Invited Paper

HIGH PRECISION OPTICAL MEASUREMENT METHODS

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1. INTRODUCTION

Noncontact optical methods are appropriate for micro- and macrostructure measurements. Time of flight and phase measuring techniques with a resolution in the order of a few mm to one mm respectively are well introduced. Furthermore active and passive triangulation techniques are very robust and appropriate for different applications in precision measurements.

Some optical 3-D-measurement techniques are summarized together with their depth resolution in table 1. Time of flight and phase measuring techniques are well established. For the measurement of the topography the principle of triangulation as well as its extension to light sectioning and projected fringe methods can be applied succesfully (1-7).

Triangulation based 3-D-sensors are appropriate tools for inspection and measurement in industrial environments. They fulfil very often the high requirements upon range, resolution and robustness.Synchronized single-spot-scanners, based on triangulation can be very versatile for industrial applications.

Moiré techniques or projected fringe techniques are useful tools for topography measurements. They can be applied to determine surface shape or deviation of the shape or vibration amplitudes. The grating like structures can be generated by projecting a ruling or grating upon a surface which is seen through a detecting system with a reference grating like structure. Alternatively a grating pattern can be generated by interference of two plane waves upon the surface.

Furthermore image plane locating systems can be applied to analyse the surface topometry. Recently confocal principles were studied to be applied for the measurement of the surface geometry and microstructure (11).

Today, laser interferometry is probably one of the most commonly used technique for very high resolution measurements in metrology. A stabilized He-Ne-laser is frequently used as light source with an absolute frequency stability of better than 10^{-7}. The accuracy for length measurements is limited, by the variation of the refractive index due to atmospheric conditions (humidity, temperature, pressure) as well as vibrations, rather than by the laser stability. Furthermore, single mode diode laser are used in metrology eventhough frequency stability is still a problem especially in interferometry.

Interferometry and Moiré techniques as well as image plane locating systems will be applied more frequently, when used with image processing. They are becoming useful tools for precision measurements in research and for industrial applications. Computer analysis is increasingly important for fringe analysis. The use of solid-state detector arrays, image memory boards together with microprocessors and computers for the extraction of the information from the interferograms and high-resolution graphic boards find important application in optical metrology. Much more information can be extracted from the sensor data, leading to higher sensitivities and accuracies (3).

Automated quantitative evaluation of interferograms requires accurate interference phase measurements, independent of fringe position and intensity variations superposed onto the interferograms. In many interferometric arrangements, Fourier- Transform, phase shifting -or heterodyne techniques have been introduced for automated fringe analysis.

The phase shifting technique is very appropriate for digital processing and TV techniques. Two-beam-interferometry together with video electronic processing lead to a sensitivity of 1/100 of a fringe at any

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point of the fringe pattern in the TV image (3-6).In heterodyne methods the relative phase increases linearly in time and the reference phase is measured electronically at the beat frequency of the reconstructed wavefields. Heterodyne interferometry offers high spatial resolution and interpolation up to 1/1000 of a fringe.

The interferometric measurements at different, well known optical wavelengths allows the generation of new synthetic wavelengths, which are much longer than the optical wavelengths. For two wavelengths λ_1 and λ_2, one obtains the synthetic wavelength $\Lambda = (\lambda_1 \lambda_2)/(\lambda_1 - \lambda_2)$. This method allows an increase of the range of unambiguity in interferometry and reduces, in addition, the sensitivity which is important especially when applying interferometry in industry. In order to obtain this new, synthetic wavelength, the different not interferring optical wavelengths have to be interrelated. For practical applications, real-time electronic signal processing is required.

2. PROJECTED FRINGE TECHNIQUES FOR INDUSTRIAL INSPECTION

Light sectioning and projected fringes are an extension of the well known triangulation methods for displacement-,deformation- and topography measurements. Projected fringe patterns can be formed by different methods. Either a grating like structure or an interference pattern can be projected onto the test surface. Height variations or deformations lead to a deformation of the projected fringes, which in turn are compared with the original or synthetic grating like structure. Typical contourline separations can vary between micrometer and millimeter. Projected fringe techniques can also be used for microsurface analysis.

In Moiré techniques a deformed grating structure is superimposed onto the original grating. The grating structures do not need to be resolved by the detection as is the case for projected fringes.

For the analysis of steps, to avoid ambiguity at least two grating periods are needed, a coarse for the absolute height measure and by contrast a fine for precision measurements. A piezo-element is used to shift the phase for the analysis of the fringes using one of the phase-stepping techniques (3). By changing the phase, the fringes on the object will move in steps of one-quarter of the period for instance. In Fig. 1 an arrangement for projected fringes is shown. A grating like structure is projected onto the object. The deformed grating is analysed by means of a CCD camera. For the fringe analysis, different techniques, such as phase shifting as well as Fourier-Transform techniques are used. When fringe projection is applied to measure the shape and microstructure of the eye, care needs to be taken to avoid disturbances due to eye movements. Therefore the information needs to be collected within a fraction of a second.

Fluorescine is useful for the improvement of the fringe contrast and is frequently used. In Fig. 1 the grating structure, such as a ronchi-ruling is projected onto the object via the lenses L2 and L3. In the image forming a telecentric arrangement is useful. The result of the analysis of the cornea of a coworker is shown in Fig. 2 as pseudo 3-D presentation. The diameter measured was nearly 10 mm and the depth resolution 2 µm.

Alternatively the use of two beam interference patterns can be useful for the generation of a cosine type grating. Projection of grating structure can be achieved by means of a liquid crystal cells as well. So far 640 grating lines are available.

To fulfil different requirements a special pattern generator was constructed by means of a light emitting diode and a computer driven galvano scanner. Modulated light from a laser diode is projected as indicated via a fast scanning galvano mirror. Period and local brightness can be adapted according to the need. Up to 3000 patterns per line can be generated in a video takt. The patterns can be adapted locally with respect to phase, frequency and brightness. In Fig. 4 different patterns for the same object region are shown, they are delayed in time. A pattern generator for its generation is shown in Fig. 3.

Real-time Moiré techniques are also useful for detecting vibration patterns as well as for identifying different kinds of motions. To improve the robustness and resolution different structures such as binary, sinusoidal, triangular and trapezoidal were analysed. Trapezoidal were found to be the most appropriate for our gray code projecting system. Furthermore it was found important to adapt the brightness of the projected structure to the local brightness of the object.

For some industrial applications it may be useful to generate a grating structure on the object that matches the topography in order to detect the deviation of the object contour from the reference only by Moiré techniques.

3. FRINGE PROJECTION METHOD FOR MICRO SHAPE AND ROUGHNESS MEASUREMENT

In addition to the macroscope application, 3 D-shape analysis by fringe projection can become an important method for micro structure analysis. A fringe projecting microscope, FPM, is similar as shown in Fig. 1, but where the final projection of the grating as well as its image forming on the CCD camera occurs with the same objective, L4. High lateral and vertical resolution of the order of 1 µm respectively 0,05 µm can be obtained.

In the modified version of Fig. 1 the spatially filtered spectrum of a binary line grating (Ronchi grating) is projected into the entrance pupil EP of the microscope objective L4. The grating needs to be projected obliquely onto the object. The spectrum therefore is shifted off-axis (laterally) by a distance d, so that the principal rays corresponding to the zero-order of the spectrum of the projected grating form an angle ß with the optical axis of the microscope objective. Therefore illumination and observation occur at the angle +ß and -ß respectively. *As the entrance pupil of a high aperture microscope objectives is not* accessible physically for spatial filtering, the filtering occurs in a plane F conjugated to the entrance pupil. Which in turn is easily accessible for filtering manipulations.

The range of applications can be extended with the projecting grating microscope. It will especially be applied where classical interference techniques cannot be used such as for rough surface measurements (mean roughness > 0,2 µm). The method can be applied for very rough surfaces like sheet-metal, grinded and turned metal surfaces, plastics, ceramics, even biological surfaces can be topographed.

A symmetrical configuration with +/- ß for the directions of projection and imaging according to Fig. 1, leads to an improvement of the depth resolution. The amount of the off-axis shift d is matched to the pupil diameter D in a way, that the outer first order of the grating spectrum can pass the entrance pupil and sufficient clearance is given for lateral displacement or dispersion of the spectrum of the back-travelling light reflected from inclined or rough surface elements.

In our telecentric FPM-arrangement both the entrance pupil of the imaging system and the exit pupil of the grating projection system lie at infinity in order to compensate variations in height sensitivity.

The grating structured image distorted by the object topography is formed onto the CCD interline transfer camera with 756 x 581 picture elements by the objective. The conversion of the height variation Δh due to a local fringe displacement Δx in x-direction is for a grating projecting angle ß and an observing angle -ß, when the sine condition is fullfilled.

$$\Delta h = \Delta x / 2 \sin \beta \qquad 1)$$

A typical measurement of an optically rough surface, a metal sheet is shown in Fig. 5, the mean roughness is $R_a = 1{,}6$ µm.

4. PROFILOMETRY WITH SHORT COHERANCE LIGHT SOURCE

Short coherence-profilometry can be very useful for the measurement of surface shapes. The basic principle is shown in Fig. 7 where a Twyman-Green interferometer setup is used with a light source with a very short temporal coherence. A beamsplitter devides the collimated light into the object and the reference arms.

For the analysis of spherical and aspherical surfaces an objective with a high numerical aperture (NAα 0.5) is introduced in the reference and object arms, in order to generate spherical waves. The centre of curvature of both the object and of the reference mirror are arranged to coincide with the focal point of the objectives. The lenses L1 and L2 image the test surface on a CCD-camera chip.

By using a low coherent light source, interference occurs only, when the optical path lengths difference of the two interfering beams is inside the coherence length. Changing continously the length of the optical path in the reference arm, a time dependent intensity distribution is obtained for each CCD pixel as is demonstrated in Fig. 6). Mathematically one can describe this distribution by the following function:

$$I(x,y,t) = I_0(x,y)\ \{1+V[\Phi(x,y)-\Phi_R(x,y,t)]\ \cos[\Phi(x,y)-\Phi_R(x,y.t)]\} \qquad (2)$$

where I_0, V, Φ and Φ_R describe the mean intensity, the time dependent visibility, the phase of the object beam and the time dependent phase of the reference beam.

The profile z(x,y) is coded in the visibility function of the interference signal. To achieve a small depth uncertainty, a short temporal coherence is advantageous. On the other hand a high spatial coherence is needed, to get a good interference contrast.

In practice a simple low-cost multimode laser diode, which is used normally in compact disc technology, provides good results, if the injection current is kept far away from the maximum rating.

For the experiments the injection current was 60 mA and the wavelength 670 nm, leading to a FWHM of about 11 µm of the envelope of the interferogram. The spatial coherence -on the other hand- is high.

A piezo electric actuator in the reference arm is used in combination with a high speed CCD-camera, with a resolution of 124 x 128 Pixels, leading to frame rates of 830 frames/second. The signal of the CCD-camera is digitised to 8 bit and stored on a frame grabber. 1000 frames continuously are achieved when the maximum frame rate is used. 100 µm can be scanned in z-direction within less than 1 second. The dataset is processed in the frame grabber with a high speed DSP processor and in the PC afterwards.

Figure 7b) shows a measurement of the backside of a contact lens. The peak-to-valley-difference is 11,5 µm. This measurements demonstrate the possibility of optional sectioning by low coherence interferometry. Figure 9) shows the results obtained by measuring the anchor of a relais contact. Several separated surfaces can be measured in parallel.

5. TWO WAVELENGTH INTERFEROMETRY

The application of interferometry could be drastically increased, when the technique is extended to optically rough surfaces. In addition, with interferometry phase measurements can only be determined with modulo 2π.

An increase of the laser wavelength such as by using CO_2-laser would be useful for the metrology of technical surfaces. Laser sources and the appropriate detectors are frequently not or not yet available. In addition, the high lateral resolution is lost by IR- laser wavelengths.

In two-wavelength interferometry where laser emits light at two slightly different wavelengths, λ_1 and λ_2, the interferometer detects two separate interference patterns.

By an appropriate processing of the two individual interferece patterns a new interference term of the form $\cos(4\pi z/\Lambda)$ is created where Λ is an equivalent beat wavelength given by

$$\Lambda = \lambda_1\ \lambda_2\ /(\lambda_1-\lambda_2)$$

Since the wavelength differenceλ_1-λ_2 is usually small, the equivalent wavelength is much larger than the original wavelength used. Since laser diodes can be easily tuned they are capable of generating a wide range of equivalent wavelengths, making them a good alternative to more expensive dye lasers or multi-frequency gas lasers. An alternative is the use of tunable solid state lasers.

The two-wavelengths used can either by time multiplexed or can be present continuously. Furthermore, the two-wavelenght techniques can be applied in interferometry as well as in holography and Speckle-Interferometry.

6. INTERFEROMETRY AT OBLIQUE INCIDENCE

Interferometry is a powerful tool for high resolution measurements on optically polished surfaces. It can however not be applied to obtain and measure the topography of optical rough surfaces. In additon, the phase variation $\Delta\Phi$ as a function of the depth variation Δz, can be measured as a function of position x on the surface. A problem occurs when the surface has step height variations greater than $\lambda/2$ in reflection, the interferometer can only determine the phase F modulo 2π.

A reduction in sensitivity is obtained by an oblique incidence of the wavefront onto the test object. The optical path difference in air is $w = 2\,\Delta z \cos(\Theta)$,

where Δz is the z variation with respect to the reference surface and Θ is the angle of incidence onto the object. The optical sensitivity is therefore reduced by cos Θ (frequently used was $\Theta = 80{,}3°$).

In Fig. 8, the incident beam is separated by the prismen surface into the reference and the object beam at oblique incidence. The reference wave is phase shifted by the piezo driven reference mirror MR before the reference and object beams are combined. The fringe pattern is projected onto the CCD chip. The special arrangement avoids multiple reflections and partly image distortions. In addition to oblique incidence the wavelength can be changed. A synthetic wavelength of 25 µm was implemented in the exprimental setup when using, in addition to obligue incidence two laser diodes with slightly different wavelenghts $\lambda_1 = 690$ nm and $\lambda_2 = 826$ nm, leading to

$\Lambda_\lambda = 4{,}19$ µm. The result of the analysis of a discontinuous metallic optically rough object is shown in Fig. 10 with $\Lambda_S = 25$µm.

7. TWO WAVELENGTH HETERODYNE INTERFEROMETRY

Two wavelength heterodyne interferometry can overcome some of the drawbacks of classical interferometry.

In a heterodyne interferometric set-up two waves are superposed to lead to an interference phenomenon. One of the two beams is frequency shifted by the frequency f.

In double heterodyne interferometry two laser wavelengths and two heterodyne frequencies are used simultaneously. A low frequency detection signal with a phase shift that corresponds to the effective wavelength is generated. A two-wavelength double heterodyne interferometer (DHI) setup consists basically of two independent heterodyne interferometers working at different wavelengthsλ_1 and λ_2 and different heterodyne frequencies f_1 and f_2. The phase of the beat frequency f_1-f_2 depends on the effective wavelength and can therefore be examined for distance evaluation as has been shown (8,10).

The detected heterodyne signal is arranged to be shot noise limited. There are different technique to introduce the frequency shift such as using an acousto optical modulator (AOM), a rotating grating or by using the Zeeman splitting in a laser cavity. In the DHI (double heterodyne interferometry) two heterodyne interference systems are superposed to lead to a beat frequency of the two wavelengths for absolute distance measurement at optically rough surfaces.

Double heterodyne detection permits high-resolution measurements at arbitrary synthetic wavelengths without the need for interferometric stability at the optical wavelengths λ_1 and λ_2. In some cases, a simpler detection method might be of interest. The interference fringe function for the synthetic wavelength can be obtained by detecting the power of the interference signal at the optical wavelength, which is essentially the square modulus of the coherence function.

Modern laser sources provide a great variety of optical wavelengths to get interesting synthetic wavelengths. Examples are: different lines of HeNe lasers such as 629,4 nm, 632,8 nm, 635,2 nm; 640,1 nm) leading to synthetic wavelengths of 58 µm and 0,1 mm for instance.

GaAlAs diode lasers tunable by current ($\Lambda > 10$ mm) by an external cavity grating ($\Lambda > 3$ mm), or by temperature ($\Lambda > 0,5$ mm); tunable Nd: YAG lasers ($\Lambda > 10$ mm). For highly accurate distance measurements ($\Delta\Lambda/\Lambda \leq 10^{-6}$), the synthetic wavelength has to be known with at least the same accuracy. Therefore the two laser sources have to be stabilized with respect to each other. This can be done with the help of a common reference length in the form of a Fabry-Perot resonator. Absolute accuracy can be obtained, if the Fabry-Perot is stabilized with respect to a frequency stabilized master laser. In the case of a multiline laser, the wavelengths λ_1 and λ_2 are perfectly combined and have a good relative stability.

An interesting way to obtain various wavelengths is the use of a single laser diode in combination with a high frequency Brag cell and two acousto optic modulators. (AOM's)

One of different arrangements for double heterodyne interferometry is shown in Fig. 10 where the wave of a laser diode source is seperated by a UHF-AOM (f = 500 MHz) in two waves. Each wavelength passes a two beam interference arrangement before being combined on the detector. Hence, there are two heterodyne interferometer with an AOM1 and AOM2 respectively. The phase of the signal at the detector is proportional to the difference of the heterodyne frequencies given by AOM1 and AOM2 and the distance z is compared to the synthetic wavelength $\Lambda = 60$ cm or 200 m respectively, when the UHFAOM is driven with 501,5 MHz. A result obtained from an object with an optically rough surface at a distance of 3 m is shown in Fig. 11. It should be mentioned that a mirror was cemented onto the back side of the object to be moved and compared with an incremental HP interferometer. Absolute distance measurements with a resolution of 0,1 mm were obtained with the double heterodyne interferometer. Cascading with shorter synthetic wavelengths can lead to depth resolutions of micrometers or better.

CONCLUSION

Different optical methods can be used for distance and topography measurement. The range and sensitivity need to be selected. The methods are contactless and fast. Interferometric methods are sometimes, however, too sensitive, hence environmental disturbances limits the accuracy for the measurement. Furthermore, surface roughness leads to unwanted Speckles to be taken care of by the analysis and information processing.

Two wavelength techniques become very interesting for absolute distance measurement. It has been shown, that a synthetic wavelength can be generated by two shorter ones, leading to techniques for measuring optically rougher surfaces. The theory is based on the assumption that the optical path difference is to be compared with the synthetic wavelength. Therefore optically rougher surfaces can be measured and furthermore the unambigiuty range can be extended.

Heterodyne interferometry is a powerful tool for high precision distance measurements and vibration analysis. Double heterodyne techniques lead to improveements with respect to environmental disturbances and to absolute distance measuring procedures. To measure the topography of optically rough surfaces fringe projection, short coherence techniques as well as confoacal methods oblique incidence and 2λ interferometry are possibilities to overcome some of the limitations pointed out. The absolute distance measuring technique can further be combined with a technique for topography measurements.

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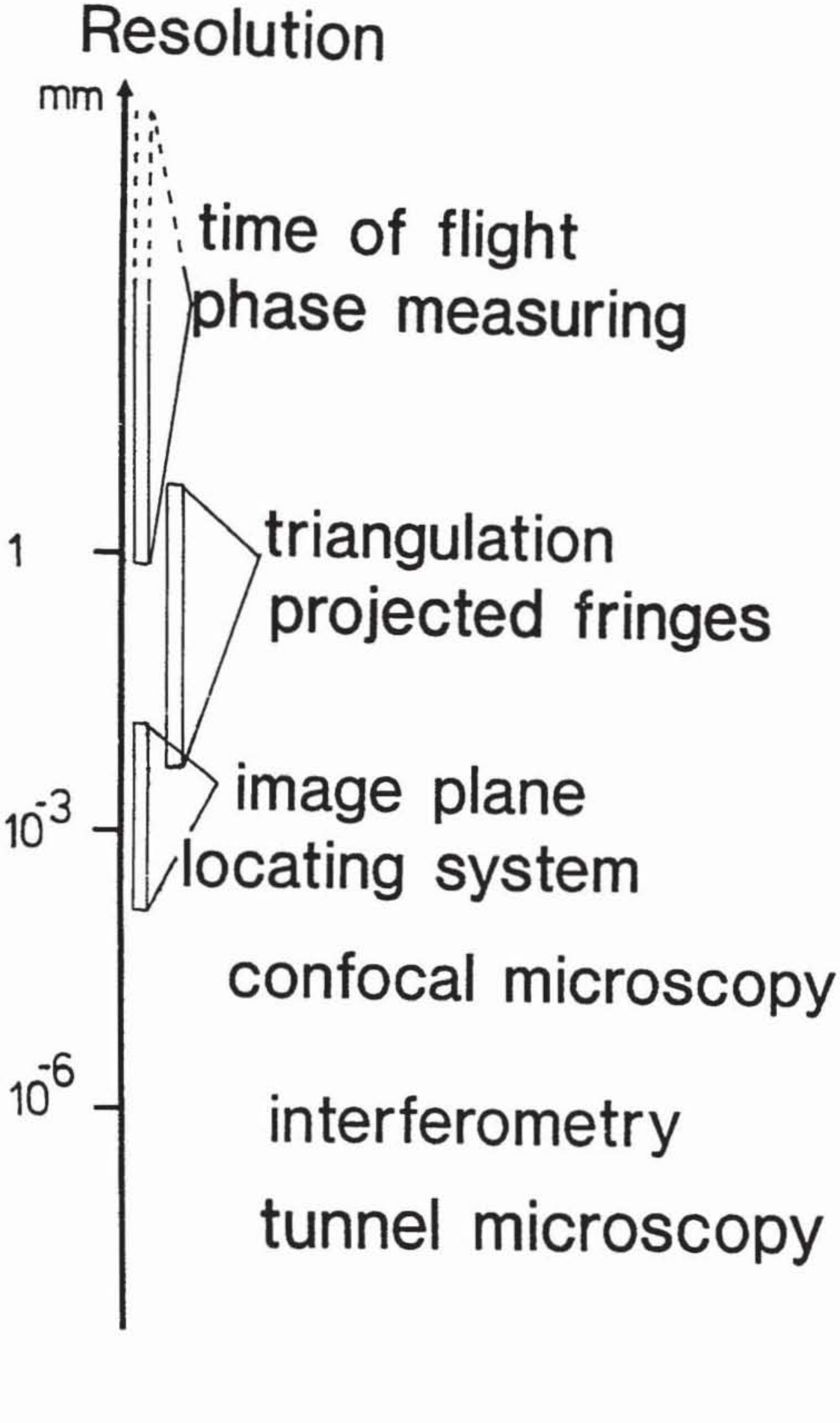
Optical methods



time of flight
phase measuring

triangulation
projected fringes

image plane
locating system

confocal microscopy

interferometry

tunnel microscopy

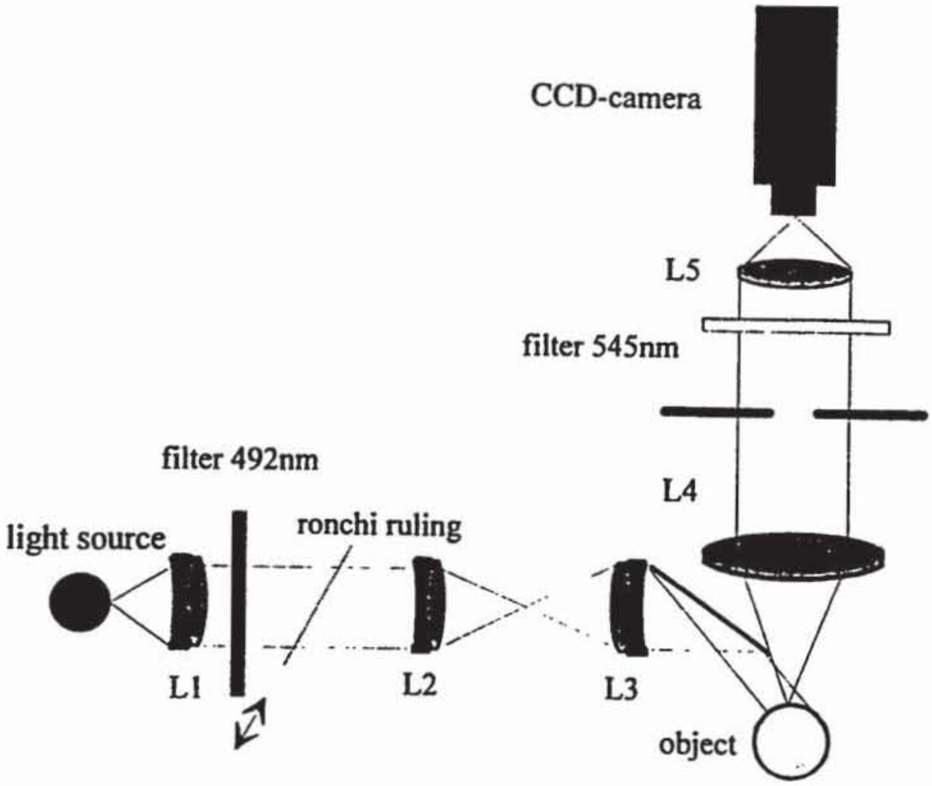


Fig. 1 Arrangement for fringe projection (macro- and microscopic)

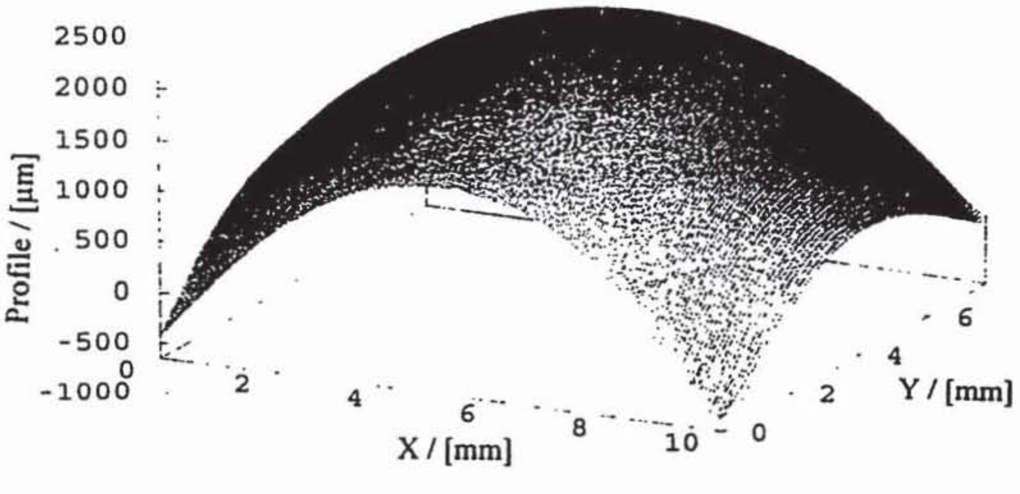


Fig. 2 Results of the in vivo measurement of the cornea of a human eye

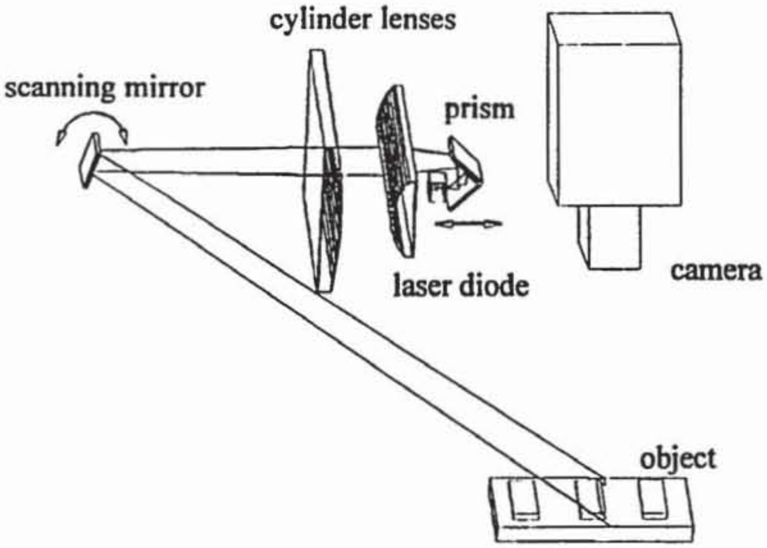

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Fig. 3

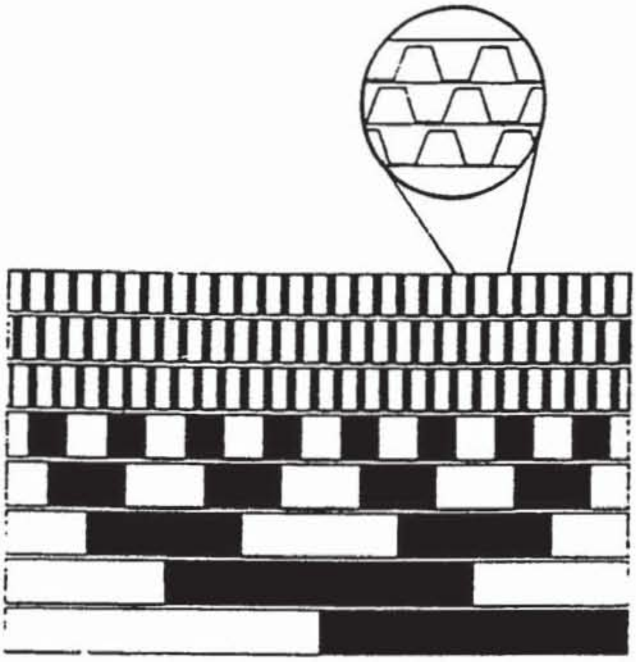

Fig. 4

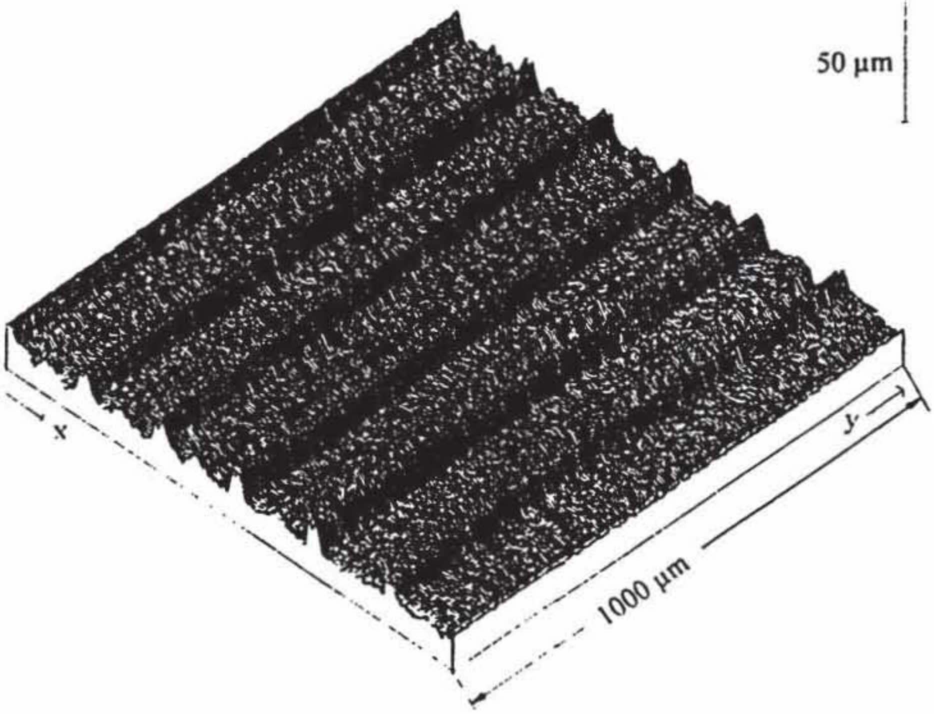
50 µm
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Fig. 5

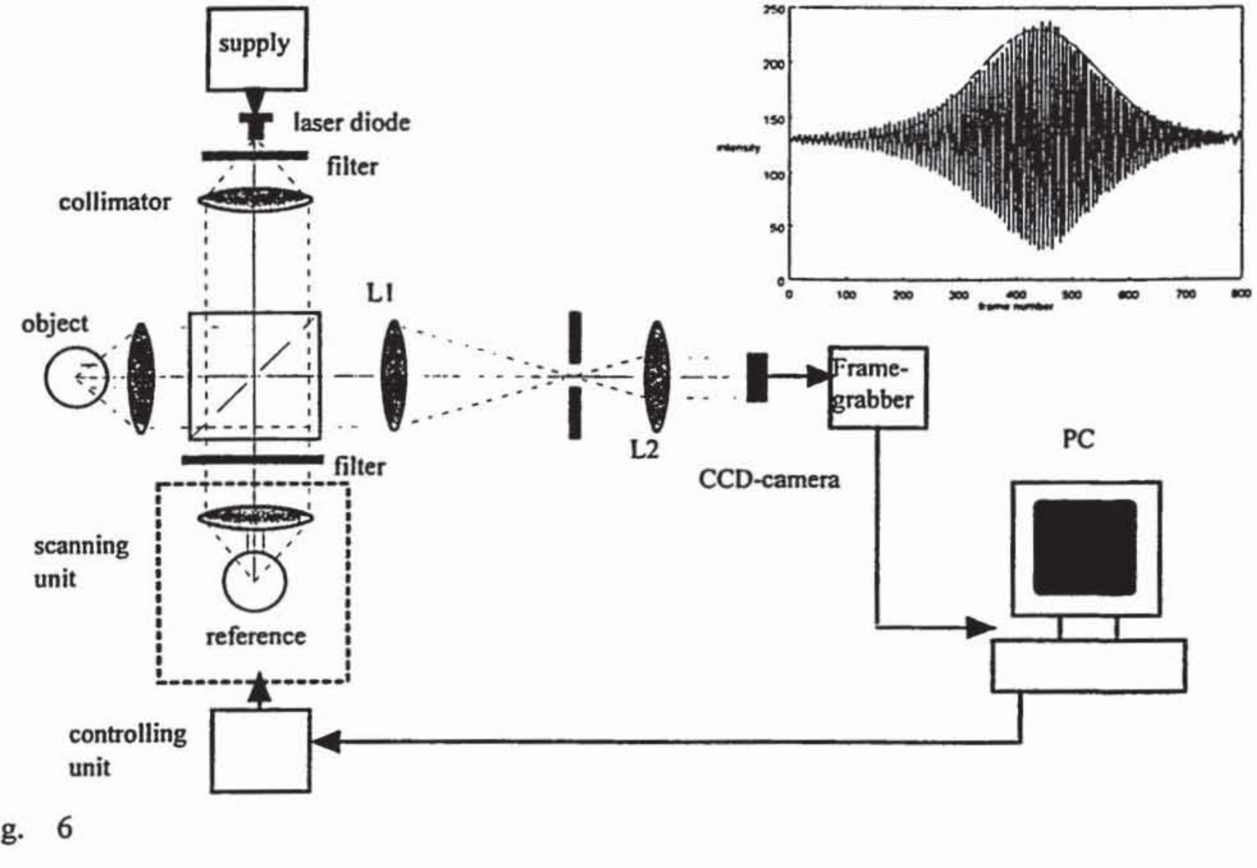
supply
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Fig. 6

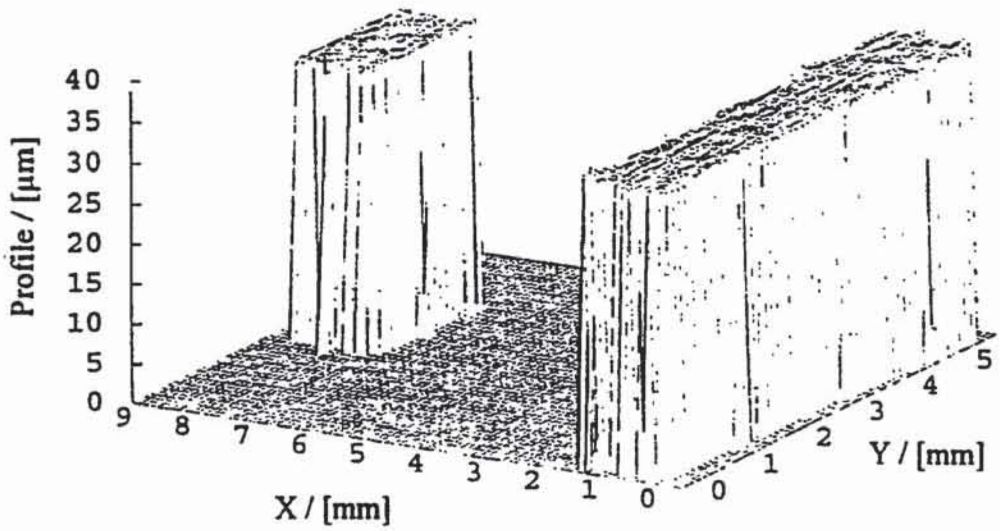

Fig. 7a) Topography of a relais anchor

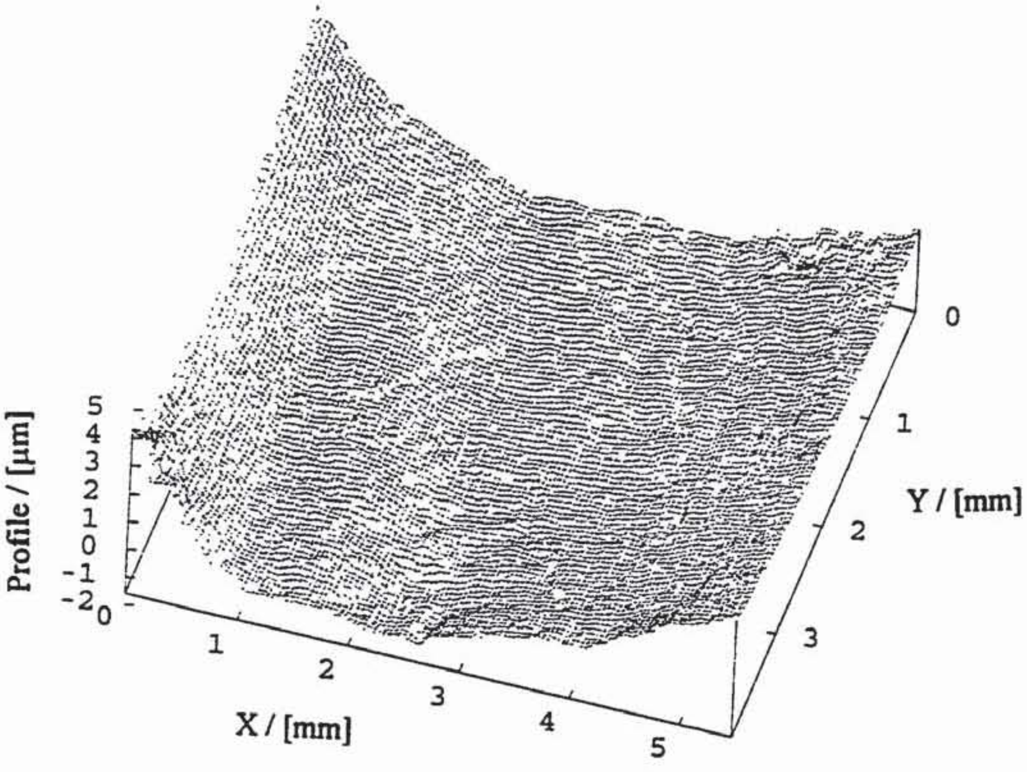

Fig. 7b) Analysis of the back side of a contact lens as compared to a spherical reference

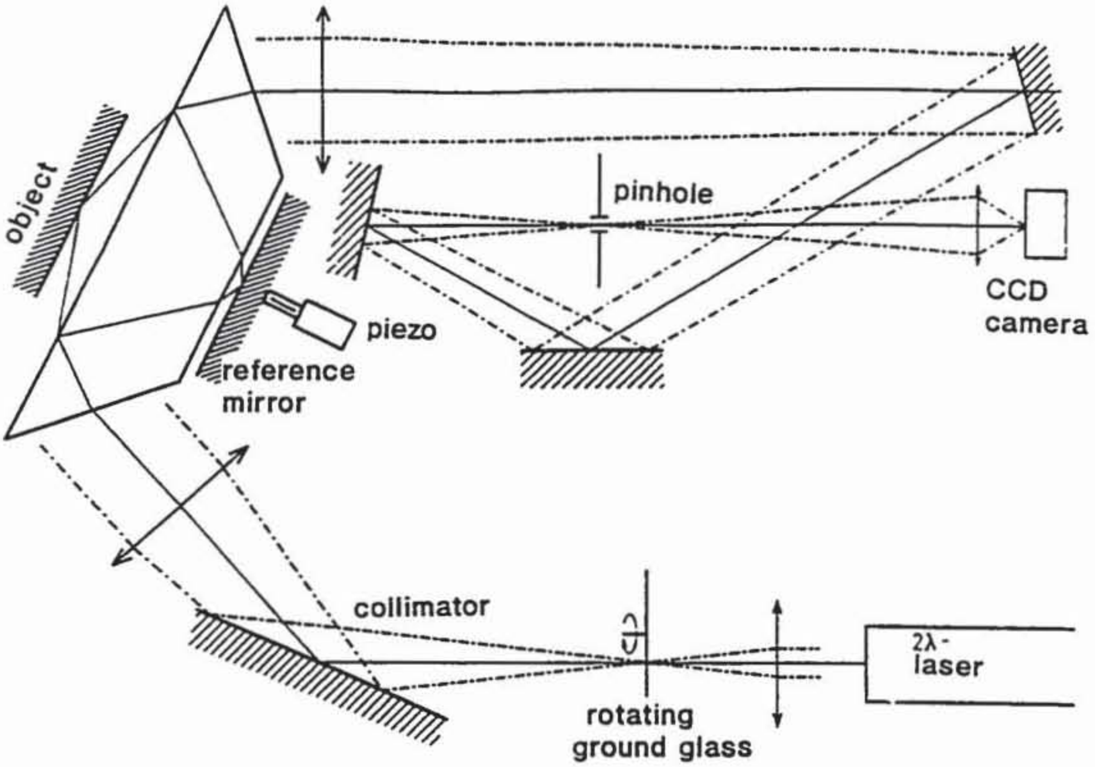

Fig. 8 Arrangement for oblique incidence interferometry together with 2λ- technique.

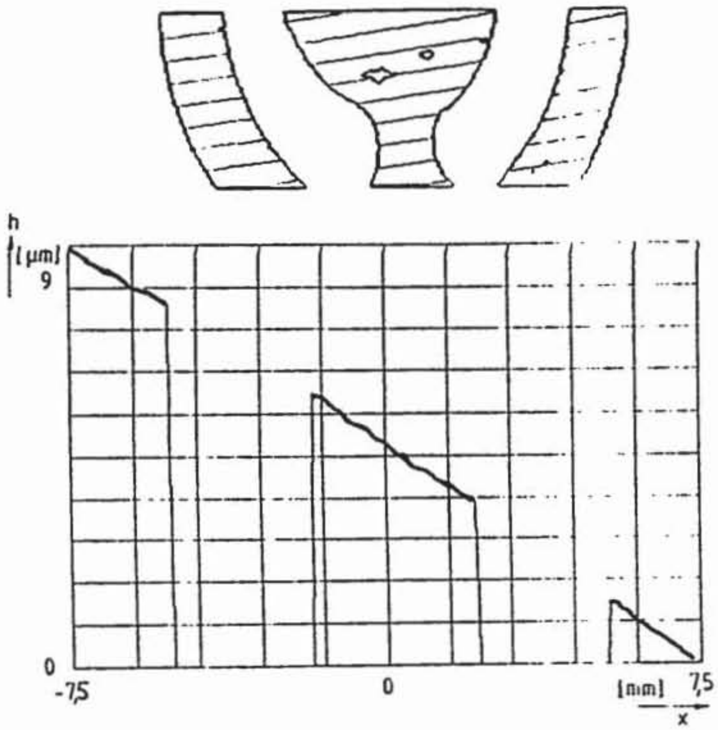

Fig. 9 Result obtained of a metallic anchor of a relais with an oblique incident interferometer together with 2λ, leading to Λ = 25 μm

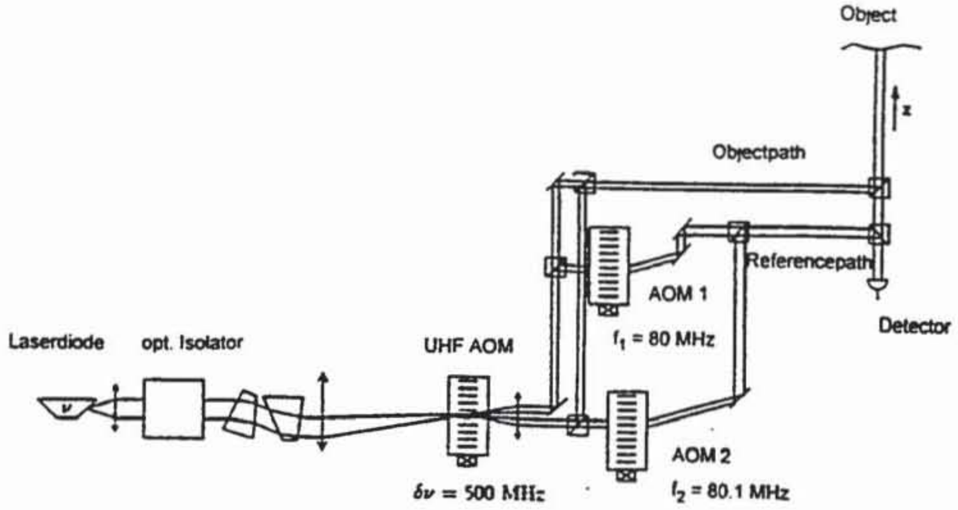

Fig. 10 Arrangement for Double heterodyne interferometry using a high frequency AOM (500 MHz) driven in addition at 501,5 MHz to lead to Λ of 60 cm, respectively 200 m (by 1,5 MHz)

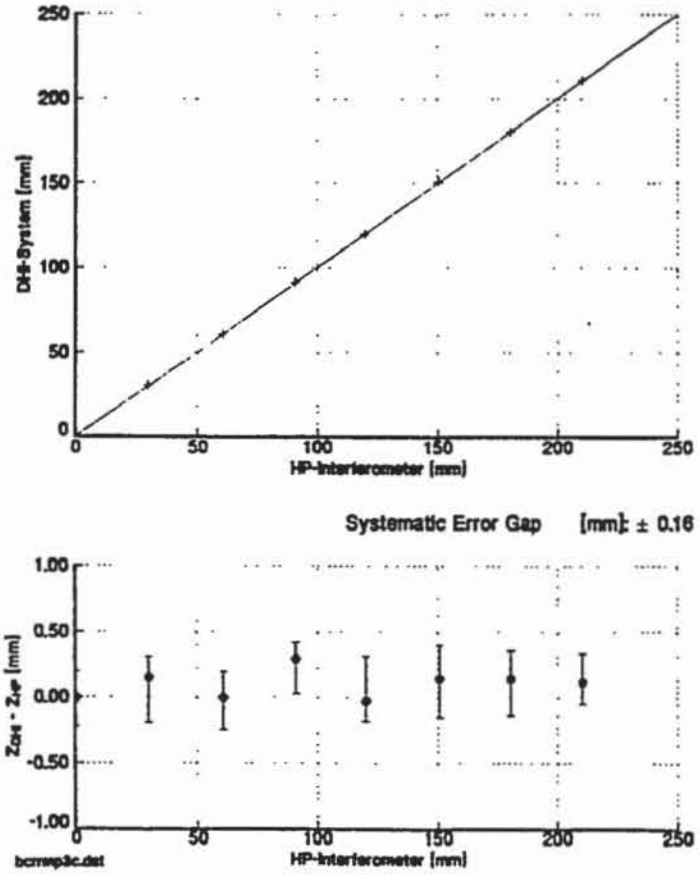

Fig. 11 Absolute distance measurement at a rough surface at a distance of 3 m.