Analysis of Interferograms Using Simulated Annealing

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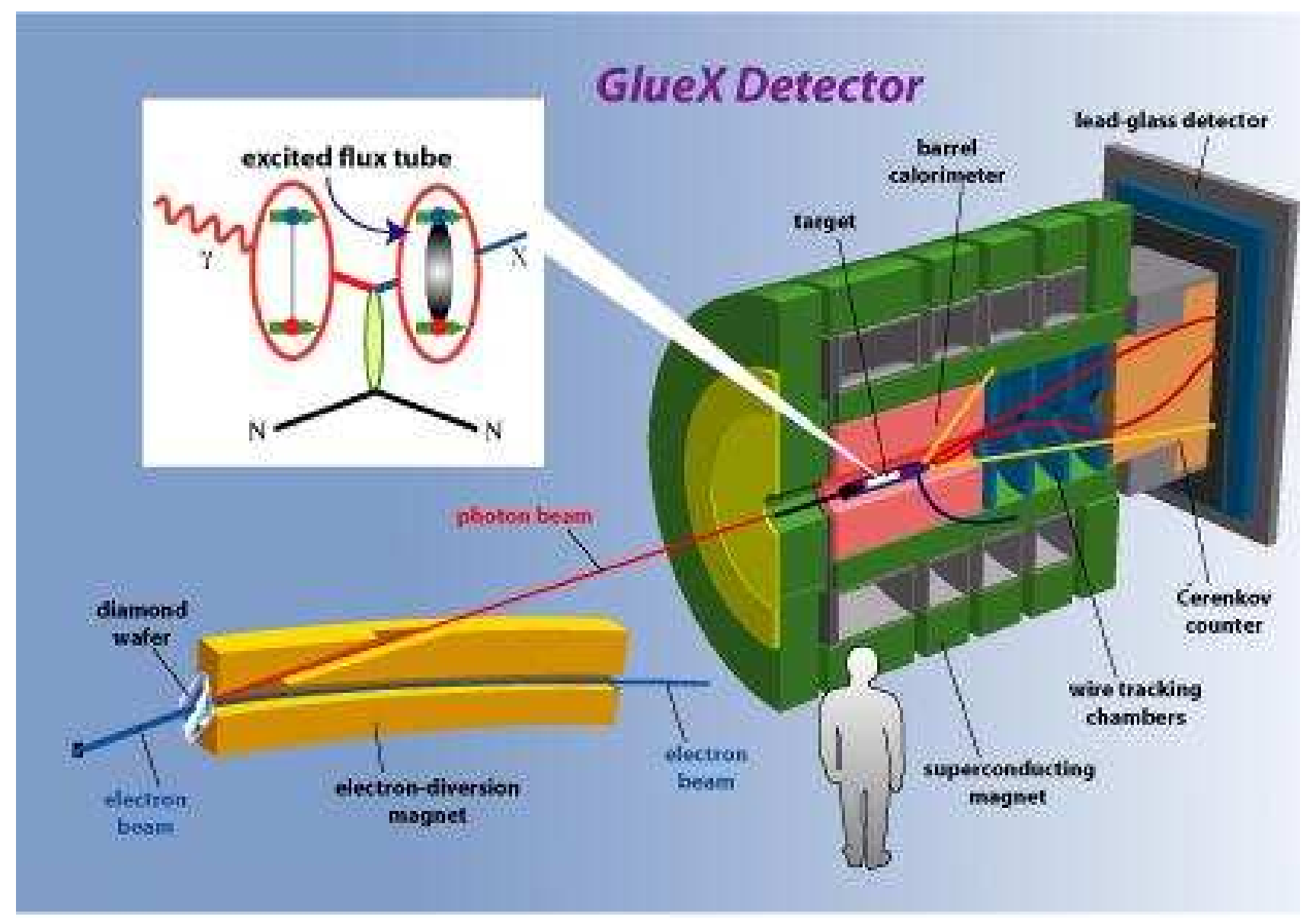
Abstract:

Diamonds are known for both their beauty and their durability. Jefferson National Lab in Newport News, VA has found a way to utilize the diamond's strength to view the beauty of the inside of the atomic nucleus with the hopes of finding exotic forms of matter. By firing very fast electrons at a diamond sheet no thicker than a human hair, high energy particles of light known as photons are produced with a high degree of polarization that can illuminate the constituents of the nucleus known as quarks. The University of Connecticut Nuclear Physics group has responsibility for crafting these extremely thin, high quality diamond wafers. These wafers must be cut from larger stones that are about the size of a human finger, and then carefully machined down to the final thickness. The thinning of these diamonds is extremely challenging, as the diamond's greatest strength also becomes its greatest weakness. The Connecticut Nuclear Physics group has developed a novel technique to assist industrial partners in assessing the quality of the final machining steps, using a technique based on laser interferometry. The images of the diamond surface produced by the interferometer encode the thickness and shape of the diamond surface in a complex way that requires detailed analysis to extract. We have developed a novel software application to analyze these images based on the method of simulated annealing. Being able to image the surface of these diamonds without requiring costly X-ray diffraction measurements allows rapid feedback to the industrial partners as they refine their thinning techniques. Thus, by utilizing a material found to be beautiful by many, the beauty of nature can be brought more clearly into view.



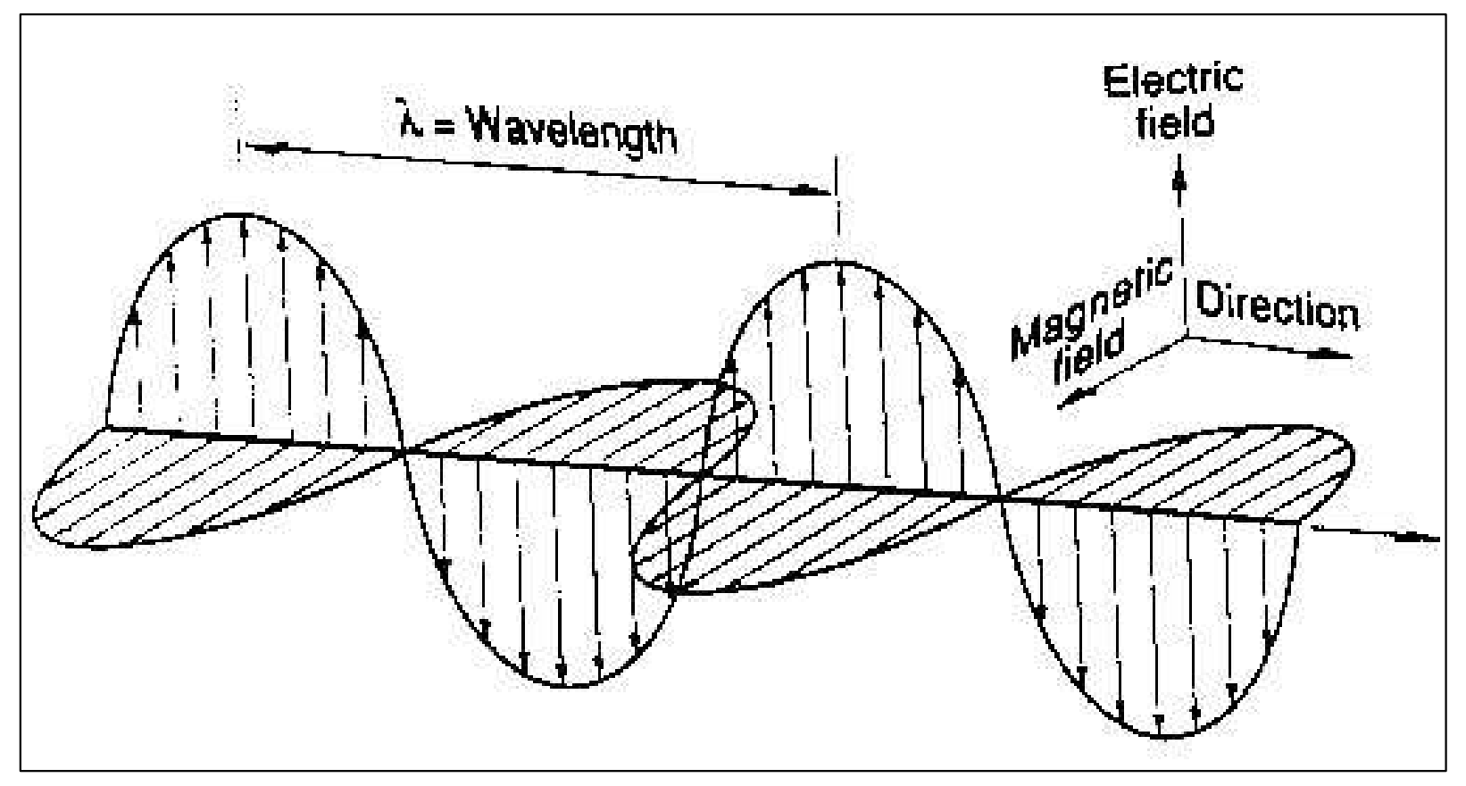
Background:

To the right is a schematic of the GlueX experiment. The goal of this experiment is to find excitations in the gluonic spectrum by firing high energy photons known as gamma rays at a target. Amongst these exotics are glue-balls and four quark systems. In addition to being high energy, the photons must be highly polarized. This can be achieved by decelerating a beam of electrons by shooting them through a very thin diamond wafer.

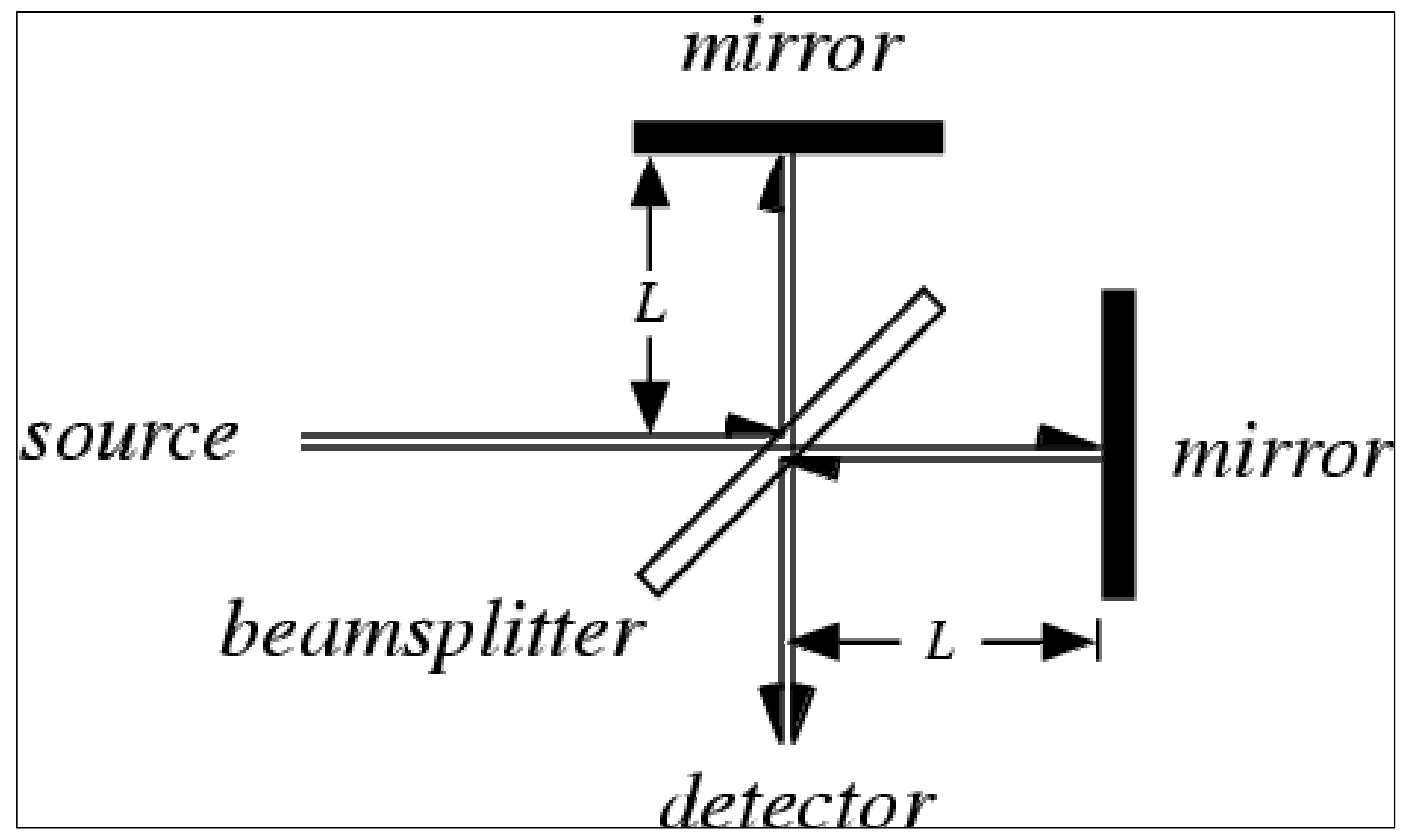
$$\nabla^2 \boldsymbol{E} = \frac{1}{c^2}\frac{\partial^2 \boldsymbol{E}}{\partial t^2} \quad \nabla^2 \boldsymbol{B} = \frac{1}{c^2}\frac{\partial^2 \boldsymbol{B}}{\partial t^2}$$

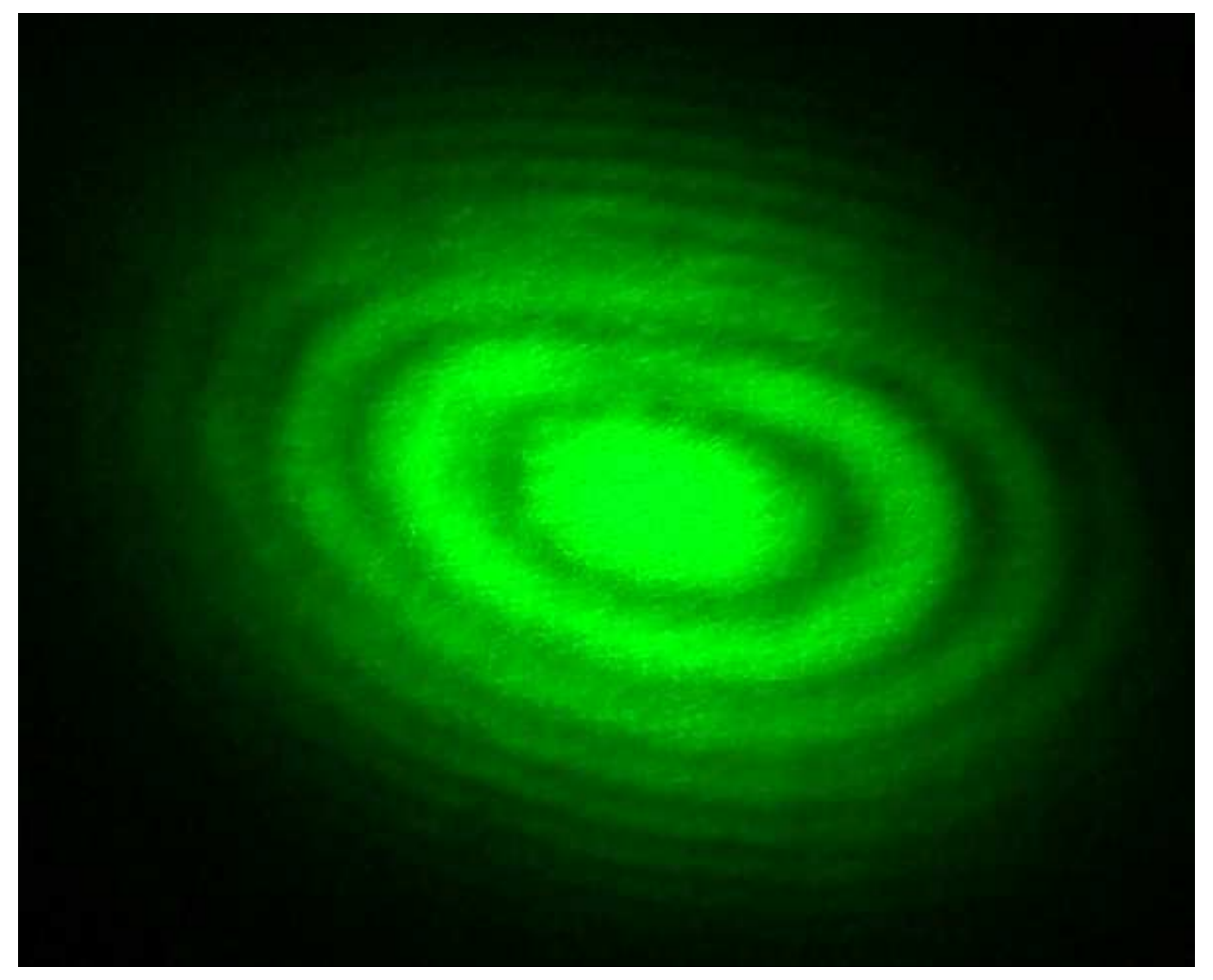
Electromagnetic Radiation:

Light (electromagnetic radiation) is comprised of an temporally and spatially oscillating electric and magnetic field components. These components are orthogonal to each other as well as to the direction of propagation given by the Poynting vector. Wave equations for the electric and magnetic fields can be derived using Maxwell's Equations.



$$\boldsymbol{E} = \boldsymbol{E}_0 e^{i(\boldsymbol{k}\cdot\boldsymbol{x} - \omega t)}$$



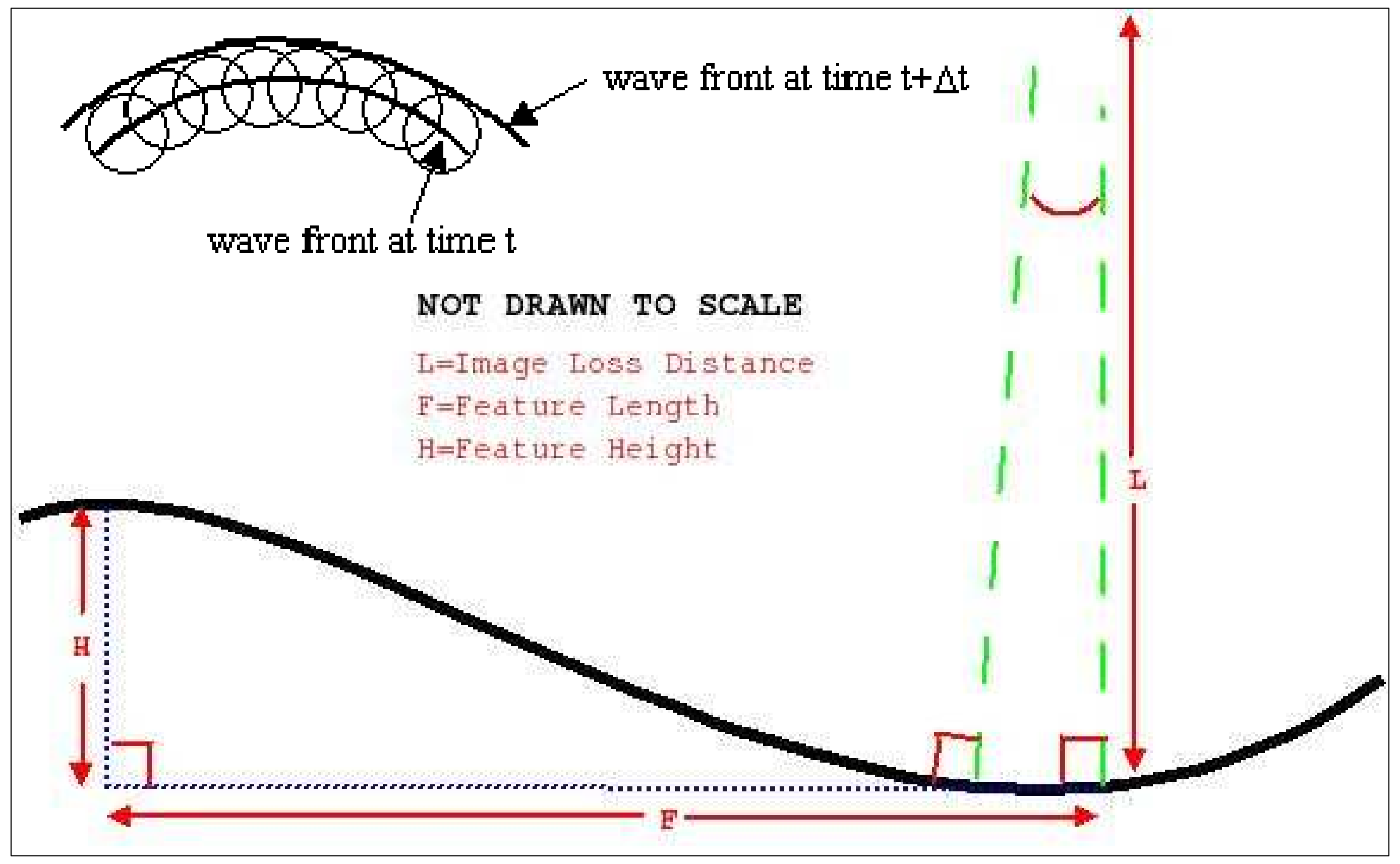


Interference and the Michelson Interferometer:

Like mechanical waves, EM waves can interfere destructively or constructively, but, unlike mechanical waves, there is an additional condition for light wave interference. In order for this to occur, the light waves must be traveling in the same direction, be of the same wavelength and have a constant phase with respect to each other.

Interferometry is the splitting of light beams into two or more paths and the recombining of those different beams to measure difference in optical path length and refractive index via interference fringes that form as a result of the recombined beams.

The Michelson interferometer was invented by Albert Michelson in 1882 “to detect a change in the velocity of light due to the motion of the [ether].” The findings of Michelson's experiment eventually went on to support Einstein's theory of relativity [1].

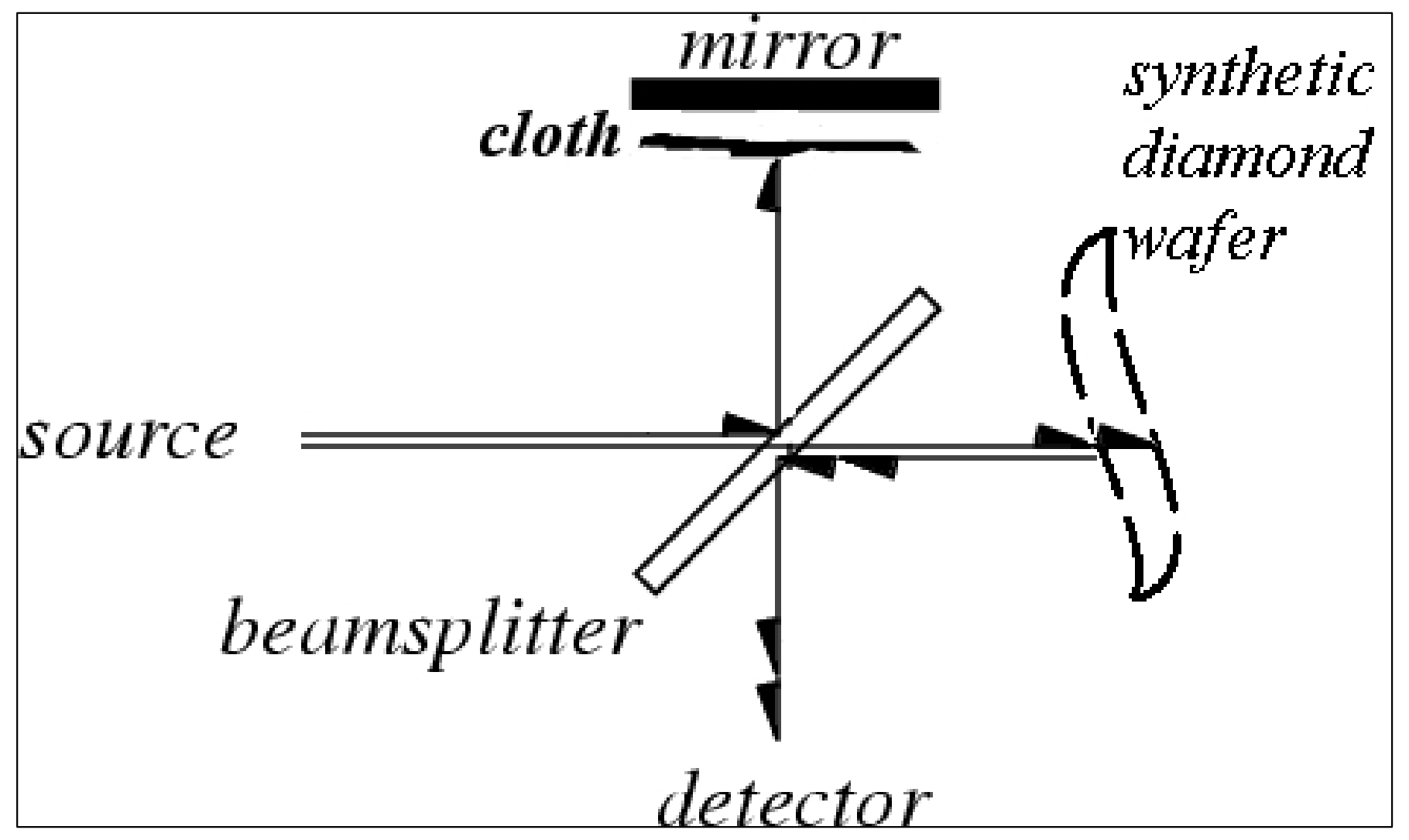


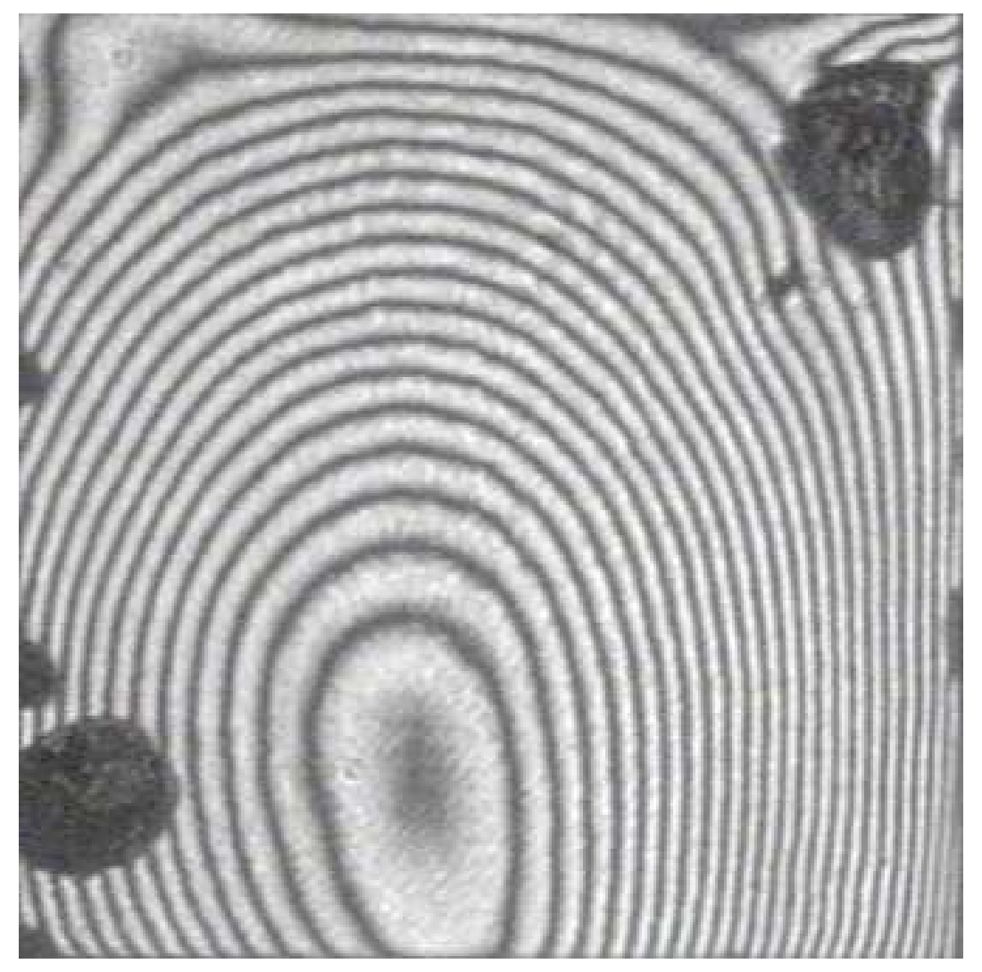
Huygen’s Principle and Surface Resolution:

An important part of topological interferometry is that the surface profile is imprinted on the phase of the wave reflected from the surface. Plane wave solutions can be used when the height of surface features is much smaller than the features' transverse size. Huygen's principle can be used to estimate the distance the reflected wave propagates before there is significant smearing due to transverse diffusion of the phase gradient.

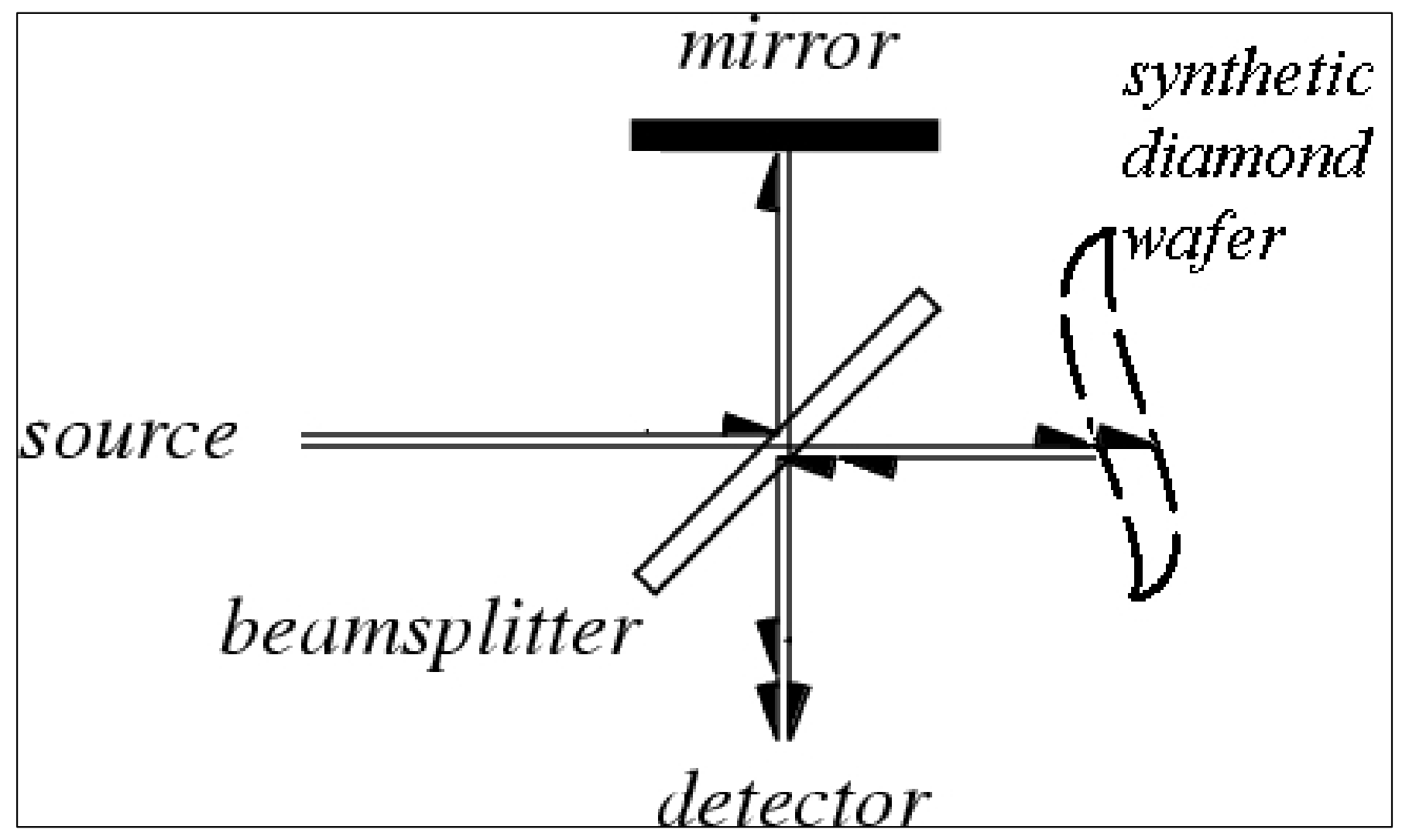
Each point on the surface can be approximated by an outgoing spherical wave. The shape of the surface is imprinted on the phase of these outgoing spherical waves, but will gradually diffuse as the wave propagates forward. For nearly flat surfaces this diffusion will only occur gradually, and approximate plane wave solutions can be used as long as the wave has traveled significantly less than some diffusion length scale.

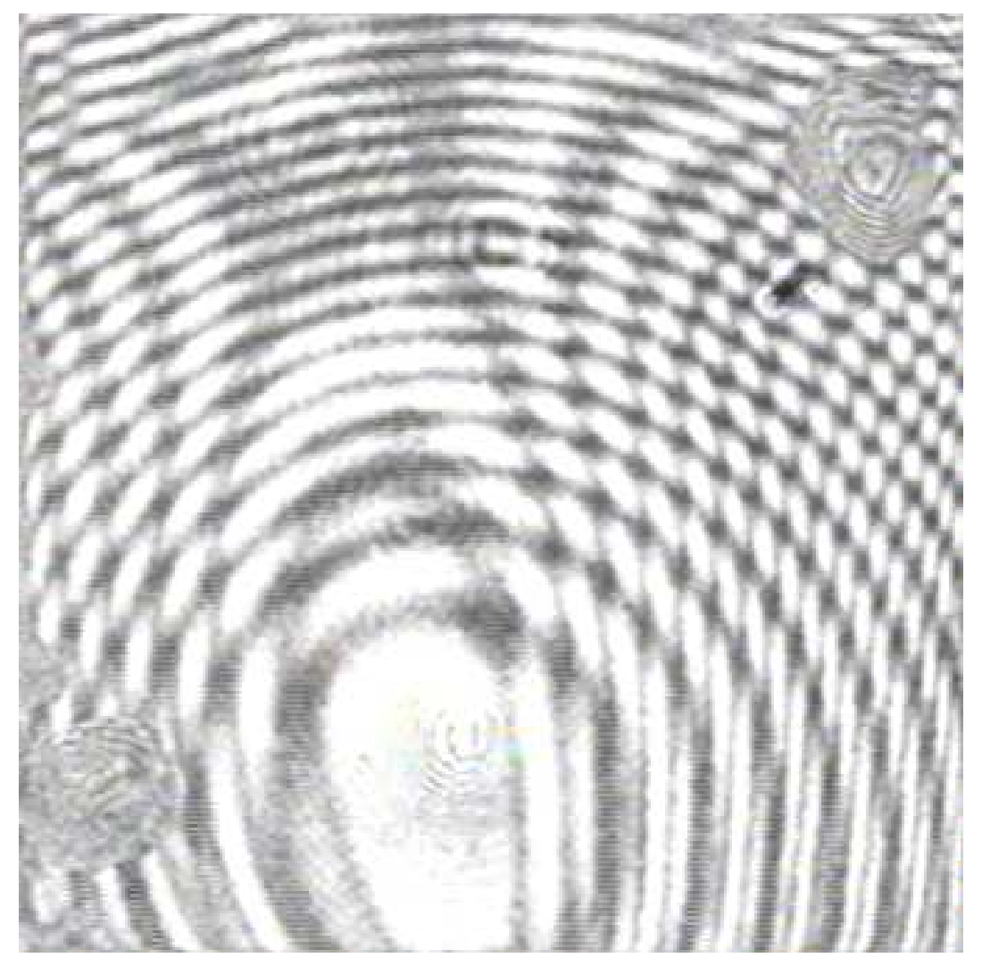
Two wave pattern:





Three wave pattern:





Simulated Annealing:

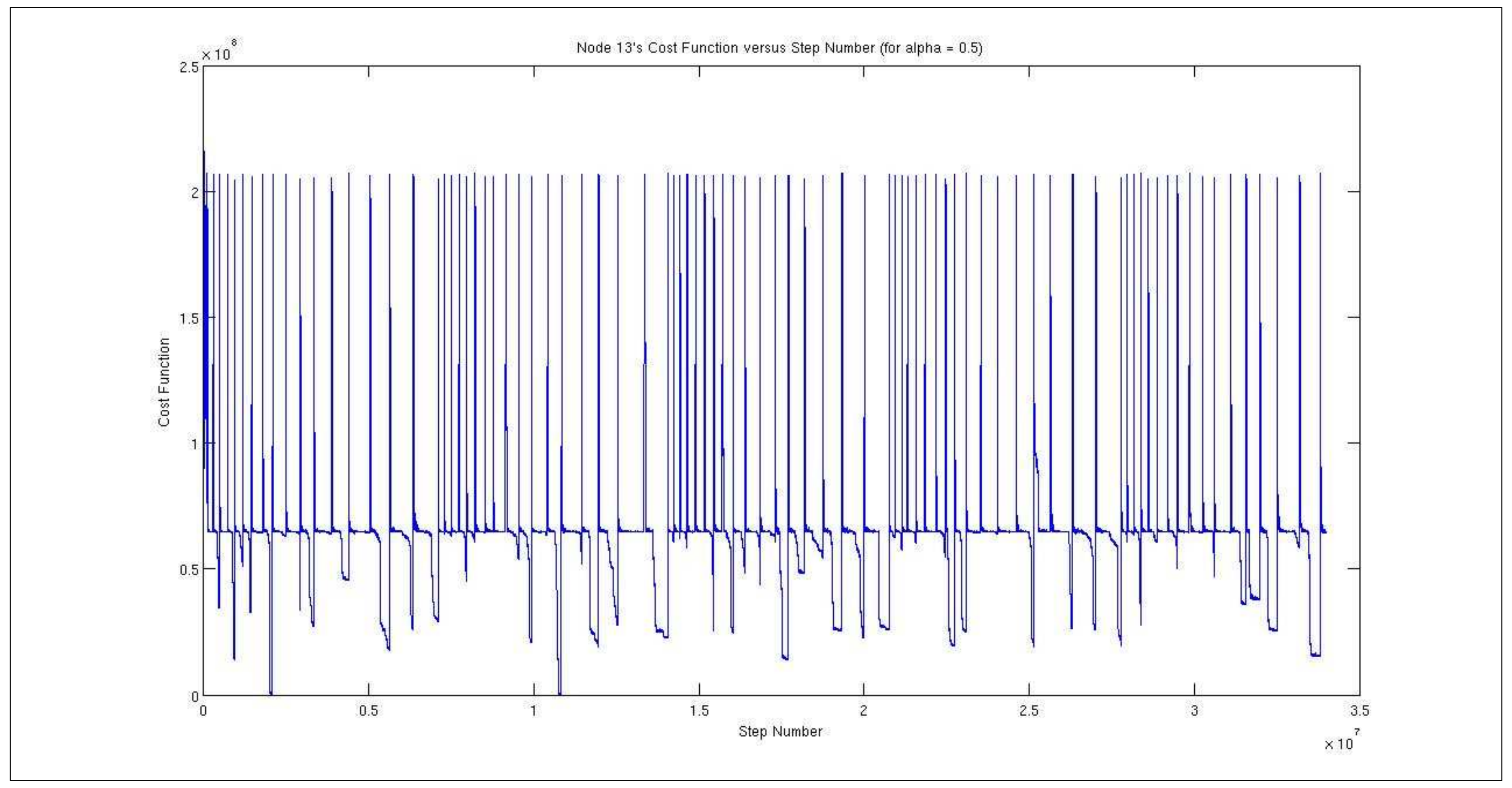
...bringing a fluid into a low-energy state such as growing a crystal, has been considered...to be similar to the process of finding an optimum solution of a combinatorial optimization problem. Annealing is a well-known process for growing crystals. It consists of melting the fluid and then lowering the temperature slowing until the crystal is formed. The rate of the decrease of temperature has to be very low around the freezing temperature. The Metropolis Monte Carlo method...can be used to simulate the annealing process. It has been proposed as an effective method for finding global minima of combinatorial optimization problems. [2]

Terminology:

Energy - the function whose global minimum is being searched for.
Temperature - the criterion for accepting or rejecting a solution based on the Metropolis algorithm.
Metropolis Algorithm - an optimization algorithm that employs a random step generator and a binary choice at each step to accept or reject the step according to the probability max{1,exp(-ΔE/T)} where ΔE is the change in energy with the step and T is the temperature.

ParSA:

The “Parallel Simulated Annealing Library (parSA-Library) provides a comfortable and efficient parallel framework in order to have a simulated annealing optimization system, which can be applied to many different optimization problems.” [4]



Temperature Scheduling:

Temperature scheduling in simulated annealing refers to the process of controlling the *temperature* in a particular run, either through a simple geometric sequence or by an adaptive sequence. The effect that temperature has on an annealing run is that it determines the probability that a solution with a higher cost function value will be accepted over one with a lower value, which is known as *hill climbing* [1], [5]. . There are two main stages of temperature scheduling (warming up and cooling down), which are punctuated by two stopping conditions (equilibrium and frozen criterion respectively).

$$P(X_n \notin Cost_{min}) = \left(\frac{K}{n}\right)^{\alpha}$$

Current Work:

Currently, time is being devoted to exploring the effect of temperature scheduling on the annealing process and determining the most efficient parameters to use. A test fringe pattern with a known answer is being used to determine the parameters K and alpha in the above equation. Once these parameters are known, the convergence speed can be determined. Knowing how to make the algorithm converge faster is of great importance when the actual interferograms are analyzed.

References:

[1] C. Candler, *Modern Interferometers*, Hilger & Watts Ltd., 1951.

[2] Debasis Mitra, Fabio Romeo, and Alberto Sangiovanni-Vincentelli. *Convergence and Finite-Time Behavior of Simulated Annealing.* Advances in Applied Probability. 1986.

[3] Georg Kliewer and Karsten Klohs. *Parallel Simulated Annealing Library (parSA) User Manual.* Version 2.2.

[4] http://wwwcs.uni-paderborn.de/~parsa/

[5] Esin Onbasoglu and Linet Ozdamar. *Parallel Simulated Annealing Algorithms in Global Optimization.* Journal of Global Optimization. 2001.