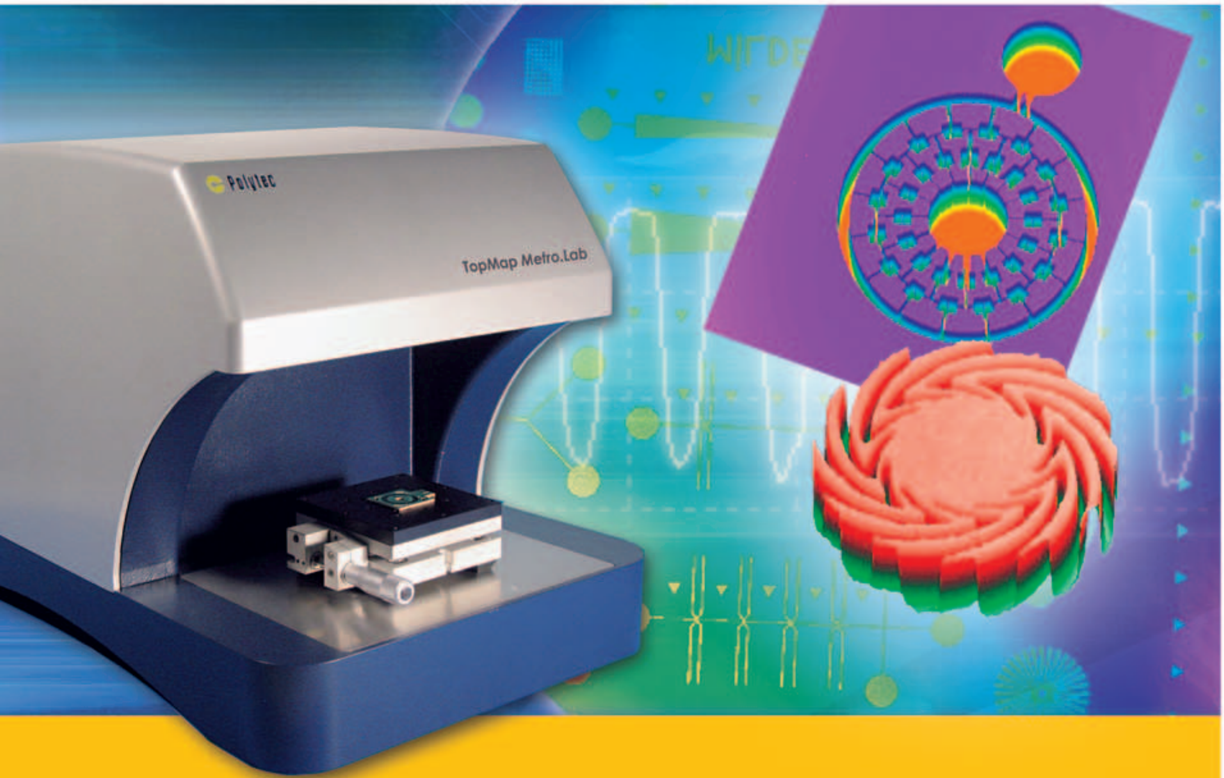
Basics of White-Light Interferometry



Vertically scanning white-light interferometry is a non-contact optical method for surface height measurement on 3-D structures with surface profiles varying between a few micrometers to a few centimeters. Surface features ranging from gradual slopes to vertical steps, with rough or smooth finishes, can be characterized with excellent precision using Polytec's white-light interferometers.

Interferometer Setup

The Twyman–Green interferometer (Figure 1) is a special configuration of the well-known Michelson interferometer with optics that superimpose the images of the object and the reference planes. Polytec engineers use this interferometer and place a CCD image sensor like those used for digital photography at the point where the two images are superimposed. A broadband "white-light" source is used to illuminate the test and reference surfaces.

A condenser lens collimates the light from the broadband light source. A beam splitter separates the light into reference and measurement beams. The reference beam is reflected by the reference mirror, while the measurement beam is reflected or scattered from the test surface. The returning beams are relayed by the beam splitter to the CCD image sensor, and form an interference pattern of the test surface topography that is spatially sampled by the individual CCD pixels.

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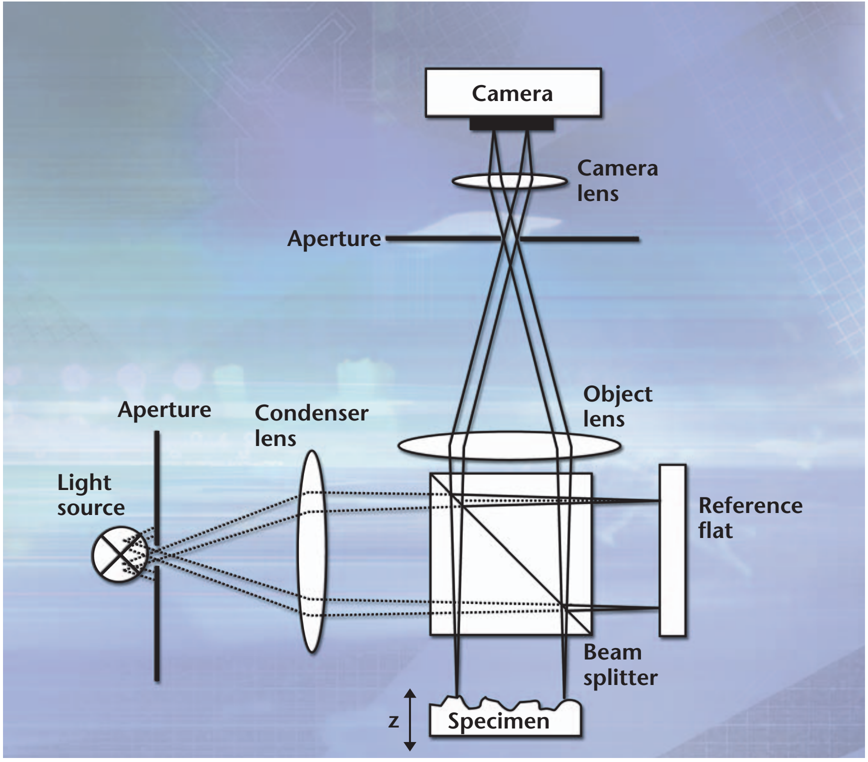


Figure 1: Optical setup of a Twyman–Green interferometer with a CCD image sensor.

The interference occurs for white-light when the path lengths of the measurement beam and the reference beam are nearly matched. By scanning (changing) the measurement beam path length, a correlogram is generated at each pixel when the path-length condition is met and moved through. The width of the resulting correlogram is the coherence length and depends strongly on the spectral width of the light source.

A test surface having features of different heights leads to a phase pattern that is mixed with the light from the flat reference in the CCD image sensor plane. An interference appears on the CCD pixel if the optical path lengths of the two arms differ less than half the coherence length of the light source. Each pixel of the CCD samples a different spatial position within the image of the test surface. A typical white-light correlogram (interference signal) is produced when the length of the reference or measurement arm is scanned by a positioning stage through a path length match.

The interference signal of a pixel has maximum modulation when the optical path length of light impinging on the pixel is exactly the same for the reference and the object beams. Therefore, the z-value for the point on the surface imaged by this pixel corresponds to the z-value of the positioning stage when the modulation of the correlogram is greatest. A matrix with the height values of the object surface can be derived by determining the z-values of the positioning stage where the modulation is greatest for every pixel.

The vertical uncertainty depends mainly on the roughness of the measured surface. For smooth surfaces, the accuracy of the measurement is limited by the accuracy of the positioning stage. The lateral positions of the height values depend on the corresponding object point that is imaged by the pixel matrix. These lateral coordinates, together with the corresponding vertical coordinates, describe the surface topography of the object.

White-Light Interferometric Microscopes

To visualize microscopic structures, it is necessary to combine an interferometer with the optical setup of a microscope. Such an arrangement is shown in Figure 2.

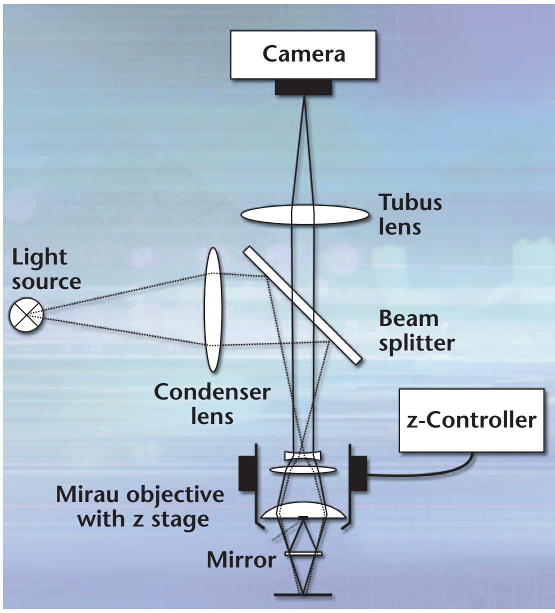
This setup is similar to a standard optical microscope. The only differences are an interferometric objective lens and an accurate positioning stage (a piezoelectric actuator) to move the objective vertically. The optical magnification of the image on the CCD does not depend on the distance between tube lens and objective lens if the microscope images the object at infinity.

The interference objective is the most important part of such a microscope. Different types of objectives are available. With a Mirau objective, as shown in Figure 2, the reference beam is reflected back in the direction of the objective front lens by a beam splitter. On the front lens there is a miniaturized mirror the same size as the illuminated surface on the object. Therefore, for high magnifications, the mirror is so small that its shadowing effect can be ignored. Moving the interference objective modifies the length of the measurement arm. The interference signal of a pixel has maximum modulation when the optical path length of light impinging on the pixel is exactly the same for the reference and the object beams. As before, the z-value for the point on the surface imaged by this pixel corresponds to the z-value of the positioning stage when the modulation of the correlogram is greatest.

Relation between Spectral Width and Coherence Length

As mentioned above, the z-value of the positioning stage, when the modulation of the interference signal for a

Figure 2: Schematic layout of an interference microscope with Mirau objective.



certain pixel is greatest, defines the height value for this pixel. Therefore, the quality and shape of the correlogram have a major influence on the system's resolution and accuracy. The most important parameters of the light source are its wavelength and coherence length. The coherence length defines the width of the correlogram, which again depends on the spectral width of the light source. In Figure 3(a), you can see the spectral density function for a Gaussian spectrum, which is, for example, a good approximation for a light emitting diode (LED). In Figure 3(b), the corresponding intensity modulation is shown to be substantial only in the neighborhood of position z_0 where the reference and object beams have the same length and superpose coherently. The z-range of the positioning stage in which the envelope of intensity modulation is higher than 1/e of the maximum value determines the correlogram width. This corresponds to the coherence length because the difference of the optical path length is twice the length difference of the reference and measurement arms of the interferometer.

The relationship between correlogram width, coherence length and spectral width is calculated for the case of a Gaussian spectrum. The normalized spectral-density function is defined according to equation 1, where $2\Delta\nu$ is the effective 1/e-bandwidth and ν_0 is the mean frequency. According to the generalized Wiener–Khintchine theorem, the autocorrelation function of the light field is given by the Fourier transformation of the spectral density (equation 2) which is measured by interfering the light field of reference and object beams. In the case that the intensities in both interferometer arms are the same, the intensity observed on the screen results in the relation given in equation 3.

Here $I_0 = I_{obj} + I_{ref}$ where I_{obj} and I_{ref} are the intensities from the measurement arm and the reference arm respectively.

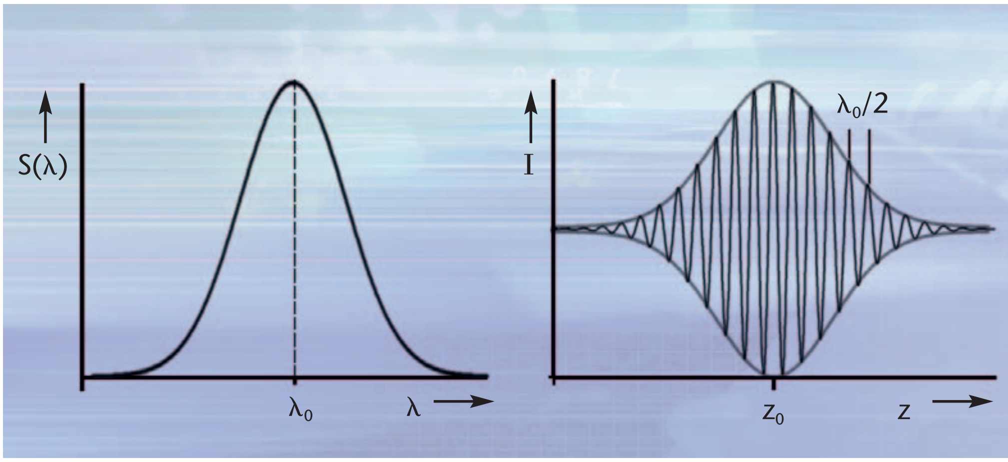


Figure 3: a) Spectral density function of the light source. b) Light intensity as a function of the object mirror position.

The mean frequency $\nu_0 = c/\lambda_0$ can be expressed by the central wavelength, and the effective bandwidth by means of the coherence length, $l_c = c/\pi\Delta\nu$. From equations 2 and 3 the intensity on the screen can be derived (equation 4), taking into account that $\tau = 2\cdot(z - z_0)/c$ with c being the speed of light. Accordingly, equation 4 describes the correlogram as shown in Figure 3(b). One can see that the distribution of the intensity is formed by a Gaussian envelope and a periodic modulation with the period $\lambda_0/2$.

For every pixel the correlogram is sampled with a defined z-displacement step size. However, phase shifts at the object surface, inaccuracies of the positioning stage, dispersion differences between the arms of the interferometer, reflections from surfaces other than the object surface, and noise in the CCD can lead to a distorted correlogram. While a real correlogram may differ from the result in equation 4, the result clarifies the strong dependence of the correlogram on two parameters: the wavelength and the coherence length of the light source.

Equation 1

$$S(\nu) = \frac{1}{\sqrt{\pi}\Delta\nu}\exp\left[-\left(\frac{\nu-\nu_0}{\Delta\nu}\right)^2\right]$$

Equation 2

$$k(\tau) = \int_{-\infty}^{\infty} S(\nu)\exp(-i2\pi\nu\tau)d\nu = \exp(-\pi^2\tau^2\Delta\nu^2)\exp(-i2\pi\nu_0\tau)$$

Equation 3

$$I(z) = I_0\mathrm{Re}\{1 + k(\tau)\}$$

Equation 4

$$I(z) = I_0\left(1 + \exp\left[-4\left(\frac{z-z_0}{l_c}\right)^2\right]\cos\left(4\pi\frac{z-z_0}{\lambda_0} - \varphi_0\right)\right)$$

Equation 5

$$E(z) = \exp\left[-4\left(\frac{z-z_0}{l_c}\right)^2\right]$$

Equation 6

$$E(z) = \sqrt{\left(\exp\left[-4\left(\frac{z-z_0}{l_c}\right)^2\right]\cos\left(4\pi\frac{z-z_0}{\lambda_0}\right)\right)^2 + \left(\exp\left[-4\left(\frac{z-z_0}{l_c}\right)^2\right]\sin\left(4\pi\frac{z-z_0}{\lambda_0}\right)\right)^2}$$

Computation of the Envelope Maximum

The envelope function (equation 5) is described by the exponential term of equation 4.

The software calculates the envelope from the correlogram data. The principle of the envelope calculation is to remove the cosine term of equation 4. With the help of a Hilbert transformation the cosine term is changed into a sine term. The envelope is obtained by summing the powers of the cosine- and sine-modulated correlograms (equation 6).

Two slightly different algorithms are implemented for the calculation of the envelope maximum. The first algorithm is used to evaluate the envelope of the correlogram; the z-value is derived from the maximum. The second algorithm evaluates the phase in addition. With the automation interface (e.g. macros), either of the algorithms can be used.

The uncertainty of the calculation of the envelope maximum depends on:

- the coherence length
- the sampling step size of the correlogram
- deviations of the z-values fromdesired values (e.g. due to vibrations)
- the contrast
- the roughness of the surface

The best results are obtained with a short coherence length, a small sampling step size, good vibration isolation, high contrast and smooth surfaces.

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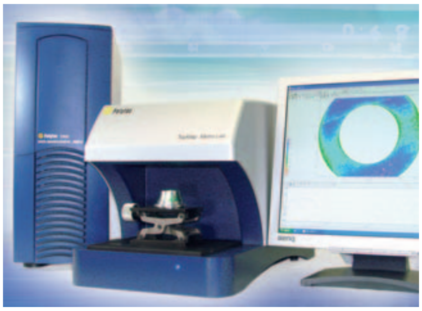
TopMap Topography Measurement Systems

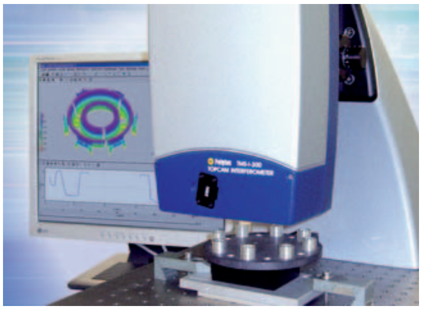


TopMap Metro.Lab

The Metro.Lab is an affordable, high-precision, non-contact topography measurement system for the metrology lab with a wide field-of-view and large vertical range designed to evaluate flat and curved surfaces. The Metro.Lab can measure flatness and general topography with 20 nm resolution and determine parallelity of two or more surfaces separated by as much as 70 mm. The TopMap Metro.Lab provides economic testing even at moderate sample throughput.

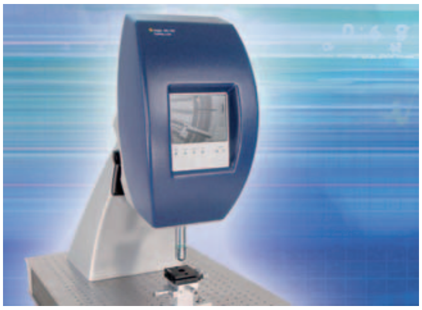
TopMap Pro.Lab

The Pro.Lab is a premium metrology lab tool, offering the maximum flexibility and accuracy for sample measurements taken for quality control. The vertical resolution is in the nanometer range and intelligent filter systems and software solutions allow measurements on any surface, from extremely rough to finely polished. The system generates high resolution 3-D topographical images, over several selectable sample areas up to 30 mm x 40 mm.



TopMap In.Line

Designed as a compact, industrial inspection system, the In.Line easily installs on a manufacturing line and rapidly verifies production specifications for flatness and topography. Surface heights down to a few nanometers can be resolved. Depending on the measurement task, various sample areas are available, ranging from a rectangular 4.2 mm x 5.5 mm to a circular 19 mm.



TopMap µ.Lab

The µ.Lab sets the benchmark for microscope-based, high-precision, non-contact topography measurement with high spatial resolution. It is specifically designed for the micro-topography evaluation of functional surfaces and microstructures. Using a scanning white-light interferometer, the µ.Lab can quickly measure flatness, waviness, roughness and general topography with sub-nanometer resolution.