal plane of mirror M2, in lieu of the focal filament. The strips must be used with a slit source, which must be in vertical position if horizontal temperature gradients are to be detected.

Deflected rays pass through different colored strips of the filter. Therefore, the image of all the points, which deflect the light beam through the same angle, has the same color.

Color schlieren method enables a whole-field visualization of the phenomenon, without the need of moving the filter and of superimposing different images. Unfortunately, the measurement range is limited and therefore color schlieren can be used only for qualitative visualization.

Focal filament method



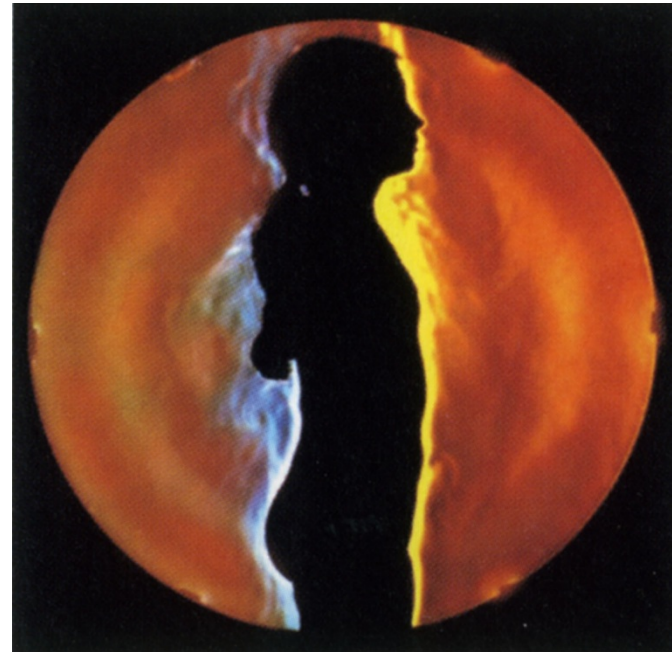
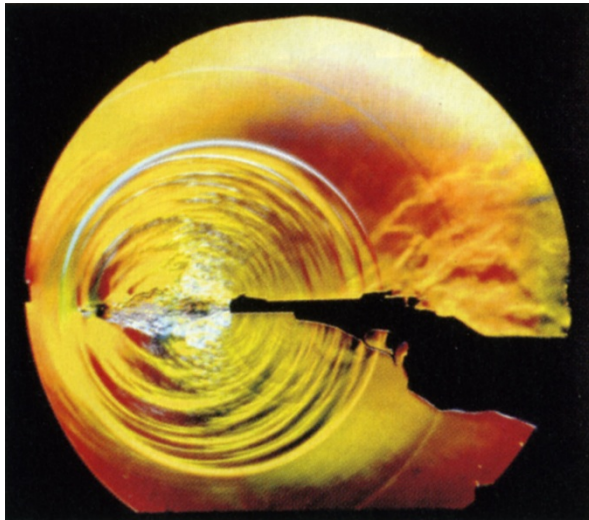
Regions of the optical field characterized by the same light deflection in the y - z plane can be identified by shifting an opaque vertical filament in the focal plane of mirror M_2 . When a disturbed light ray is stopped by the focal filament, the image of the corresponding region of fluid will appear dark on the screen, while the remaining field will be bright.

Schlieren Maths

The local heat transfer coefficient can be directly obtained from schlieren images without reconstructing the whole thermal field. Indeed, if the focal filament is moved until its shadow intersects the vertical surface profile in the image projected on the camera, the displacement of the filament corresponds to the deviation Δ_w of the light ray passing in the vicinity of the wall at the desired location. The relation between light deviation and the local heat transfer coefficient is

$$h = - \frac{k_w \Delta_w T_w^2}{\Omega (T_w - T_\infty)}$$

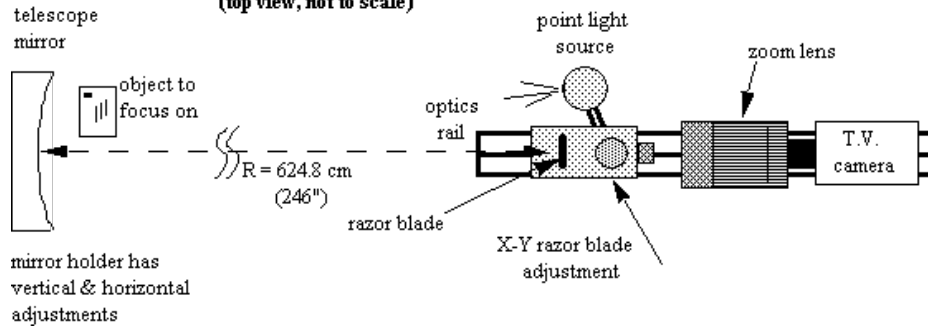
In the present experiment, Ω was equal to $-0.0456 \text{ m}^2 \text{ K}$.



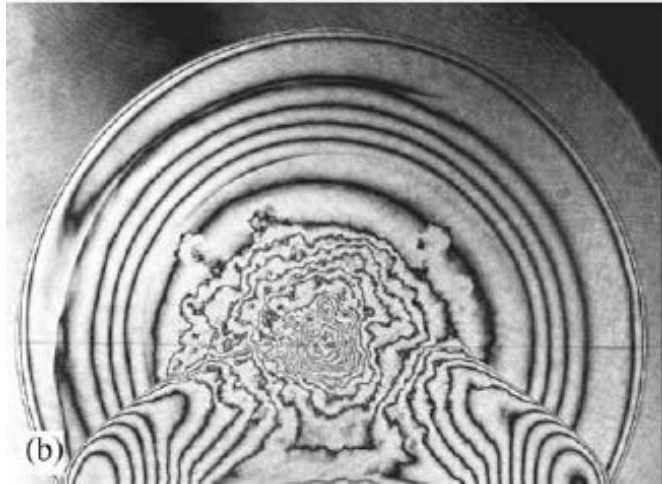
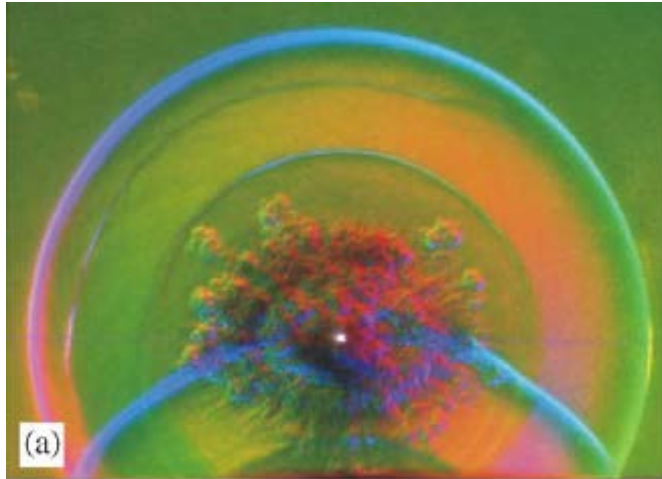
All images Courtesy G.S. Settles, Penn State University

An example from Harvard Natural Sciences Lecture Demonstrations

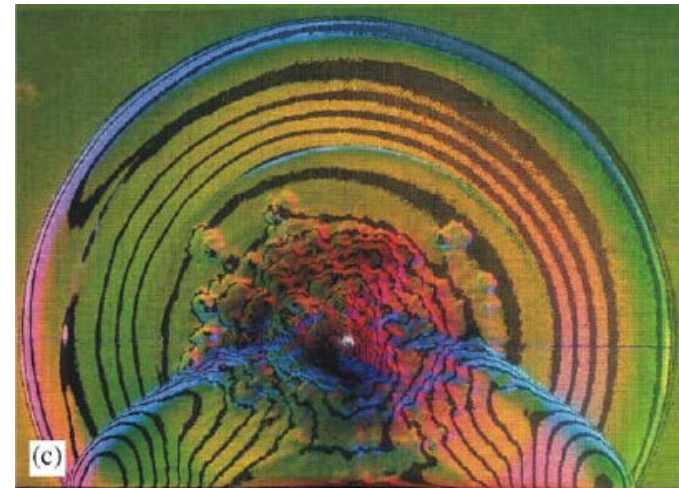
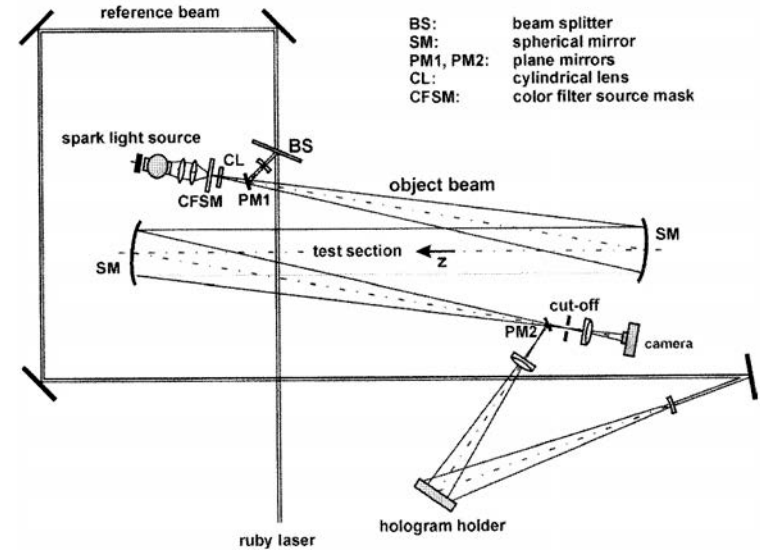
*figure 1: alignment of apparatus
(top view, not to scale)*



Simultaneous Schlieren and HI



Visualization of the explosion of a 10 mg AgN₃ charge ignited 30mm above a rigid wall; shown instant: 120 ms after ignition.



Digital Schlieren

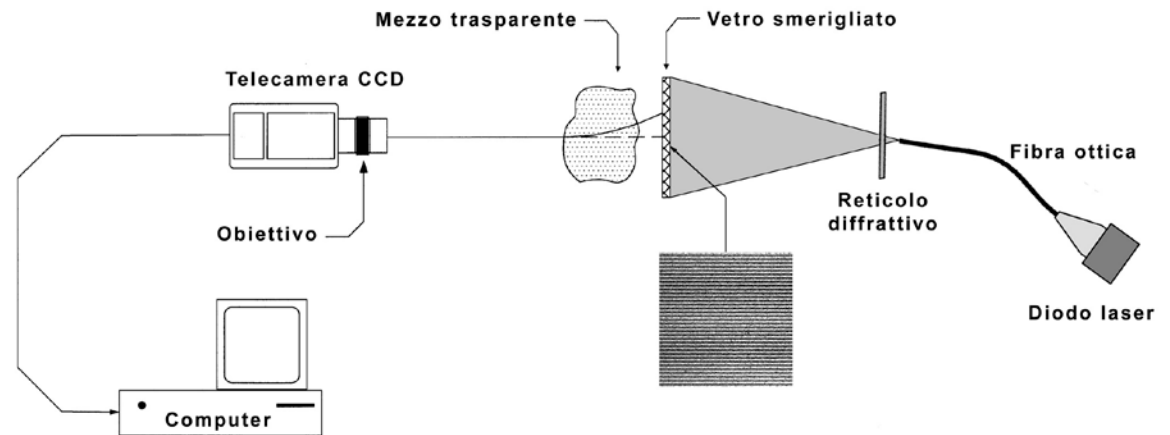
Schardin's Schlieren n. 2

Introduced by Hubert Schardin (1942).



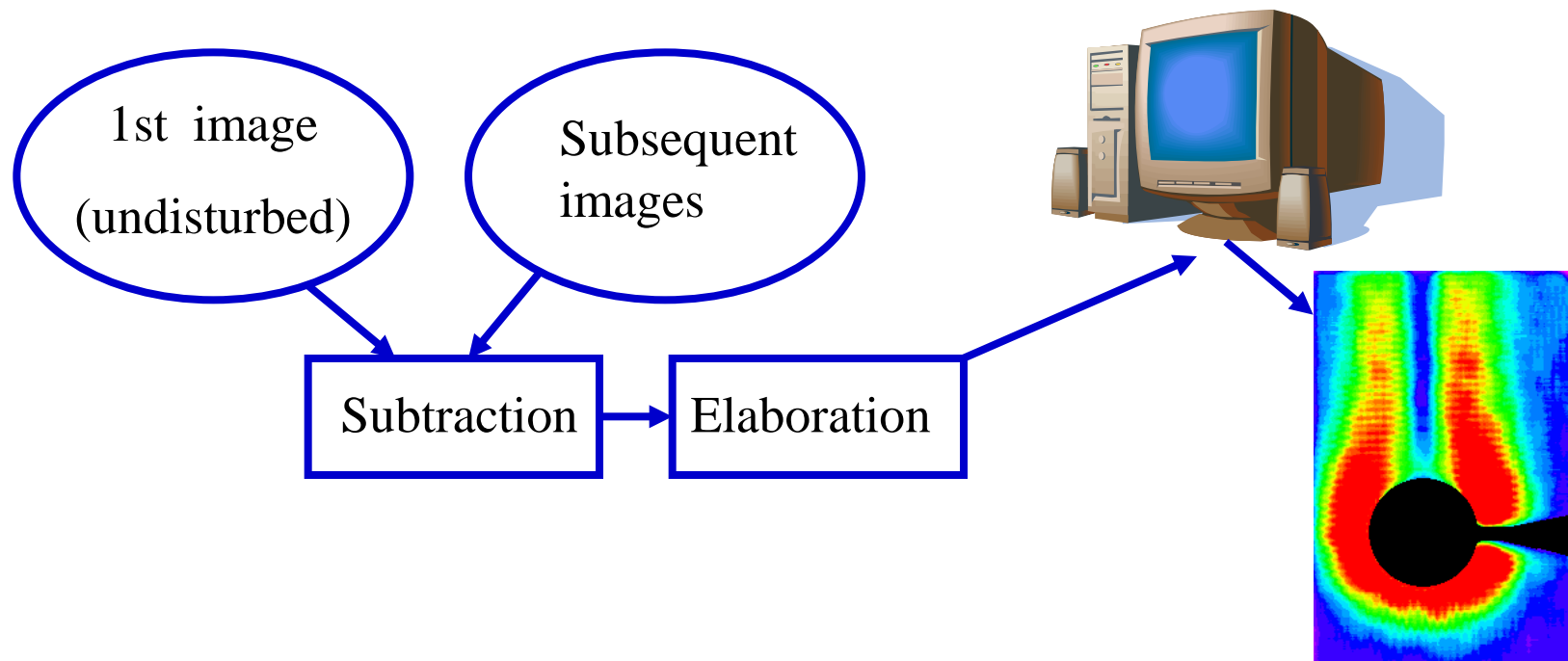
Courtesy G.S. Settles, Penn State University

Also called *Synthetic Schlieren* when “rediscovered” in 1998.



Qualitative analysis

A qualitative visualization of the temperature gradient field can be obtained by subtracting the image recorded with a refractive index gradient, from a reference image (no temperature gradient in the test field) and performing some image filtering. No complicated numerical calculations are required; therefore visualization can be recorded in quasi-real time (25 frames/s).

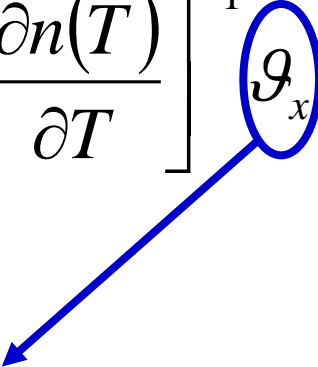


Data processing

It can be shown that the registered intensity is:

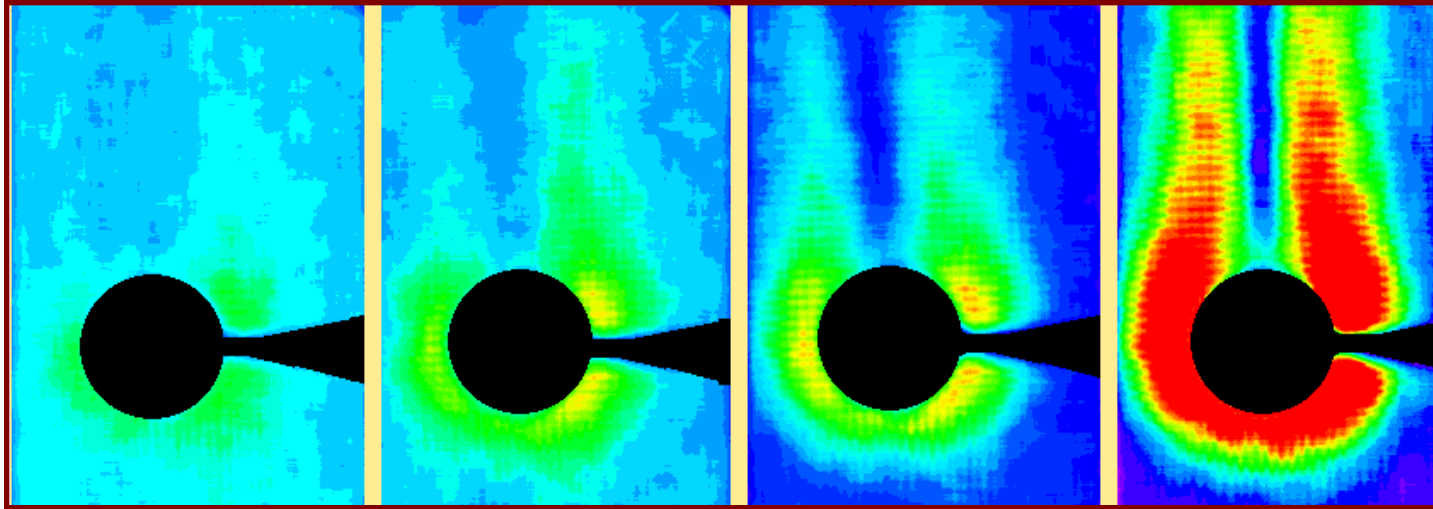
$$I_d(x) = 2A^2 \{1 + \cos[2\pi fx + \varphi + \mathcal{G}_x]\}$$

and

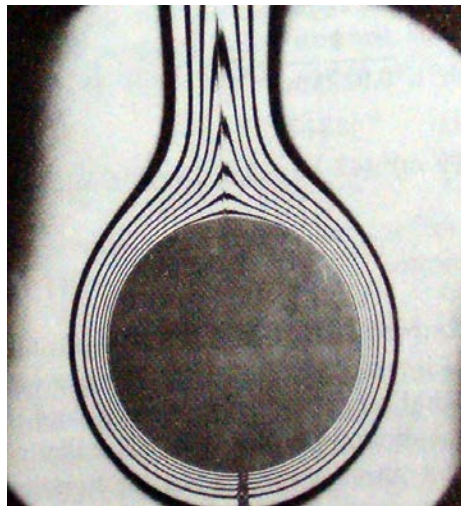
$$\frac{\partial T(x)}{\partial x} = \frac{1}{2\pi f} \frac{n(x_0)}{\ell^2} \left[\frac{\partial n(T)}{\partial T} \right]^{-1} \mathcal{G}_x$$


Can be obtained from the registered intensity by using data analysis techniques based on the Fourier transform.

Onset of convection from a heated circular cylinder in air



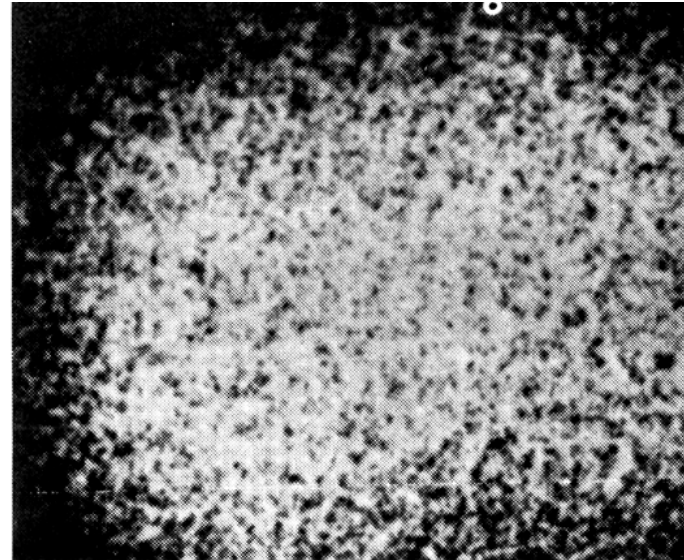
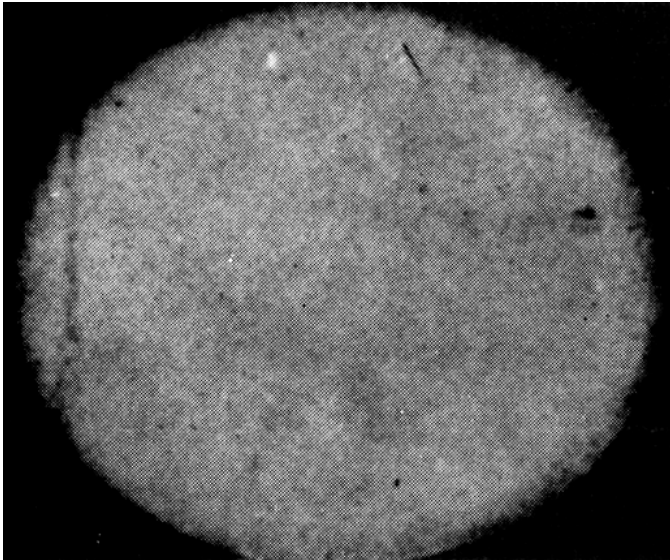
Interferometry
(U. Grigull)



Qualitative analysis



A diffuse scattering surface, illuminated by laser light, appears covered by a pattern of bright and dark spots or speckles randomly distributed in space. This remarkable granular nature, not present in ordinary light, is due to an interference phenomenon.



Photographs of a cement block illuminated by a collimated mercury arc source (left) and a He-Ne laser.

"If we cannot get rid of speckle, why don't we use it?"

Leendertz & Butters, beginning 1970's

Noise?



“Speckle noise”
reduction technique

Information?



Speckle photography (Burch
& Tokarski, 1968)

Speckle Metrology

- ***Speckle photography***
- ***ESPI (Electronic Speckle Pattern Interferometry)***

•.....



Timeline

1877 – Exner, 1880 Rayleigh

1914 – 1917 Von Laue

1919 – Raman

1943 – Ramachandran



The pioneers

1962 – Speckle (re)-discovering (Ridgen & Gordon);

1968 – Speckle photography (Burch & Tokarski);

1971 - ESPI (Butters & Leendertz; Macovski *et al.*);

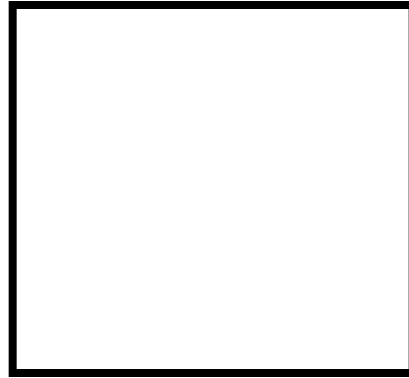
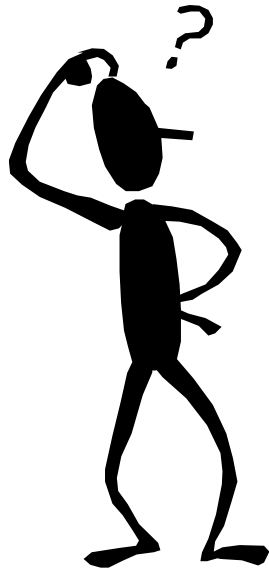
1972 – Speckle photography applied to transparent media (Kopf, Debrus *et al*, Mallick & Roblin);

1978 – First handbook devoted to *Speckle Metrology* (Erf);

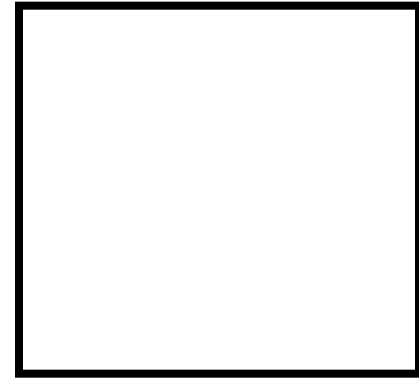
- 1984** – Speckle photography applied in flow visualization (Farrell & Hofeldt, Sivasubramanian *et al.*);
- 1985 – ESPI “rebirths” (the image processing era begins);
- 1988** – ESPI applied in heat transfer (flames) (Lu *et al.*).
- 1993 – ESPI applied in diffusivity measurements; Second handbook devoted to *Speckle Metrology* (Sirohi);
- 1998 – First handbook devoted to speckle photography in fluid mechanics (Fomin);
- 1999 – ESPI proposed for micro gravity experiments (Dubois *et al.*);
- 2001 – First handbook entirely devoted to ESPI (Rastogi);

Flow Visualization:

The Art of Seeing the Invisible 2



Picasso (?): *The Invisible Man*

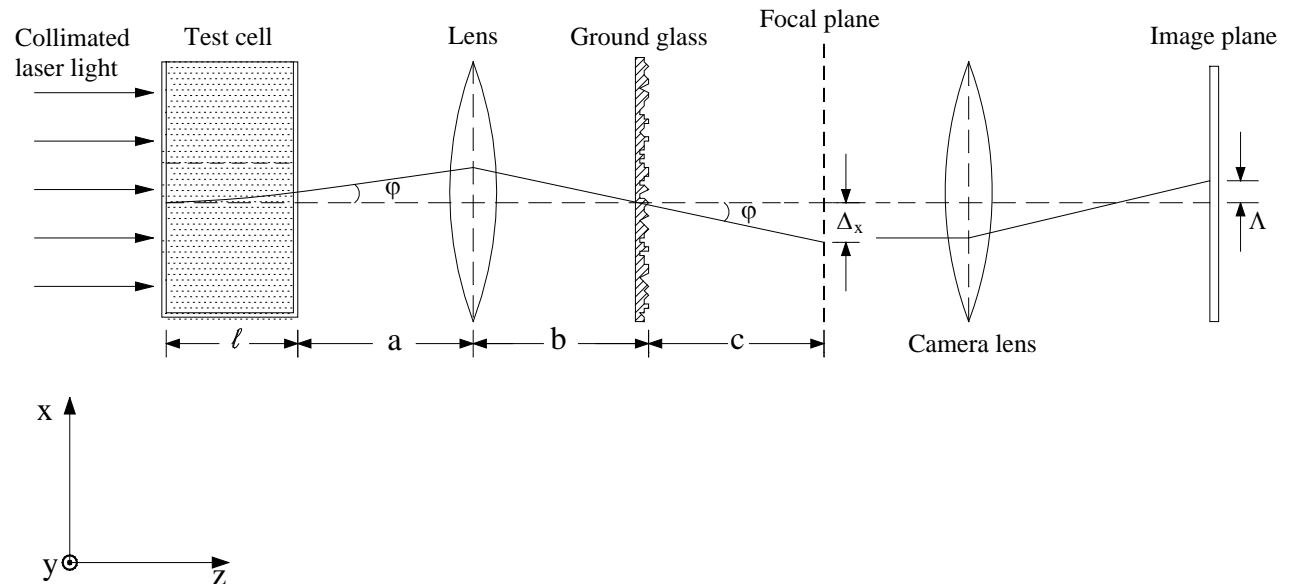


Picasso (?): *His Wife*

Speckle photography

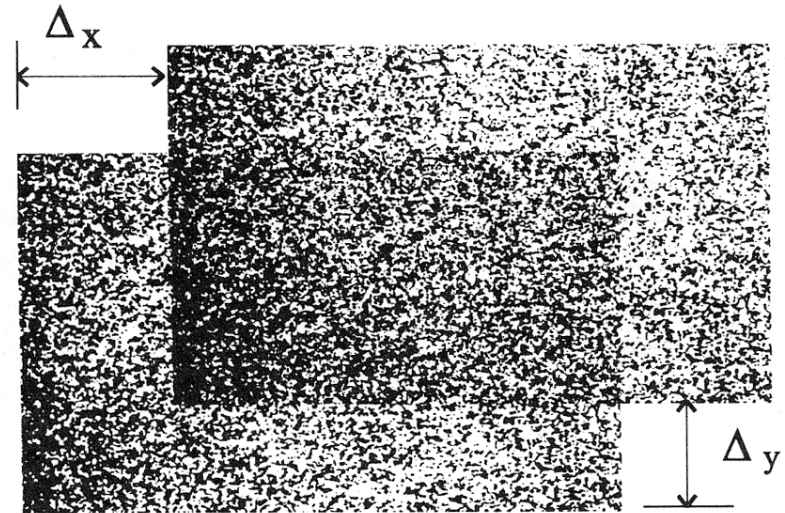
Step 1, experimental setup: different methods proposed in literature, the most used one was proposed by Debrus *et al.* (1972), and modified by Wernekinck and Merzkirch (1987). Most important features: less noisy. The beam deflection, due to temperature gradient, can be regarded as a speckle displacement.

Optical setup for speckle photography in transparent media



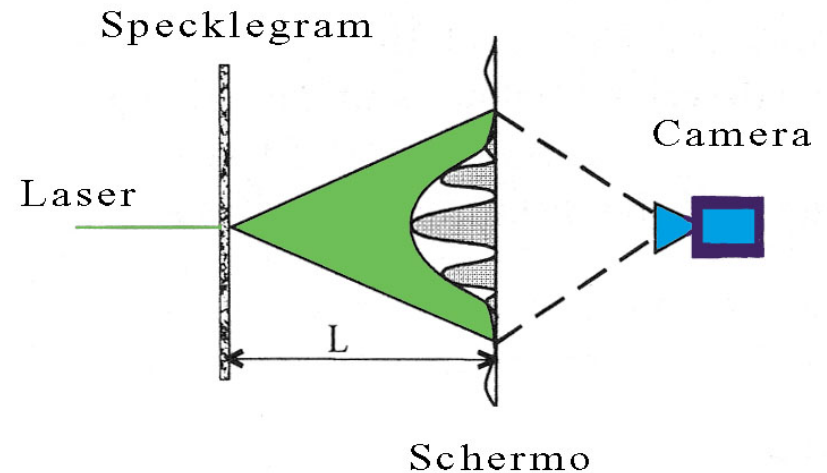
Step 2, recording: two different speckle patterns are recorded on the same photograph.

Specklegram construction



Step 3, interrogation

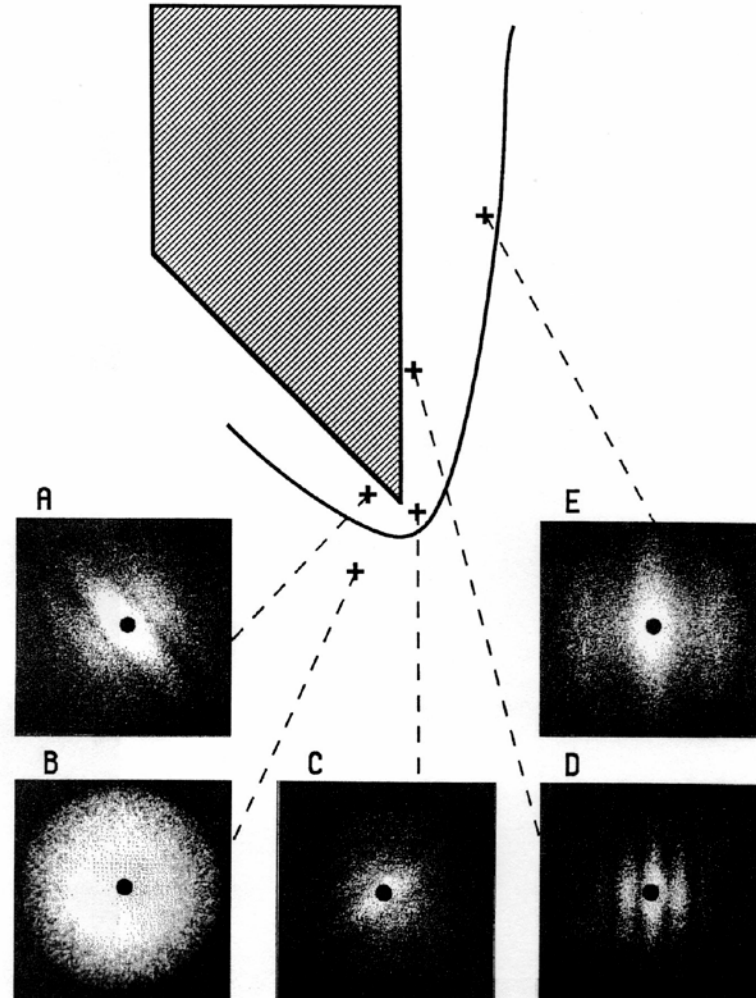
Fringes of the Young type are obtained, their spacing is proportional to the refractive index (temperature) gradient.



Examples

Free convection from a vertical plate ($T_w = 86.2 \text{ }^\circ\text{C}$)

Near the wall (steep temperature gradient) the fringes spacings are narrow (D). The fringe spacing increases approaching the boundary layer edge (E). Fringes disappear outside the thermal layer (B). Fringes orientation changes around the leading edge because the fringes are perpendicular to the local temperature gradient.

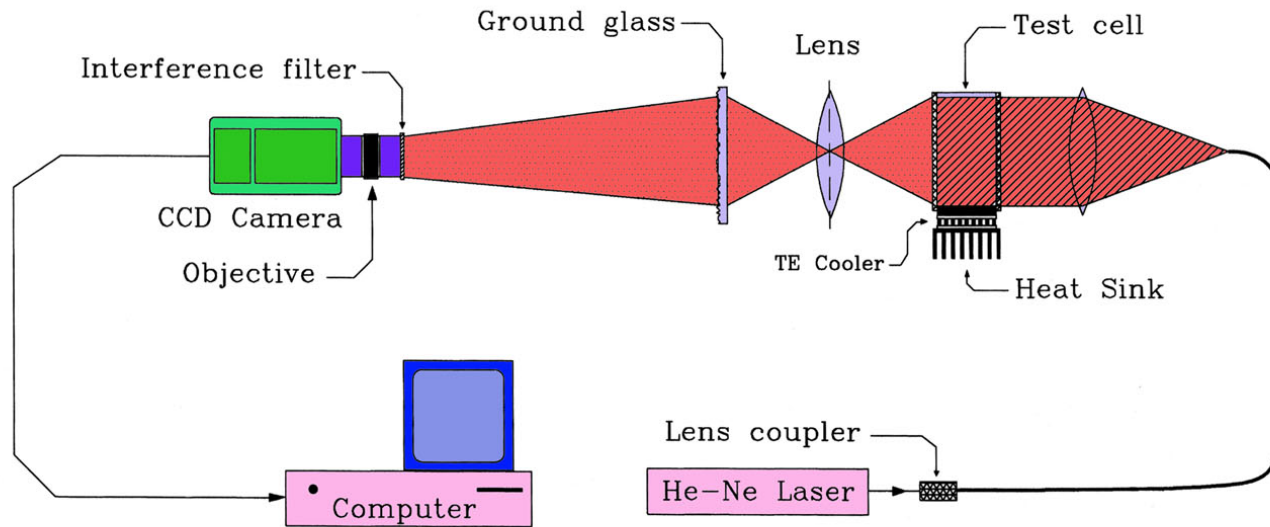


Comparison of data obtained by Speckle photography and other techniques

Free convection
from a vertical plate
in air.

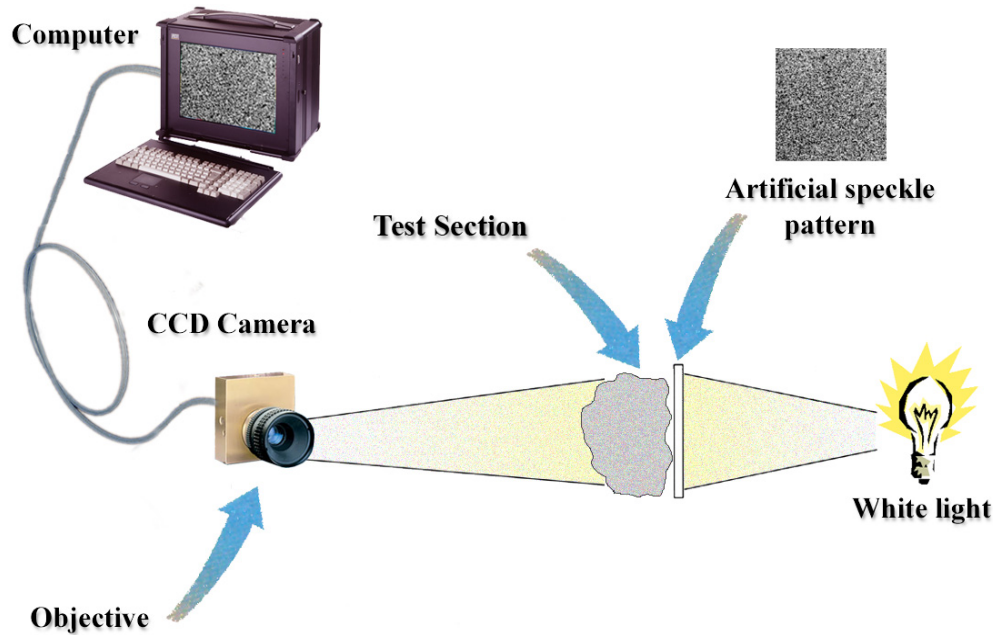
U. Wernekinck, W. Merzkirch, *Appl. Opt.* 26, 31 (1987).

Digital speckle photography



Both recording and interrogation are digitally performed.

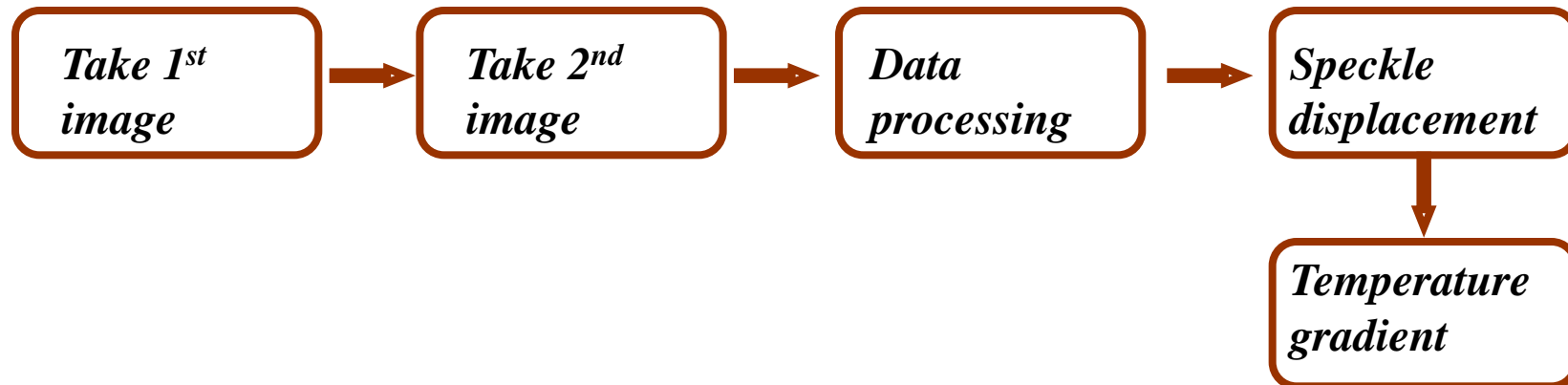
White-light digital speckle photography



Laser source not needed

Relatively simple equipment

Less noisy !!



Digital speckle photography

(vs. classical)

Pros

- No chemicals, films
- Reduced experimental times
- Large amount of digital data

Cons

- Less sensitivity
- Resolution depends on CCD sensor

White-light digital speckle photography

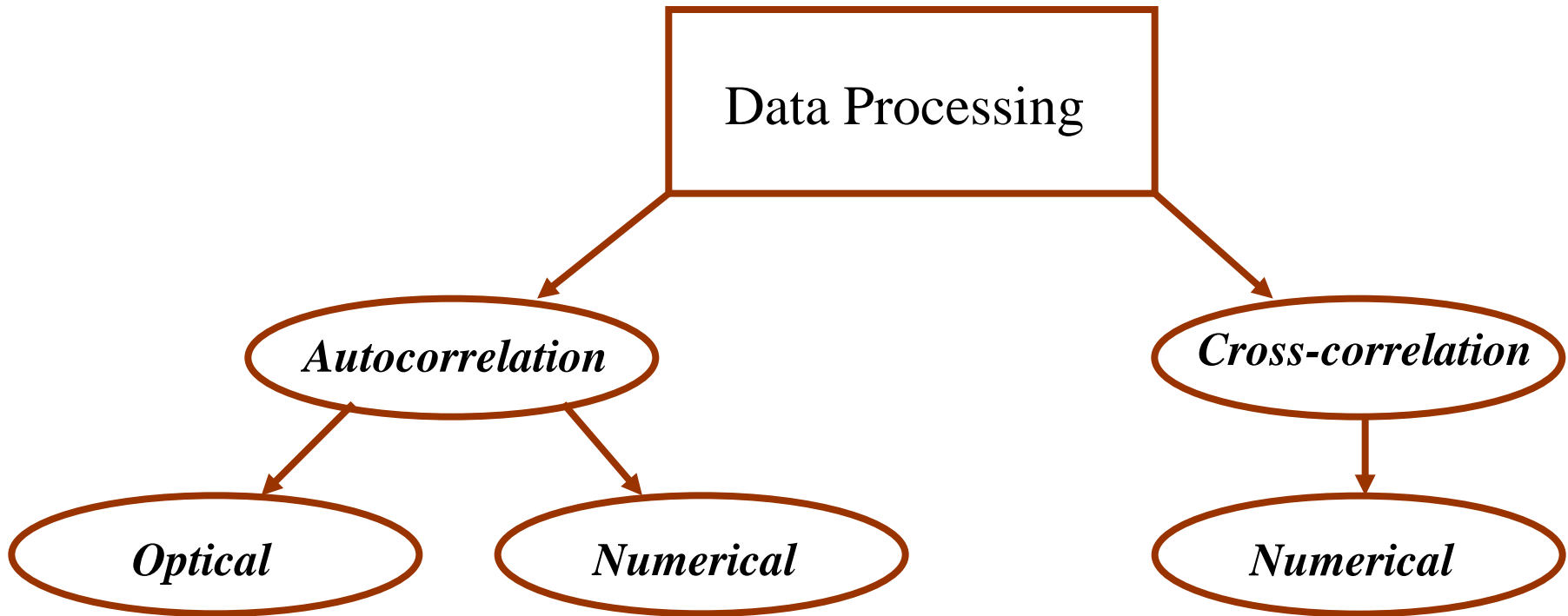
(vs. digital)

Pros

- No laser
- Less noise
- Simplified setup

Cons

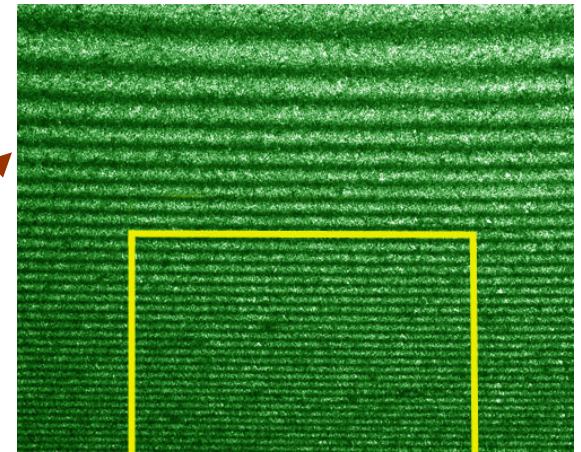
- Less flexibility
- Slight loss in sensitivity



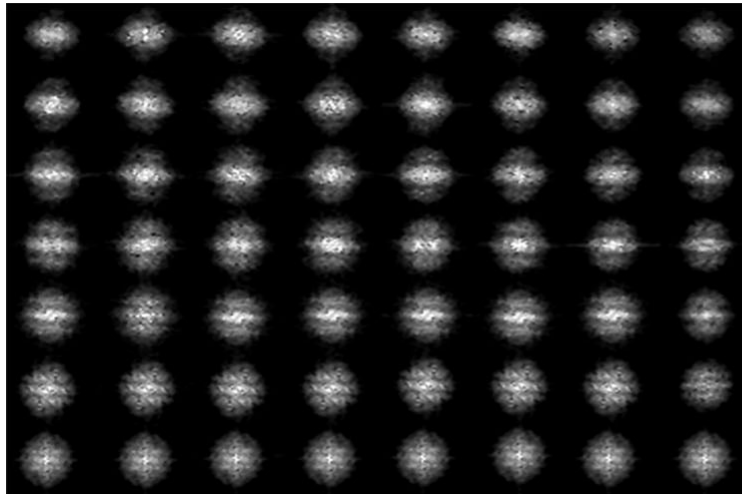
Cross-correlation is preferable to auto-correlation because the latter introduces a sign ambiguity and carries decorrelation into the final results.

*Free convection from a plane plate
in water ($T_p = 16.5 \text{ }^\circ\text{C}$, $T_a = 22.5$)*

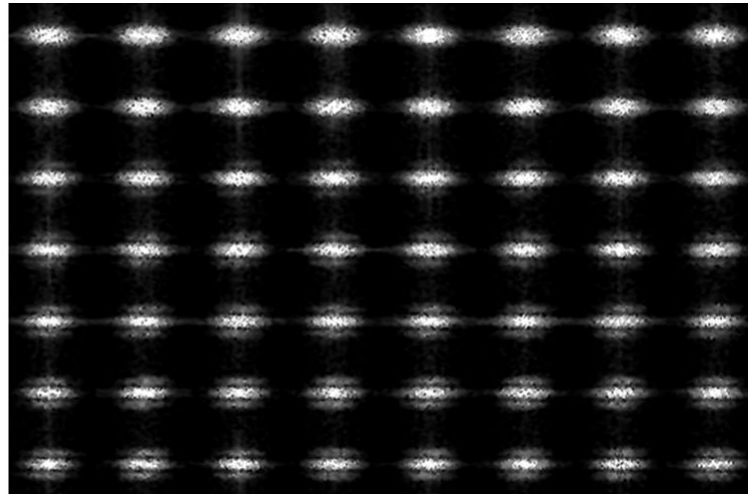
Holographic interferometry



Laser speckle photography



White-light speckle

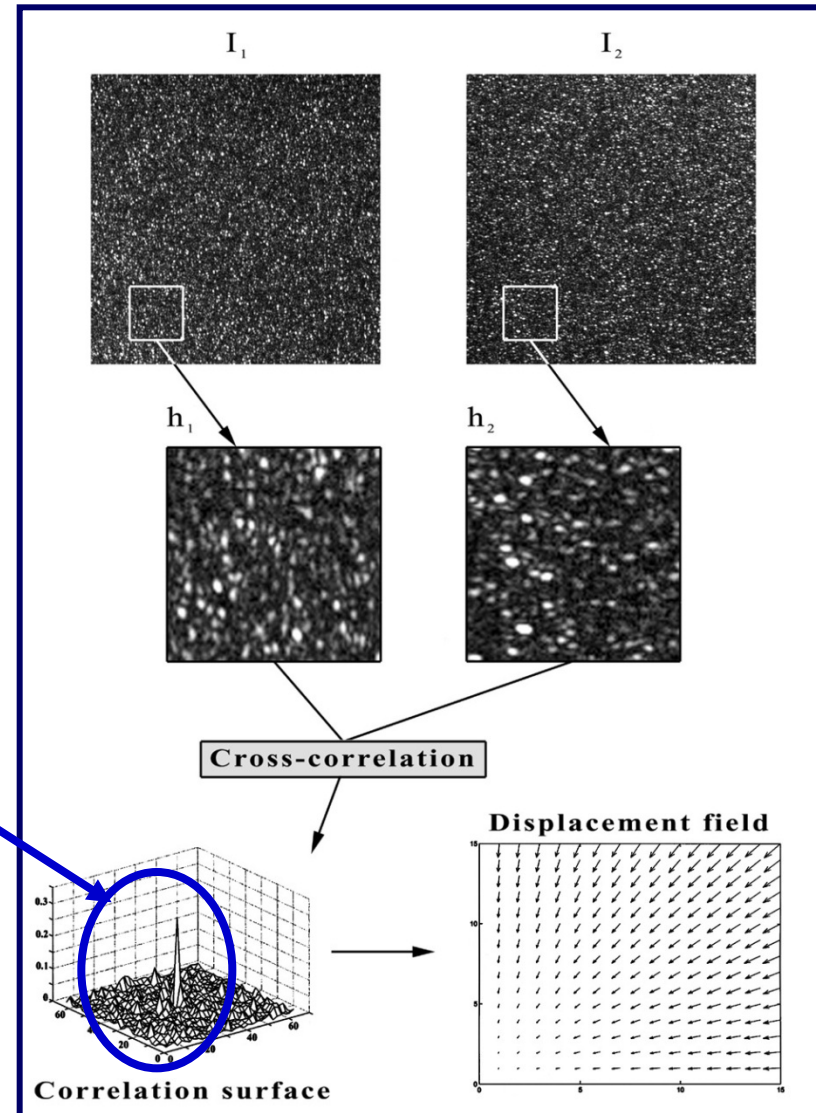


Numerical simulation of optical autocorrelation obtained through a FFT algorithm. Temperature gradient is normal to the fringes and proportional to their spacing.

Cross-correlation

In the cross-correlation approach, sub-images are extracted from the reference image I_1 and the “deformed” image I_2 , then the correlation surface is obtained using suitable correlation filters.

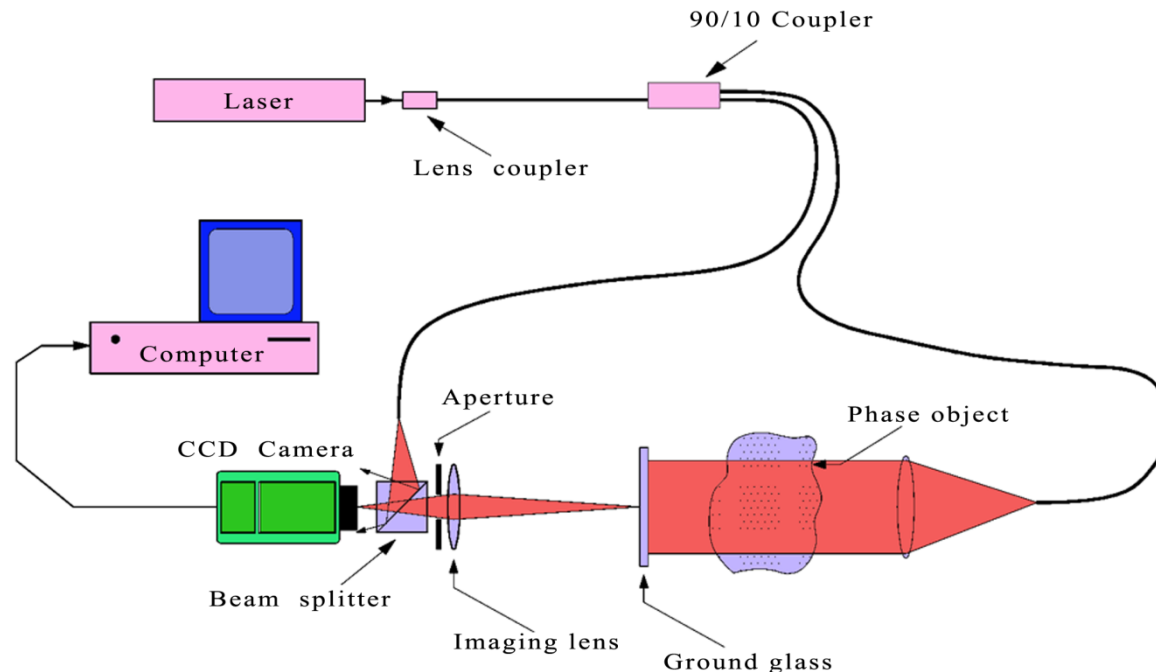
The peak location in the correlation surface gives the relative displacement between the two sub-images.



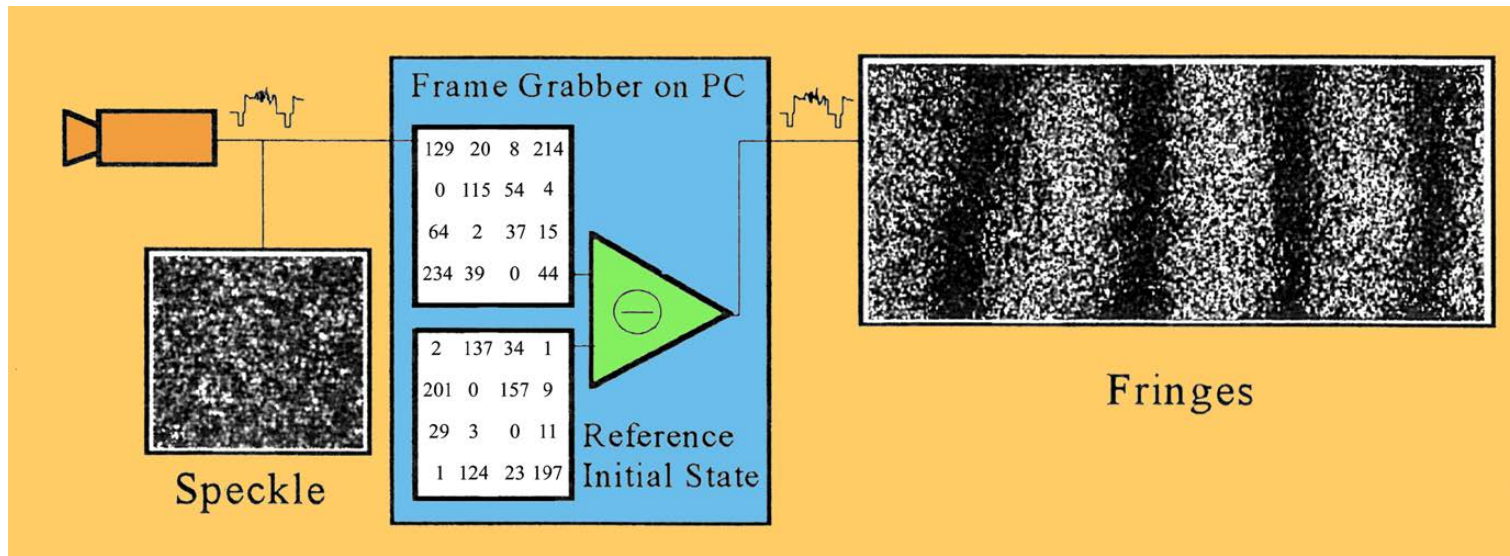
ESPI

(Electronic Speckle Pattern Interferometry)

ESPI can be considered an evolution of both holographic interferometry and speckle photography. It is also called Digital Speckle Pattern Interferometry and TV-holography. ESPI resembles holography, with TV camera replacing the holographic plate and reconstruction performed by computer.



The basic principle of ESPI is the recording of a speckle pattern sequence on the photosensor of a TV camera.



The reconstruction process is performed electronically and visualized on a monitor. The resulting fringes are similar in appearance to conventional holographic fringes but with a lower image quality, due to a much more evident speckle noise.

ESPI Maths

The intensity of an ESPI interferogram can be written as

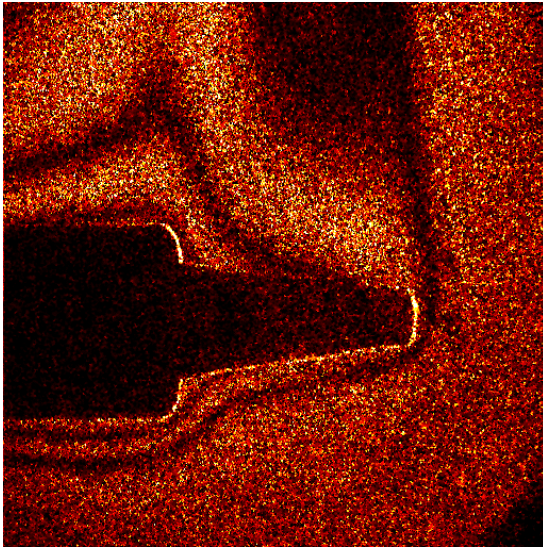
$$I(x, y) = 4I_o(x, y)I_r(x, y)\{1 - \cos[\Delta\mathcal{G}(x, y)]\}$$

Here I_o and I_r are the object and reference beam intensities, the desired information about phase variation is contained in $\Delta\mathcal{G}(x, y)$

In practice ESPI fringes have visibility < 1 .

Phase variation can be calculated by several fringe processing method (Fourier Transform, etc.)

Examples



Free convection from an iron solder.

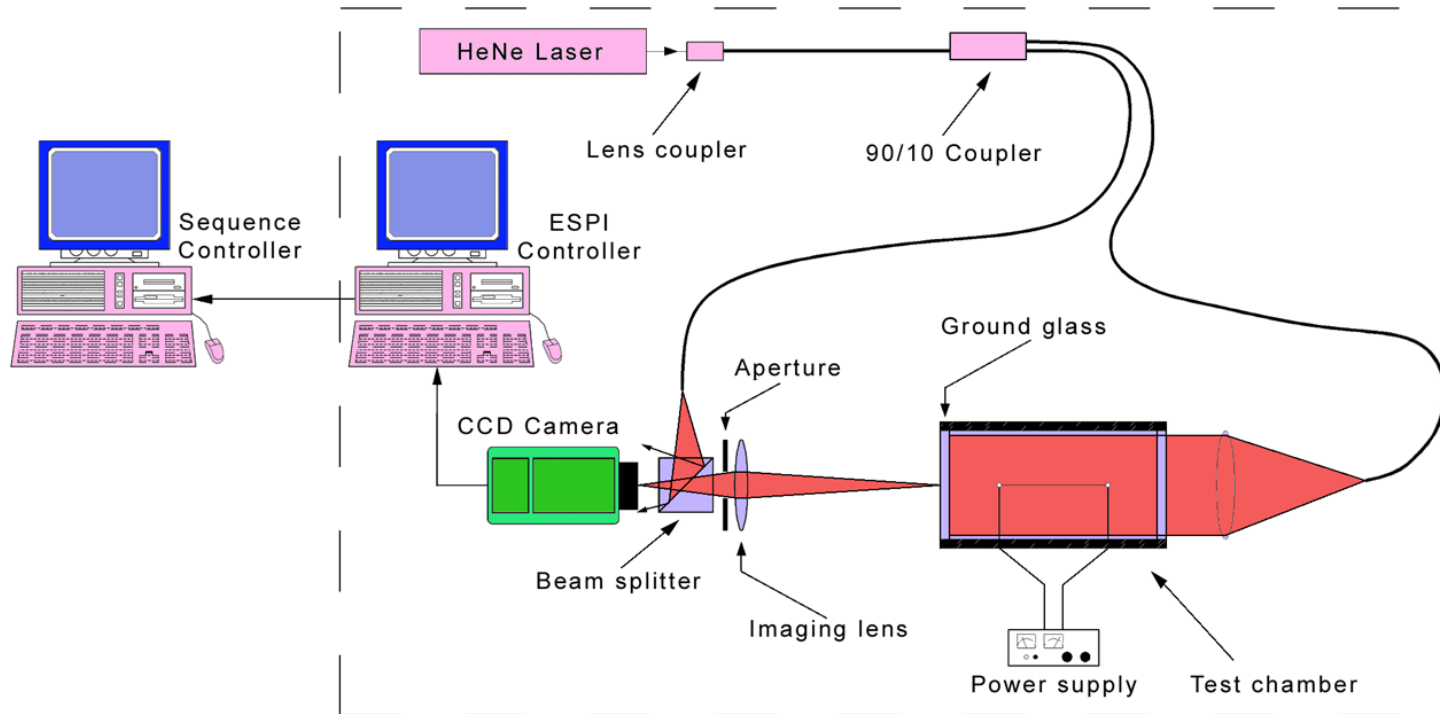


Free convection from a fin.

ESPI Pros & Cons

- Quasi real time
- Reduced stability requirements;
- Possibility to realize compact and portable instrumentation;
- Elimination of photographic processing;
- Full digital data elaboration;
- No need of good quality optics and simplification of the optical setup;
- Possibility of daylight operation (interference filter in front of the CCD camera);
- Resolution depending on the sensor
- Speckle noise!

An example: transient convection from a horizontal wire

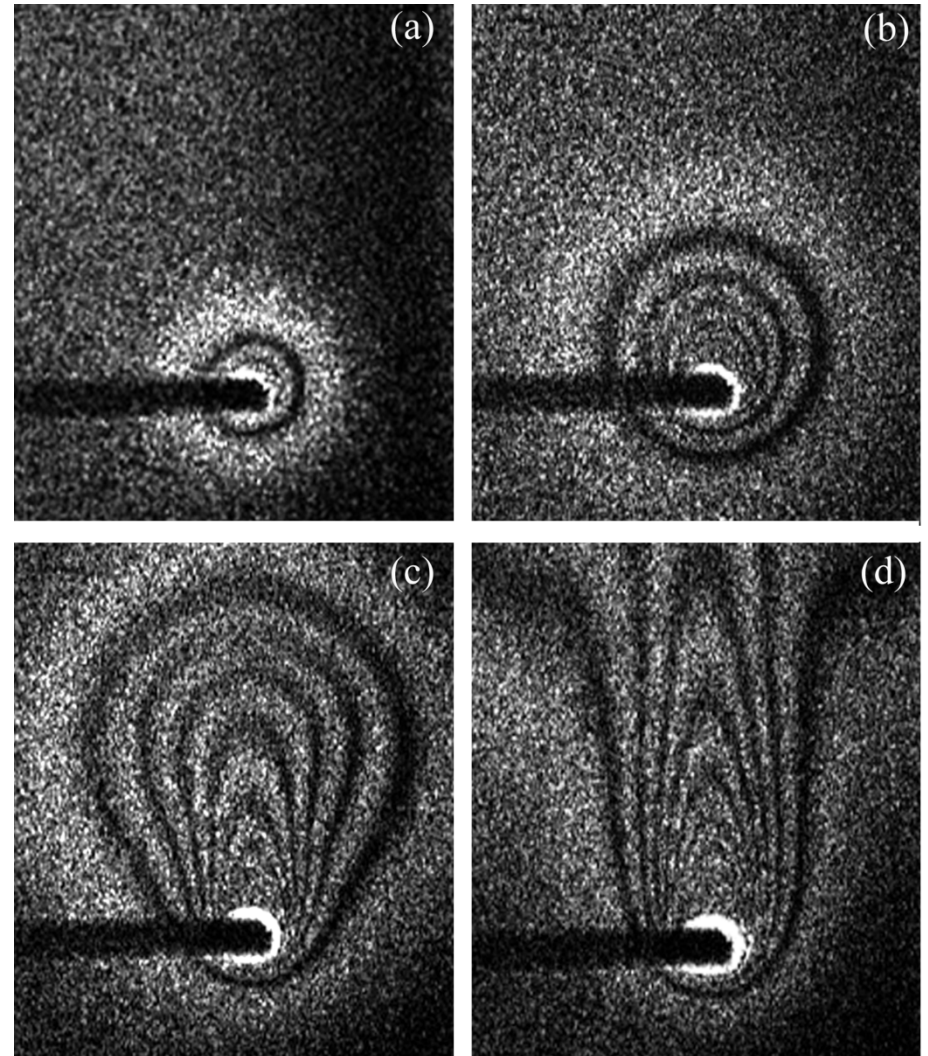


The system provides a sequence of 25 interferograms per second. Therefore, the time interval between images is 0.04 s.

D. Ambrosini *et al*, Int. J. Heat Mass Transf. 46, 4145 (2003).

Image sequence

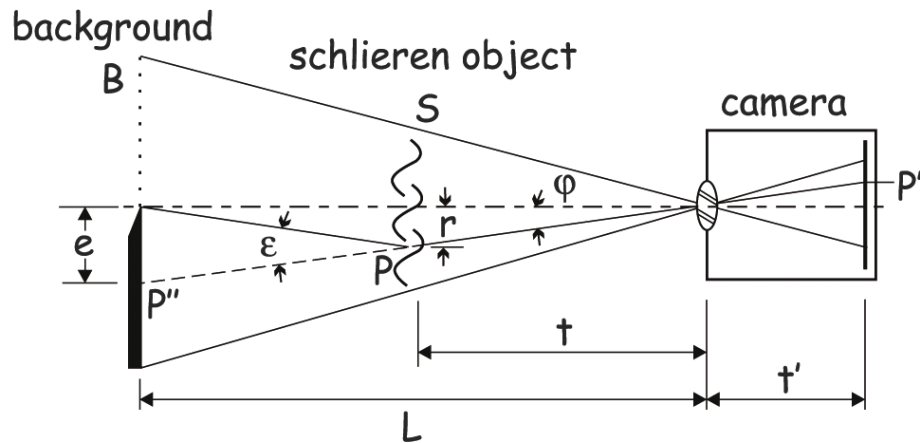
Initially the isotherms are concentric circles (a) (pure conduction). At increasing times, the isotherms become asymmetrical, as those above the wire are convected upward. The temperature difference between two fringes is about 3 °C.



(a) $t = 0.36$ s; (b) $t = 0.65$ s; (c) $t = 1.1$ s; (d) $t = 1.56$ s. Time indetermination is ± 0.04 s.

BOS: a rising star

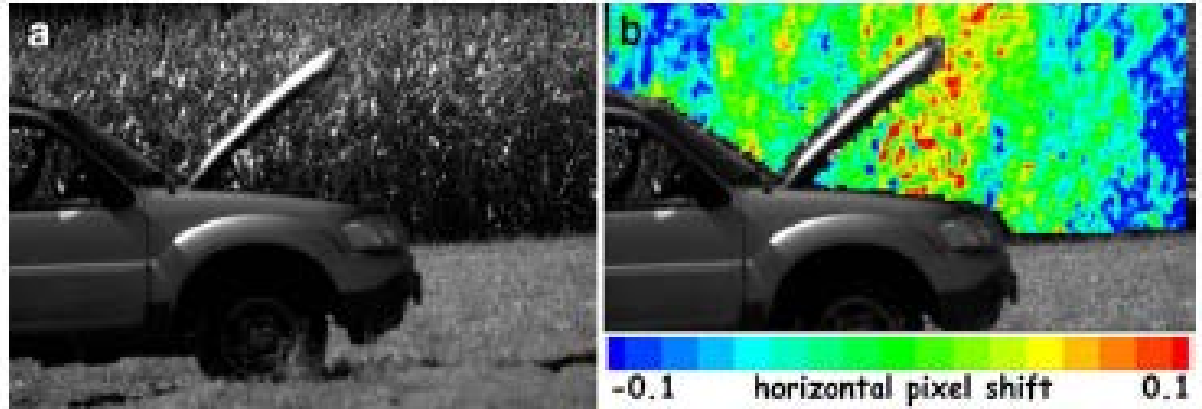
Background Oriented Schlieren (BOS) is based on the apparent distortion of a background induced by beam deflection. BOS uses background artificially generated by splashing tiny droplets of white wall paint or backgrounds naturally present (such as grass). The current success of this method no doubt comes from the spectacular progresses of automatic spatial correlation systems, developed lastly for PIV.



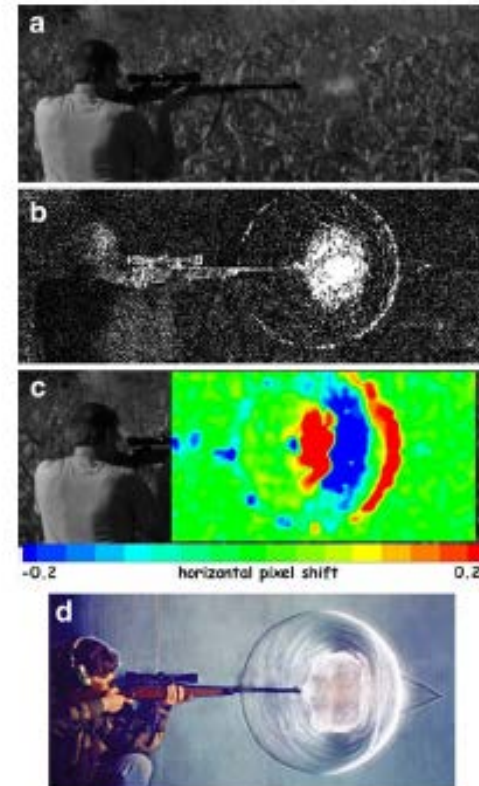
BOS is practically a Schardin's method n. 1 (1942). It was rediscovered at the end of the 90's and coupled to digital image processing.

All images Courtesy G.S. Settles, Penn State University

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



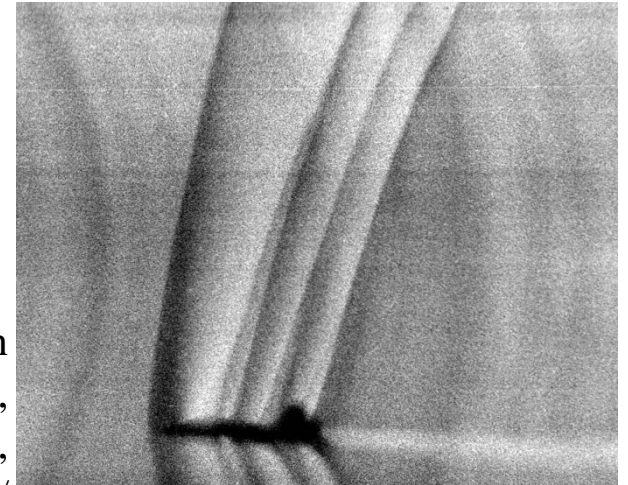
High-speed images of a 0.30-06 rifle discharge showing the muzzle blast and supersonic bullet. A raw image (a) is compared with a tare image to find the pixel intensity change (b) and the horizontal pixel shift (c). The BOS images b and c show different views of the gunshot also imaged using the PSGDL Full-Scale Schlieren system (d).



The Art of Flow Visualization: final remarks



Schlieren images (1962) of an Apollo Command Module and Launch Escape System model being tested in a wind tunnel. NASA / Courtesy of nasaimages.org



This is Dr. Leonard Weinstein's Schlieren photograph of a T-38 at Mach 1.1, altitude 13,700 feet (about 4176 m), taken at NASA Wallops in 1993. NASA / Courtesy of nasaimages.org.

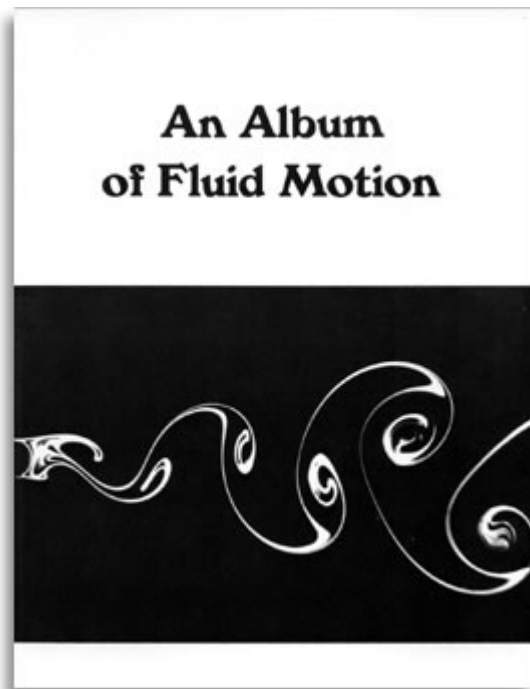


Laser tomography combined with fluorescent dyes employed to capture the fluid motion in traditional champagne flutes to better highlight the fluid dynamics inside a glass. Courtesy Prof. Polidori, Reims, France.



Water splash by water drop. A. Davidhazy, RIT, USA.

Flow visualization images are experimental records of observations conducted in the course of research, and thus represent a special form of scientific data. They are also, in many cases, images of stunning beauty. And there are some discussions in literature about their “artistic side”.



Visualization of flow patterns past various objects in two-dimensional flow using soap film

Mohamed Fayed, Rocco Portaro, Amy-Lee Gunter, Hamid Alt Abderrahmane and Hoi Dick Ng
Department of Mechanical and Industrial Engineering, Concordia University, Montréal, Québec, H3G 1M8 Canada

The use of flowing soap films has long been considered as an educational tool and economical visualization technique to study fluid-structure interaction and hydrodynamic instability in two-dimensional fluid flows^{1,2}. Taken from a home-made continuously flowing soap film tunnel using a high-speed pco.1200hs camera and a low-pressure sodium lamp, these images display the two-dimensional wake flow structure behind various objects from simple to complex geometries and arrangements. The wake created from the interaction between the objects and the flow with different flow rates creates a number of beautiful and artistic vortex patterns.

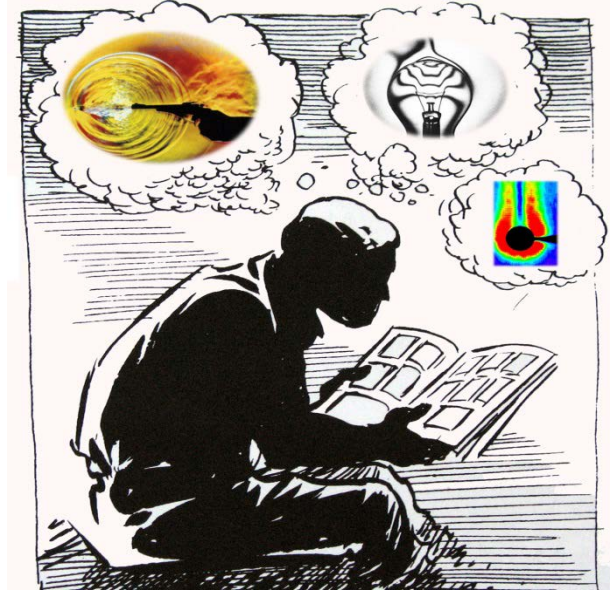
A grid of 10 grayscale images showing various flow patterns past different objects. The patterns are highly artistic and complex, featuring vortices, eddies, and intricate wake structures. The objects are not clearly visible, but the flow patterns are the focus of each image.

¹ J. Zhang, S. Chikara, A. Libchaber, M. Shelley, *Nature* 409 (2006) 530-536.
² M. Szwed, M. Ghark, *Experiments in Fluids* 23 (1997) 130-142.

References

*“I’m afraid I can’t put it more clearly”,
Alice replied very politely, “for I can’t
understand it myself, to begin with.”*

LEWIS CARROL, Alice in Wonderland



Starting points:

- *Optics & Lasers in Engineering, Special issue 2006, 2008 and 2012* (in particular, see the 2012 editorial)