Laser Speckle interferometry: theory and applications

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The Abdus Salam International Centre for Theoretical Physics

Winter College on Optics 2017: Advanced Optical Techniques for Bio-imaging. 13-24 February 2017

Outline

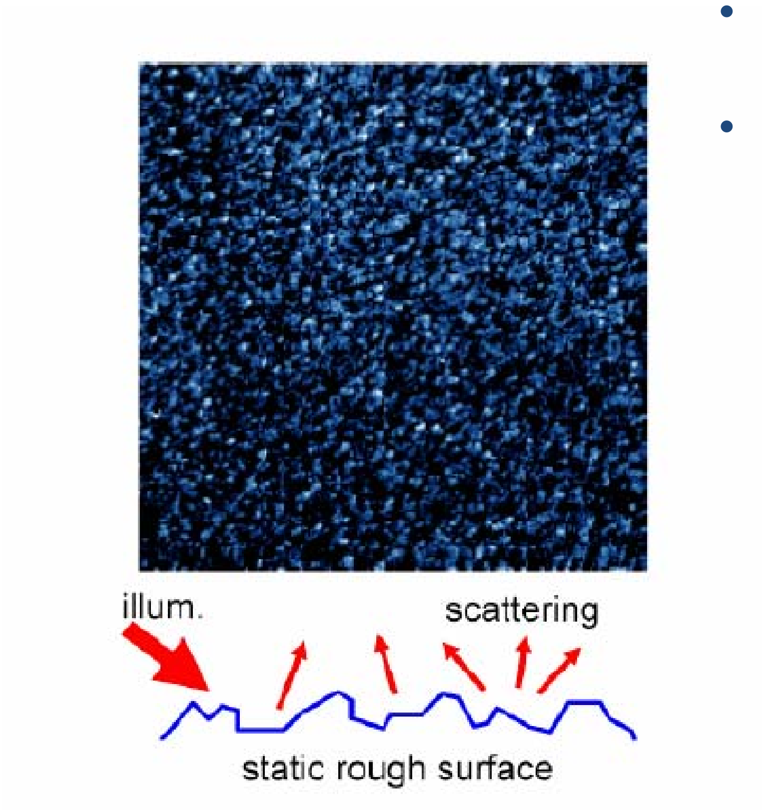
- To introduce, study and discuss the concept and fundamentals of laser speckle.
- To interpret the speckle formation: first order statistics.
- Some classical techniques: stationary and dynamic laser speckle imaging.
- Dynamic speckle in an image forming system.
- Applications in biomedicine: biospeckle

Contents

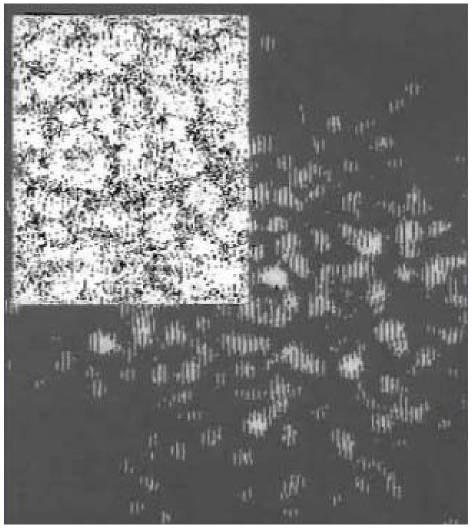
- Introduction: speckle phenomenon.
- Speckle formalism: first order statistics. Random interference phenomenon.
- Speckle formation in an image forming system.
- Dynamic speckle in image forming systems: basic principles.
- Contrast function in dynamic laser speckle.
- Speckle equivalent phenomena in non-linear optics
- Applications in Biomedicine: examples of biospeckle.
- Experimental laboratory.
- Conclusions
- Main references.

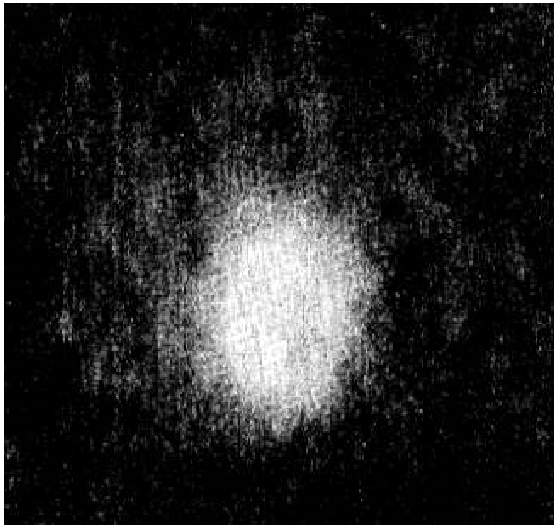
Introduction: Speckle phenomenon

- Observed in early 60's as the use of laser sources started to be introduced in the laboratories.
- Pioneering work of J. W. Goodman and J. C. Dainty.



- Speckle effect is readily observed with highly coherent illumination.
- There is a granular structure of the coherent pattern.

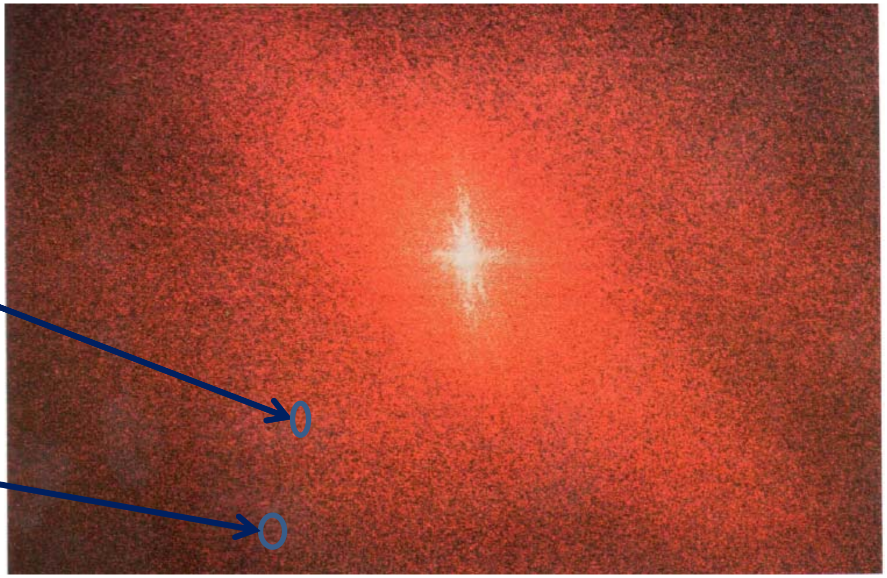




Formation and observation of speckle requires high spatio-temporal coherence.

Speckle pattern

- Speckle pattern consists of a multitude of bright spots where the random interference has been highly constructive.
- Dark spots where the random interference has been highly destructive.
- Irradiance levels in between these extremes.



Randomly varying intensity pattern

We observe a continuum of values of irradiance which has the appearance of a chaotic jumble of "speckles".
It is a coherent light scattering phenomenon becoming visible to the naked eye, with visible laser sources. (i.e., He-Ne laser).

Reference: M. L Calvo, "Coherencia óptica", Investigación y Ciencia (*Spanish version of Scientific American*), p.p. 66-73 (May 1995).

First-order statistics of a polarized speckle pattern

- **Random walk model**

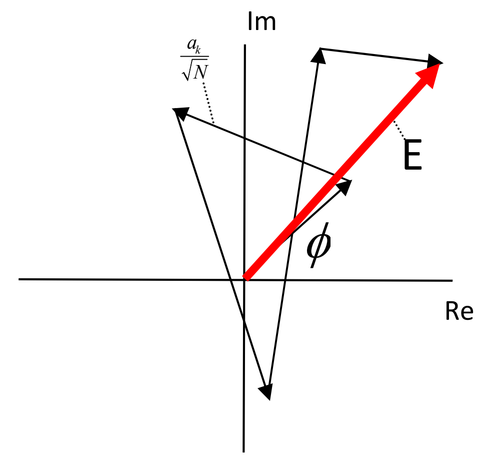
- Single scattering of coherent (laser) light by a collection of particles (roughness or scatterers) dispersed through a volume.
- Scatterers dimension is much greater than the wavelength of the illuminating radiation.
- Single polarized component of the scattered complex field amplitude ***E***

$$E = \sum_{n=1}^{N} a_n \exp(i\varphi_n)$$

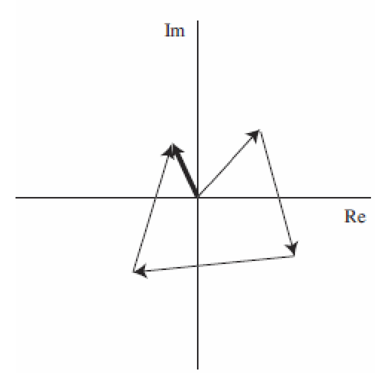
The phase: $-\pi \leq \varphi_n \leq +\pi$, statistically independent from a_n.

N: number of independent contributions.

The scattering amplitude a_n has a probability density $p(a_n)$.



Constructive addition



Destructive addition

Reference: J. W. Goodman, *Speckle Phenomena in Optics: Theory and Applications*, 2006.

Probability density function of the intensity

- Assume φ_n independent of a_n
- Lord Rayleigh (1919) showed that the radial profile of the joint probability density function is:

$$p(I)=\frac{1}{2}\int_0^{+\infty} J_0\left(u\sqrt{I}\right)u\left\langle J_0\left(u\frac{a}{\sqrt{N}}\right)\right\rangle^N du$$

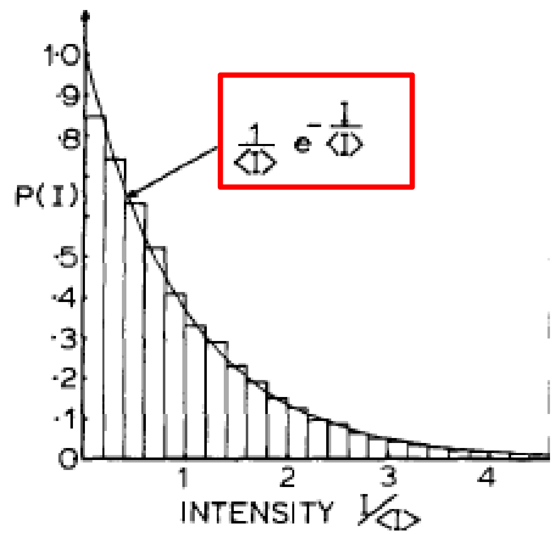
J_0 : zeroth order Bessel function. N: finite number.

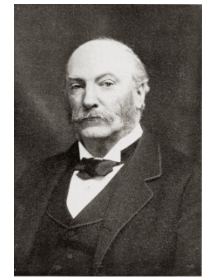
$\langle\ \rangle$: average over the ensemble of the scattering amplitudes.

- Statistical properties of the amplitude:
  Gaussian and non-Gaussian statistics.

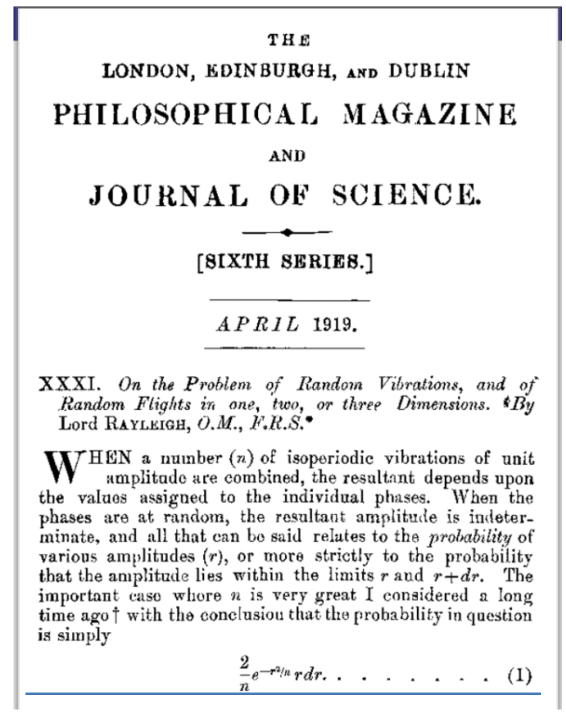
$$\left.\begin{aligned}\langle I\rangle &= N\langle a^2\rangle\\ \frac{\langle I^2\rangle}{\langle I\rangle^2} &= 2\left(1-N^{-1}\right)+N^{-1}\frac{\langle a^4\rangle}{\langle a^2\rangle^2}\end{aligned}\right\}$$

As: $N\rightarrow+\infty$, the process is interpreted as Gaussian statistics.





Lord Rayleigh
(1842-1919)



THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[SIXTH SERIES.]

APRIL 1919.

XXXI. *On the Problem of Random Vibrations, and of Random Flights in one, two, or three Dimensions.* By Lord Rayleigh, *O.M., F.R.S.*

WHEN a number (n) of isoperiodic vibrations of unit amplitude are combined, the resultant depends upon the values assigned to the individual phases. When the phases are at random, the resultant amplitude is indeterminate, and all that can be said relates to the *probability* of various amplitudes (r), or more strictly to the probability that the amplitude lies within the limits r and $r+dr$. The important case where n is very great I considered a long time ago† with the conclusion that the probability in question is simply

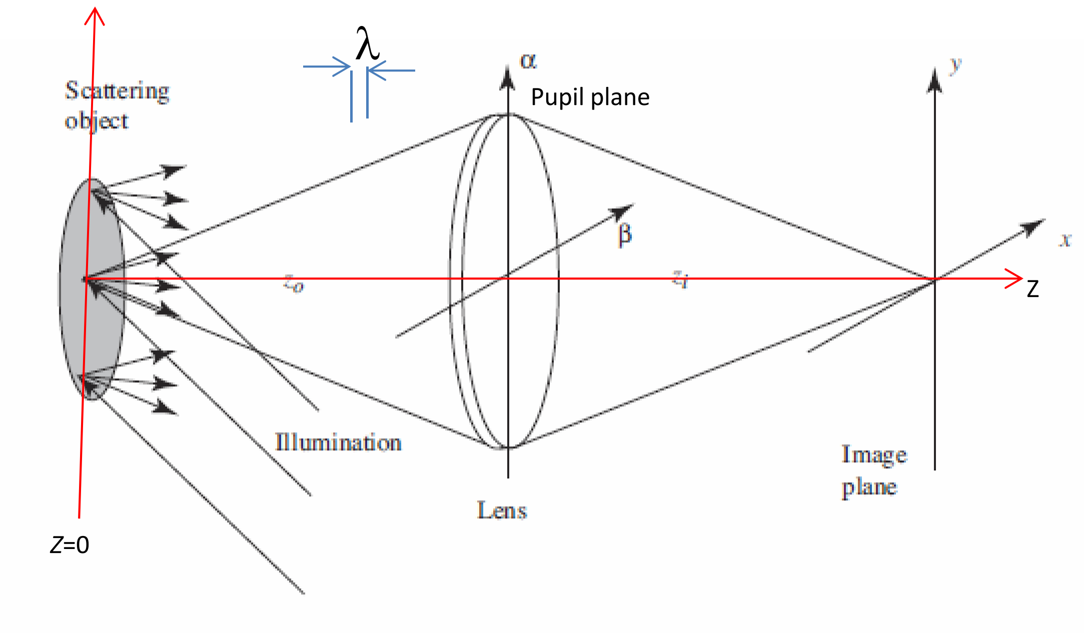
$$\frac{2}{n}e^{-r^2/n}\,r\,dr. \quad \quad (1)$$

Measured histogram taken from a speckle pattern. N=23,000

Reference: J. C. Dainty, *Progress in Optics*, Vol. XIV, 1976.

Speckle formation in an image forming system:

- Speckle is ubiquitous in coherent imaging.
- The image is itself a speckle field.

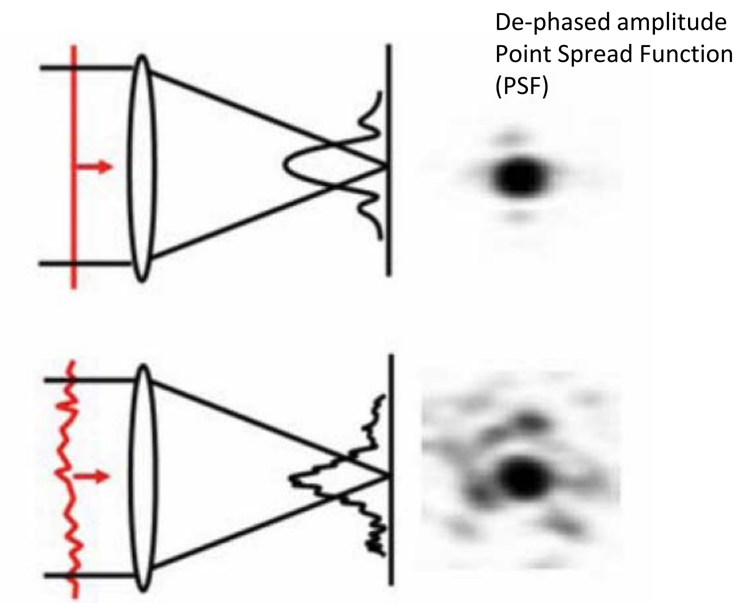


Minimum size of image speckle (aberration free). Defined from the radius of the Airy disk.

$$S_{speckle} = 2.44\lambda(1+M)\frac{f}{D}$$

It does not hold for high resolution optical systems.

In the stationary case, the object is a static body with a rough surface.

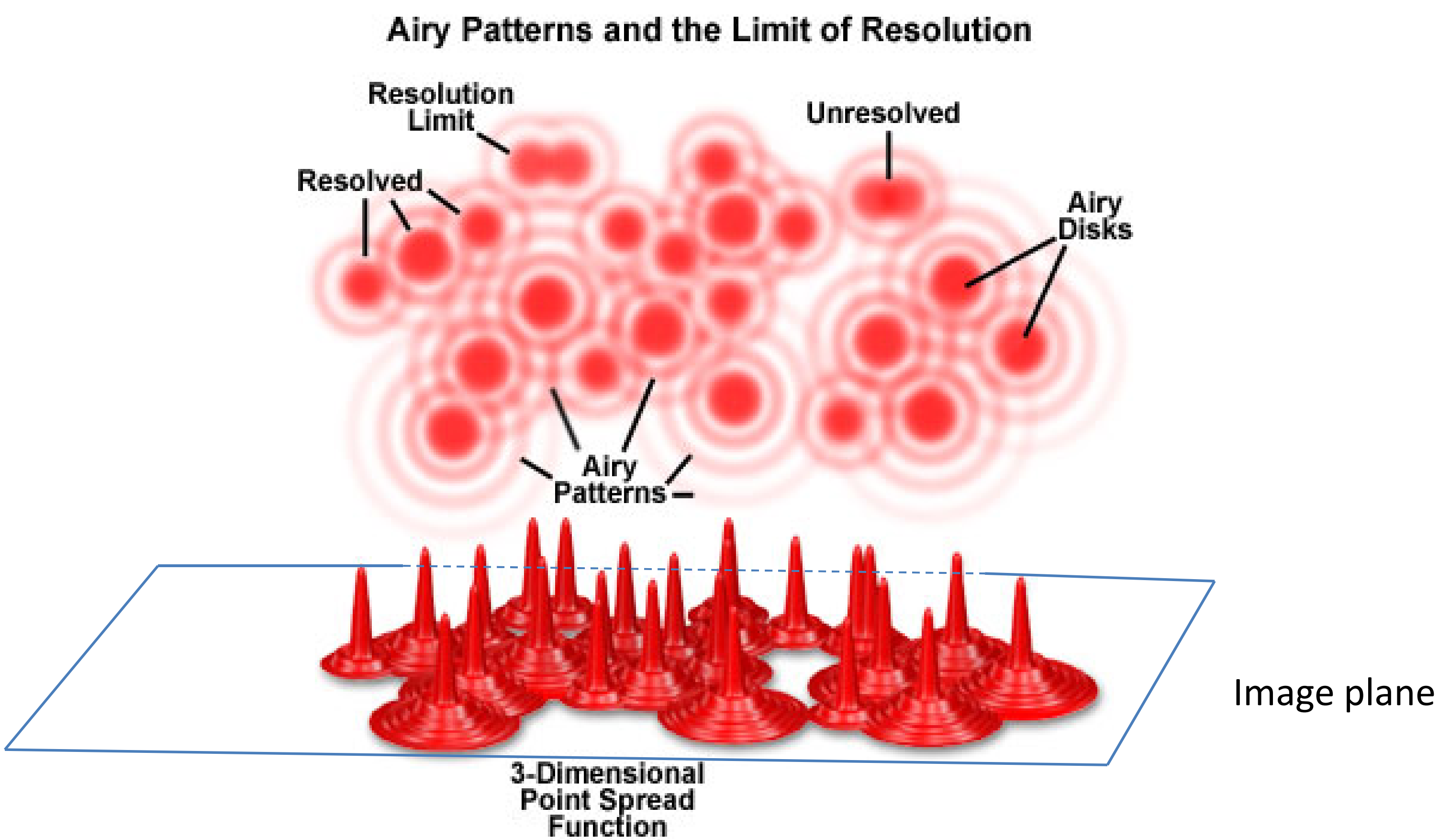


Particular case, in a Hart-Shartmann sensor

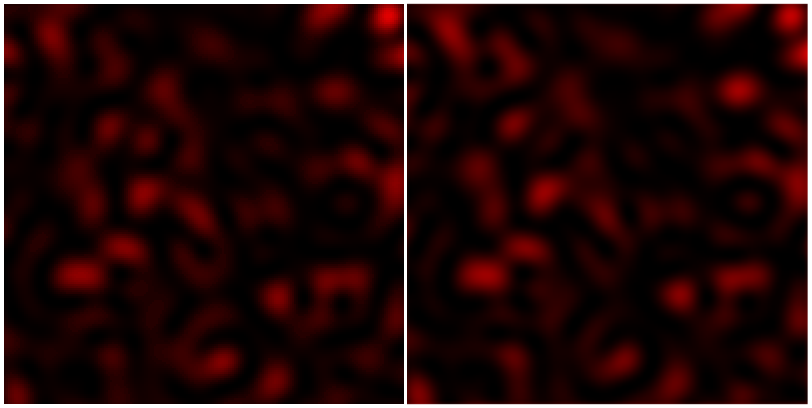
And the speckle contrast is: $K = \frac{\sigma}{\langle I \rangle}$

Reference: J. Senarathna et al., IEEE *reviews in biomedical engineering,* **6**, 99–110 (2013).

Understanding the speckle structure at the image plane



Dynamic speckle in image forming systems: basic principles



Static speckle   Moving speckle pattern

$$K = \frac{\sigma_I}{\langle I \rangle}$$

$$K(r) = \frac{\sigma(r)}{\mu(r)} \sim \sqrt{\frac{\tau_c}{T}}$$

- If the scattering medium changes with time, the speckle pattern also evolves: time-varying speckle or dynamic speckle.
- The speckle fluctuates in intensity.
- The level of blurring is quantified by the speckle contrast. The formulation depends on whether the speckle is static or dynamic.

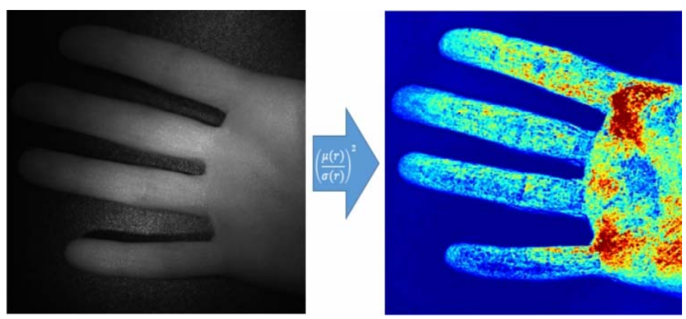
τ_c: speckle autocorrelation time. *T*: exposure time. And:

$$V(r) \sim \frac{1}{TK(r)^2}$$

The contrast variable can be utilized to infer information about velocity of the dynamic medium.

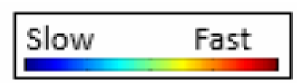
Applications: Fluctuations provide information about the motion. The speckle pattern is imaged with an exposure time longer than the shortest speckle fluctuation time scale: $T \gg \tau_c$.

Technique: Flowmetry



Source: G. Satat, 2014 IEEE INTERNATIONAL CONFERENCE ON COMPUTATIONAL PHOTOGRAPHY (ICCP)

Example of mapping: from speckle image to perfusion map through Laser Speckle Contrast Imaging (LSCI).

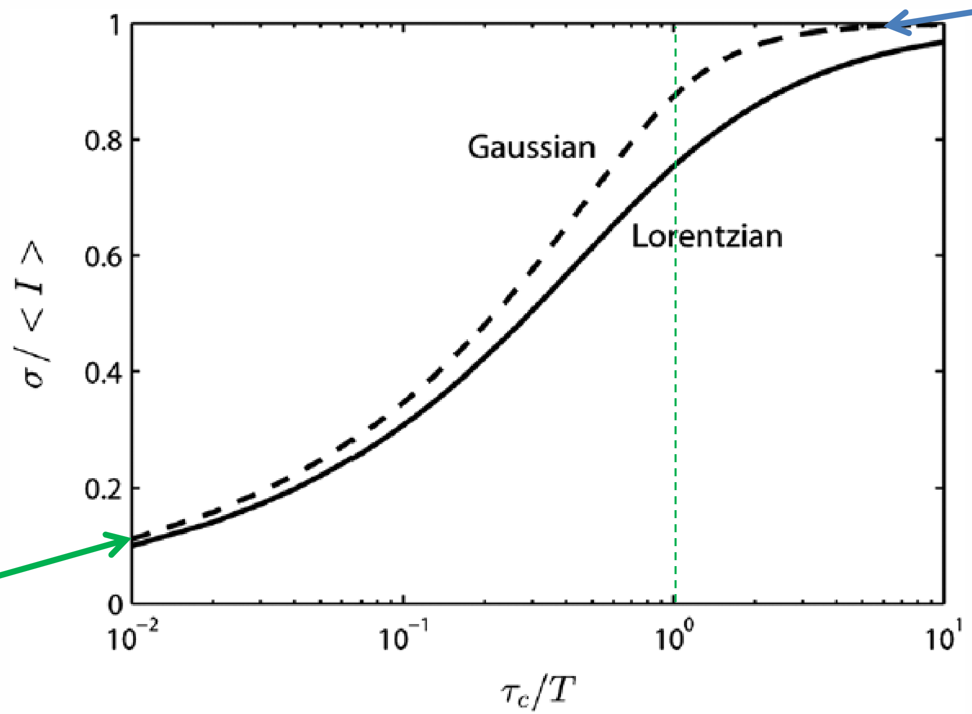


Movie courtesy: https://www.perimed-instruments.com/laser-speckle-contrast-imaging

Dynamic speckle contrast function

Assuming all photons Doppler-shifted and a Lorentzian velocity distribution

$$K = \frac{\sigma}{<I>} = \left(\beta\left\{\frac{\tau_c}{T} + \frac{\tau_c^2}{2T^2}\left[\exp\left(\frac{-2T}{\tau_c}\right) - 1\right]\right\}\right)^{\frac{1}{2}},$$



No blurring
No motion

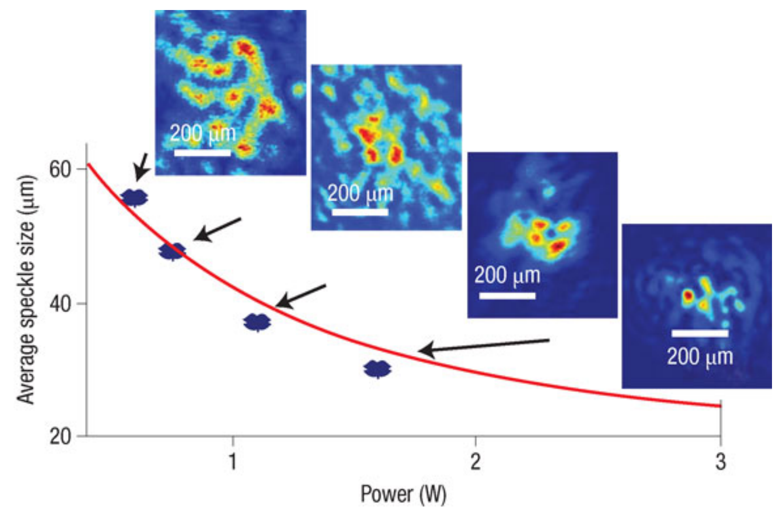
The scatterers are moving fast enough to average out all of the speckles.

Reference: D. Briers et al., J. Biomedical Optics, **18**(6) 066018 (June 2013).

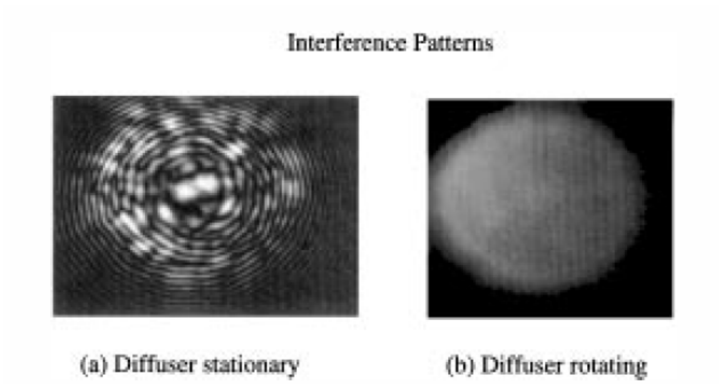
Some phenomena equivalent to speckle in non-linear media: incoherent optical spatial solitons

Main foundations:

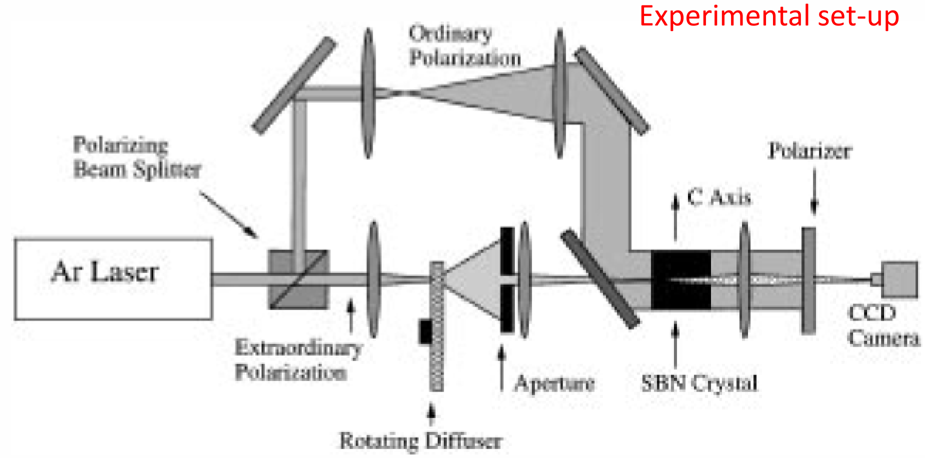
- Incoherent beams are multimode entities whose structures vary randomly in time.
  These beams can self-trap, forming an incoherent spatial soliton.
- Monochromatic spatially incoherent light can be modelled as a sequence of coherent multimode (speckled) beams.
- Self trapping of optical beams for speckle observation.



Average speckle size of the incoherent soliton as a function of the total power of the beam

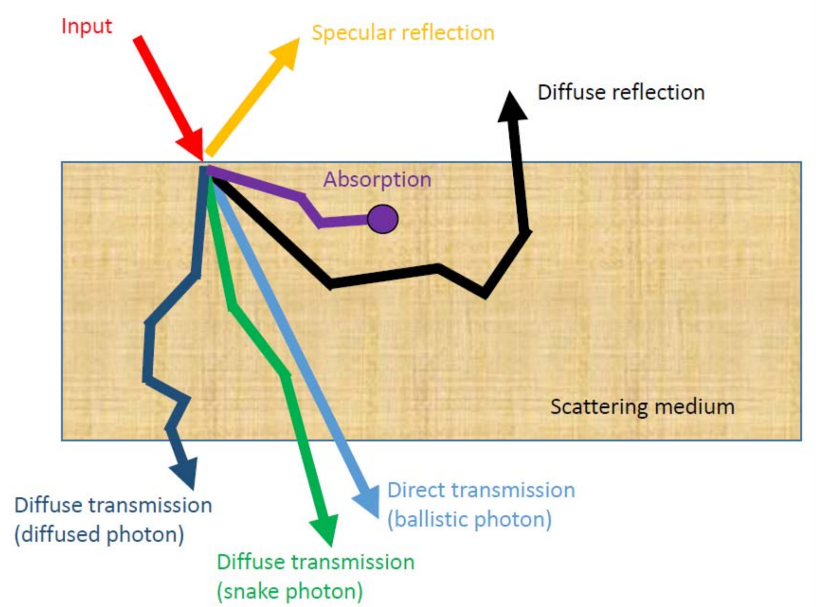


Experimental set-up



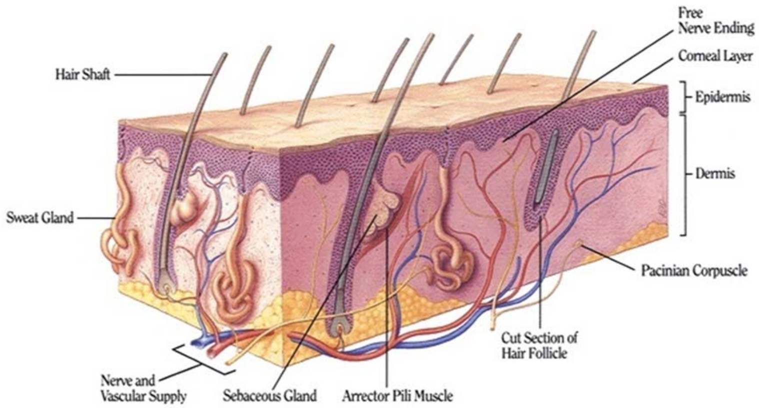
Source: C. Rotschild et al., Nature Photonics, **2**, 371 (2008) and references therein.

Applications of speckle in Biomedicine: Bio-speckle

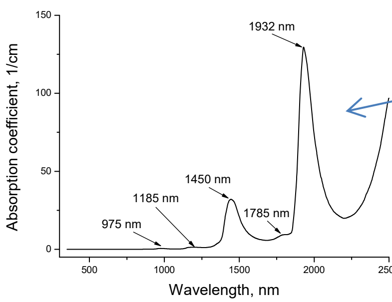


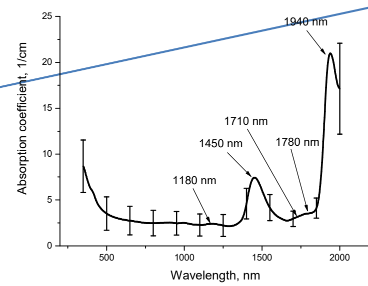
Light can undergo different phenomena as it interacts with a material medium

Dynamic speckle or bio speckle: some examples

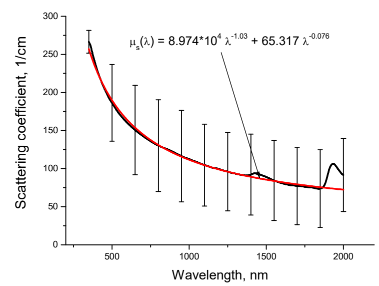


The human skin has a complex structure with inclusion of capillaries, nerve supplies, hair, and corneal layer.
Epidermis thickness: 0.1-0.3 mm
Dermis thickness: 1.0-3.0 mm.
Main component is water.



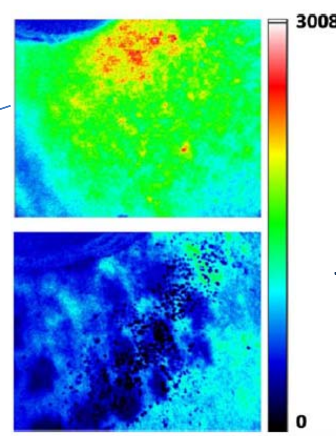


Skin absorption coefficient



Skin scattering coefficient

Applications of LSCI to biomedicine



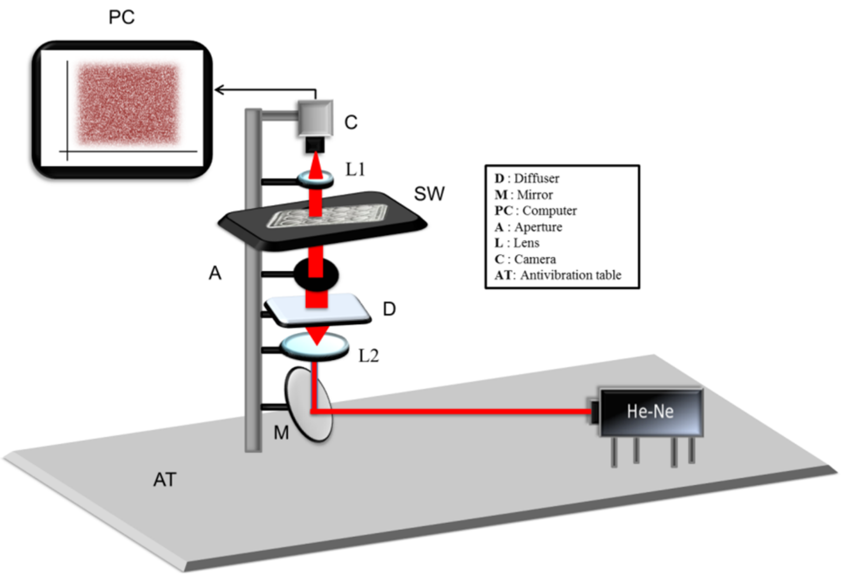
LSCI before laser therapy treatment

LSCI 15 minute after therapy laser treatment

References: A. N. Bashkatov et al, Proc. PALS'15, Helsinki, 2015; D. A. Boas, A. K. Dunn, JBO, **15**(1), 011109, 2010.

Experimental laboratory: Introduction to the practical work. Laser dynamic speckle interferometry

- **Objective**: we want to obtain the temporal evolution of the sample structure via dynamic speckle.



Schematic diagram of the speckle experimental set-up.

Example of experimental speckle pattern observed

Experimental procedure:

- Sample: Ethanol drop.
- Capture by the CCD camera.
- A sequence of frame-by-frame mode in the image processing.
- Detection time: it is the order of 15 sec.
- LabView capture system
- Program with MathLab to compose the frame sequences data.
- Application of an algorithm.
- Method: Temporal Difference Method (TDM).
- The activity of the biospeckle is calculated through the interpretation of the Contrast as a function of the number of frames.

Reference: H. C. Grassi et al., "Quantitative Laser Biospeckle Method for the Evaluation of the Activity of *Trypanosoma cruzi* Using VDRL Plates and Digital Analysis", PLOS Neglected Tropical Diseases, 2016 Dec 5;10(12):e0005169. doi: 10.1371/journal.pntd.0005169. eCollection 2016.

Conclusions

- <u>Definition</u>

When coherent light scatters from a random medium, the scattered light produces a random interference pattern called speckle.

- <u>Assuming</u>:

1. Optical beam highly coherent.
2. Random medium introduces phase fluctuations > 2π.
3. Medium does not depolarize the light
4. Number of scattering centers : $N \to \infty$.

Then, the speckle is interpreted as a statistical phenomenon . The intensity is distributed according to a *negative exponential* probability density function.

- <u>Applications</u>

Speckle pattern analysis provides a wide variety of applications: information processing, imaging, non-destructive testing, non-linear optics, dynamic speckle, biospeckle in the biomedical field.

- <u>Simple experiments in an optics laboratory</u>

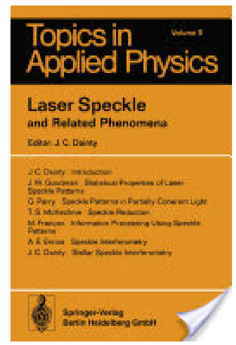
There are simple experiments to be developed in a laboratory for experimental observation of speckle phenomena such as dynamic speckle.

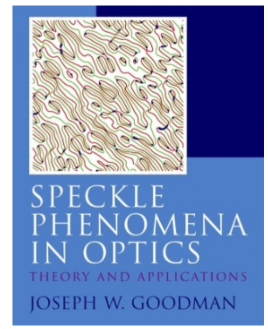
Main references

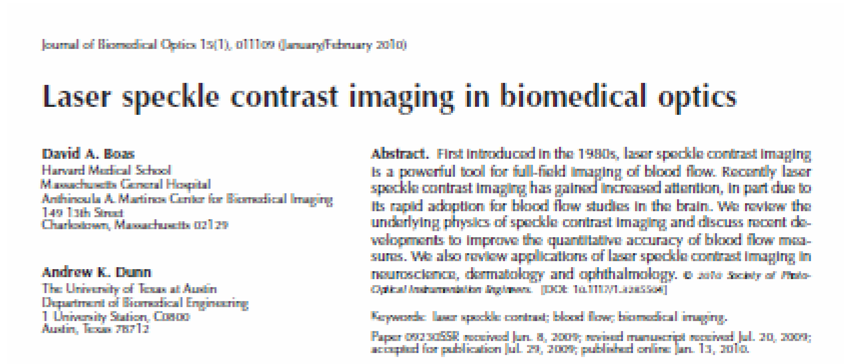
- C. Dainty (Editor), *Laser Speckle and Related Phenomena*, Springer-Verlag, Berlin, 1984.

- J. W. Goodman, *Speckle Phenomena in Optics. Theory and Application*, Roberts and Company Publishers, Englewood, Colorado, 2007.

- D. A. Boas and A. K. Dunn, J. Biomedical Optics, **15**(1), 011109 (2010).







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Laser speckle contrast imaging in biomedical optics

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Abstract. First introduced in the 1980s, laser speckle contrast imaging is a powerful tool for full-field imaging of blood flow. Recently laser speckle contrast imaging has gained increased attention, in part due to its rapid adoption for blood flow studies in the brain. We review the underlying physics of speckle contrast imaging and discuss recent developments to improve the quantitative accuracy of blood flow measures. We also review applications of laser speckle contrast imaging in neuroscience, dermatology and ophthalmology. © 2010 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3285504]

Keywords: laser speckle contrast; blood flow; biomedical imaging.

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http://pendientedemigracion.ucm.es/info/giboucm/

Many thanks for your attention