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## Influence of curved surface roughness on white light interferometer microscopy

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# Influence of curved surface roughness on white light interferometer microscopy

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## Abstract

We outline the basic theory behind white light interferometry and the workings of a typical light interferometer microscope. We study WLI images obtained for rough and smooth chrome steel spheres to illustrate the principle that curved rough surfaces can be imaged with such a device as long as the surface roughness is kept within certain limits.

Keywords: interferometry, materials science, optics

In materials science and experimental physics, we often need to quantitatively determine fine peak to peak roughness of a solid surface. Students might be familiar with several techniques which could be used to do this, including scanning electron microscopy (SEM) and atomic force microscopy [1]. Larger scale roughness of a surface can also be tested with an instrument called a profilometer. This device can be based on several methods, one of the simplest of which is probably white light interferometry [2]. The basic physics behind WLI (white light interferometry) is standard and should be known to students who have studied optics at introductory level [3]. Although

the technology used in WLI is typically sophisticated, the underlying physical idea is simply that the disturbance created by a combination of two waves arriving at a single point can be found by adding the disturbance due to each wave by itself (this is known as the principle of superposition.).

One then has an interference pattern due to the phase difference between the two waves. Students should recall that in a diffraction grating, for example, dark bands occur where the disturbance caused by a normally incident wave passing through a slit cancels out the disturbance caused by the wave passing through an adjacent slit. This happens when the two waves arrive at the same point such that the optical path difference between the two adjacent slits is an odd integer multiple of half of the wavelength  $\lambda$  and is known as destructive interference. The bright bands are produced when two disturbance reinforce each other, creating a region of maximum intensity. This happens when the waves arrive at



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the same point such that the path difference is an integer multiple of the wavelength and is known as constructive interference. Roughly speaking, an interferometer is used to produce an interference pattern. Information is extracted from this pattern which is processed by a computer and converted into information about the topography of the test surface.

WLI and the ideas related to it have been studied previously in a classroom environment, including use of WLI to quickly measure group velocity dispersion of an optical material [4–7]. WLI also has a long history in academic research. Recent work of Pavliček and Soubusta has studied the influence of dispersion on the precision of measurements obtained with WLI [8]. Another interesting study considered the influence of surface roughness on measurement uncertainty for WLI [9]. WLI was originally used on optically smooth surfaces but it can also be used for rough surfaces, where the property of being ‘rough’ depends not only on the physical roughness of the surface, but also on the wavelength of the light and the size of the resolution cells which are used in the imaging system [10]. We think that this final point is pedagogically instructive and worth exploring in a classroom environment.

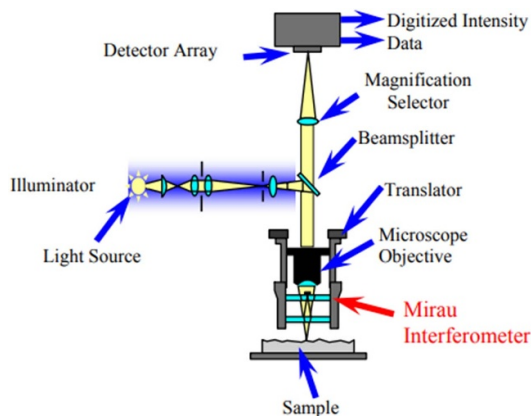
In simpler terms, the spatial resolution of the ILM (interferometer light microscope) is comparable with the wavelength, so as with the usual optical microscopes, the resolution which is available is physically restricted by the wavelength of light. In a diffraction grating interferometer, for example, the spacing of the slits in the grating must be wider than the wavelength of the light in order for diffraction to take place. One could avoid this restriction and achieve a much greater resolution using other methods such as SEM but an ILM provides the three-dimensional profile and other surface parameters, as well as being much quicker and simpler to use. We have stated previously that WLI uses the principle of superposition for waves, but how can one use the superposition principle to obtain detailed three-dimensional microscopic images? In a white light interferometer, a beam splitter splits a beam from a broadband light source into two. This light source is often an LED (light emitting diode). The two beams are known as the ‘reference’ beam (which reflects from a reference mirror) and the ‘measurement’ beam

(which reflects from the surface of the specimen). The two beams return together towards an image sensor (usually a CCD camera, where CCD stands for ‘charge-coupled device’). To get an interference pattern, imagine moving the specimen in the longitudinal direction on its arm of the interferometer whilst the surface is imaged onto the light-sensitive part of the CCD image sensor. The intensity as a function of the longitudinal coordinate is the white light interference pattern [11]. The pattern is spatially sampled for each individual pixel of the CCD sensor to obtain a detailed three-dimensional contour map. The main principle for extracting information on surface depth is that the intensity at a point in the image varies as the object is scanned in depth along the  $z$ -axis [2]. Each interference pattern is processed by the computer software to recover a fringe-visibility function. The location of the peak along the  $z$ -axis then gives the surface height at that point and one can manually vary along the  $x$ - and  $y$ -axes to obtain surface height information across a portion of the surface.

In order to obtain information on the surface at the microscopic level, we need to combine this white light interferometer set-up with the components of an optical microscope [2]. This is generally done by using a Mirau interferometer. If one is familiar with optics terminology, there is an objective lens which focuses the measurement beam onto the surface of the specimen, where the reference arm of the Mirau interferometer is situated in the objective assembly. There will also be a positioning stage so that the objective lens can be moved up and down for focus. Figure 1 shows a diagram demonstrating how the Mirau interferometer is integrated into the optical set-up. Notice that the interferometer is a relatively small component in the device and is situated very close to the positioning stage, with most of the space in the microscope being taken up by the illuminator and the beam.

The main theoretical reason for preferring multichromatic as opposed to monochromatic light is that phase ambiguities can occur at steps which involve a change in the optical path difference which is larger than the wavelength of the light. This can be avoided by using white light, since multichromatic light does not have one single wavelength associated with it. In practice,

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**Figure 1.** Schematic of the ILM with Mirau interferometer. Reproduced with permission from [12]. © (2002) Copyright Society of Photo-Optical Instrumentation Engineers (SPIE).

one normally uses monochromatic light (i.e. a ‘narrowband’ rather than a ‘broadband’ light source) for a type of interferometry called phase-shifting interferometry, which works when the surface is very smooth (which a roughness below 30 nm). A typical object with such a smooth surface would be a mirror or a lens. PSI (phase-shifting interferometry) fails when a surface has large steps in height as one varies the position. For that reason, measurements become ineffective when changes of height between adjacent pixels get close to one quarter of the wavelength of the light has been used. The name for PSI refers to the fact that in PSI the optical path length of the beam is altered, with each change to the optical path shifting the fringe pattern which is observed on the surface in the live video feed. The shifted fringes are recorded at different times to produce several interferograms which are combined by the computer software to determine the surface height profile. One reason to favour PSI is that it requires less memory and processing time to recover the fringe-visibility function which we mentioned previously.

In general, the effect of surface roughness on measurement uncertainty when using an ILM is complicated and was studied numerically by Pavliček and Hýbl [9]. To visually investigate the effect of surface roughness, we prepare two chrome steel spheres of diameter 15 mm, one of which is smooth and one of which has had

its surface roughened and scratched with sandpaper. The roughness and surface properties are then probed with an interferometric light microscope. For completeness, we will mention that the microscope which we used was a Bruker Contour GT-K. The images were obtained and analysed using Vision64 software. Although the experiment itself is relatively small and compact, both the hardware and software are somewhat specialised and will likely only be available at a university. High school students may be able to contact a technician at an Engineering department at a local university and ask if they can view a demonstration. For example, students could bring various different sample surfaces which all look equally smooth to the naked eye and then test how smooth each one is using WLI. This reinforces the general idea that qualitative statements can be made quantitative using accurate measurements.

In figure 2, we show a topographic WLI scan of the roughened sphere. Note that some of the plot in figure 2 is missing on the left-hand side. This is due to the sampling process failing to register the spatial profile at certain points because of local roughness. We can see that the scratches and surface defects have easily been picked up in the scan and that the microscope has been able to analyse a rough curved surface (except for the far left and far right sides of the  $x$  profile). We also see that there is some variation of surface height in both the  $x$  and  $y$  directions. Surface properties can be read off directly. As an example, the mean square roughness of the plot for a  $1\text{ mm} \times 1\text{ mm}$  scan is around 300 nm. It is possible that the roughness might be concentrated somewhat locally, so we rotate the sphere in the microscope to obtain another scan whose results can then averaged with those from the first scan. The results of the second scan are show in figure 3.

The surface we have used is clearly rough, but it may not meet the criterion known as ‘optical roughness’. A surface is considered to be optically rough when the height variations within the resolution cell of the imaging system exceed one-fourth of the wavelength of the light used [13]. If an optically rough surface is measured by WLI, a ‘speckle’ pattern can be seen in the image sensor. These speckle patterns for two different wavelengths become decorrelated if the surface

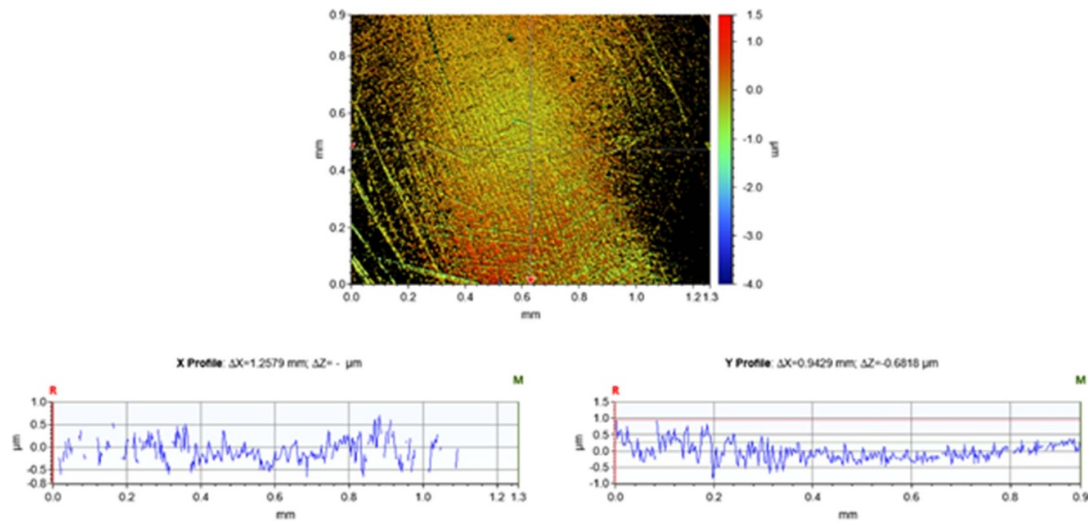


Figure 2. Topographic scan of a roughened sphere surface using WLI.

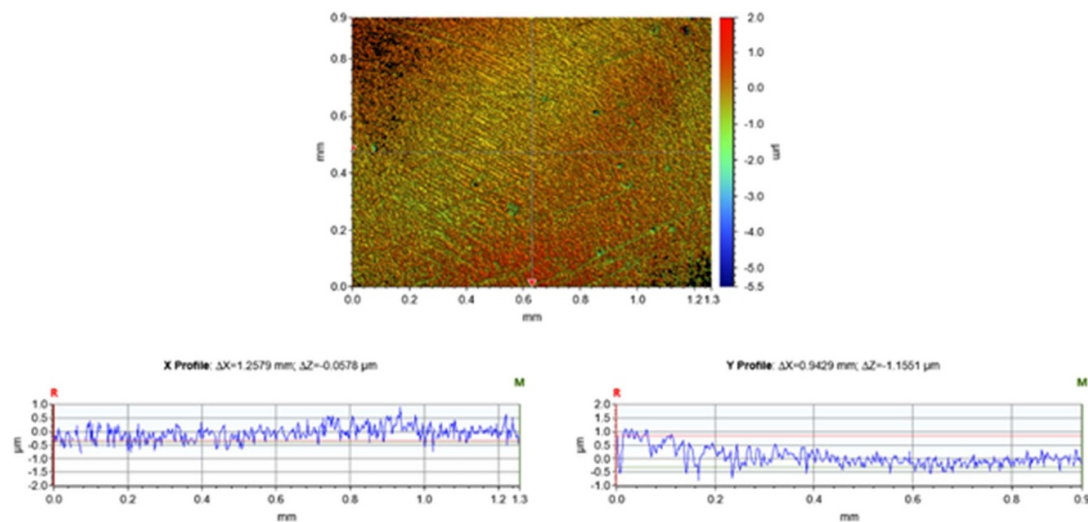


Figure 3. Repeat of the topographic scan in figure 2.

roughness exceeds a certain amount [14]. This is clearly relevant here, because white light does not have a single wavelength associated to it and is instead a mixture of all the wavelengths associated with the spectrum of visible light. Contrast this with green light, for example, which has a well-defined single wavelength of 550 nm. The interferences fringes obtained from a decorrelated speckle pattern can be distorted and difficult to interpret. The influence of the tilt of a surface can have an effect similar to that of surface roughness,

but we do not attempt to make any corrections for tilt since the surface is spherical. In our case, the height variations are small within a resolution cell, so the surface should not be rough enough to cause significant uncertainties when performing WLI measurements.

The measurements above are non-contact measurements but for pedagogical purposes, we will show how a traditional stylus scan looks in comparison (shown in figure 4). Stylus scans make contact with the surface and are typically

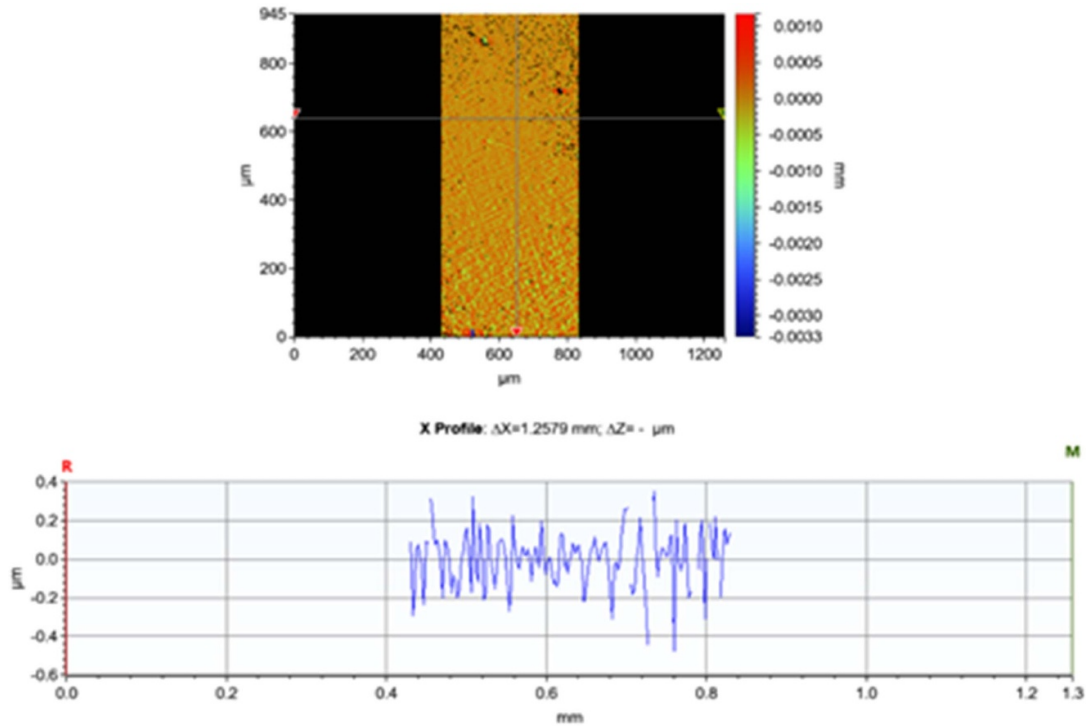


Figure 4. Stylus scan of the same portion of the rough surface used in figure 2.

of lower resolution than the non-contact methods. The image obtained using this method is somewhat less detailed. Note as expected the variation in surface height as one moves in one spatial direction by a fraction of a millimetre. Another thing we could note is that the analysis of [9] assumes a flat rough surface, whereas ours is curved, causing reflection effects. The influence of reflection becomes more obvious if we consider instead the smooth sphere. A topographic scan of the smooth sphere is shown in figure 5.

We see that there are black regions on the topographic scan where the profiler is not able to obtain meaningful data points (this is even after the software has made automatic attempts at correction of the image.). This is almost certainly due to the fact that white light reflects from the smooth sphere more than it does the rough sphere. Similarly, the shape of the  $x$  profile suggests that the profile is trying to correct for reflection from the curved surface and produces a curved

profile (although as expected the variation in surface height is extremely small due to the surface smoothness).

We mentioned earlier that white light is typically used instead of monochromatic light. Will different values be obtained for surface properties if we use monochromatic light? To test this, we repeat the topographic scan of a section of the smooth sphere but using only green light. We also noted previously that optical smoothness or roughness depends on the wavelength of the light and the size of the resolution cell used, as well as the physical roughness of the surface. This suggests the possibility that one could start to introduce measurement uncertainties and distortions of interference patterns by switching to light of lower wavelength.

However, this does not look to have happened in our case if we judge from the values which we have obtained for the surface parameters. This is perhaps not too surprising based on our

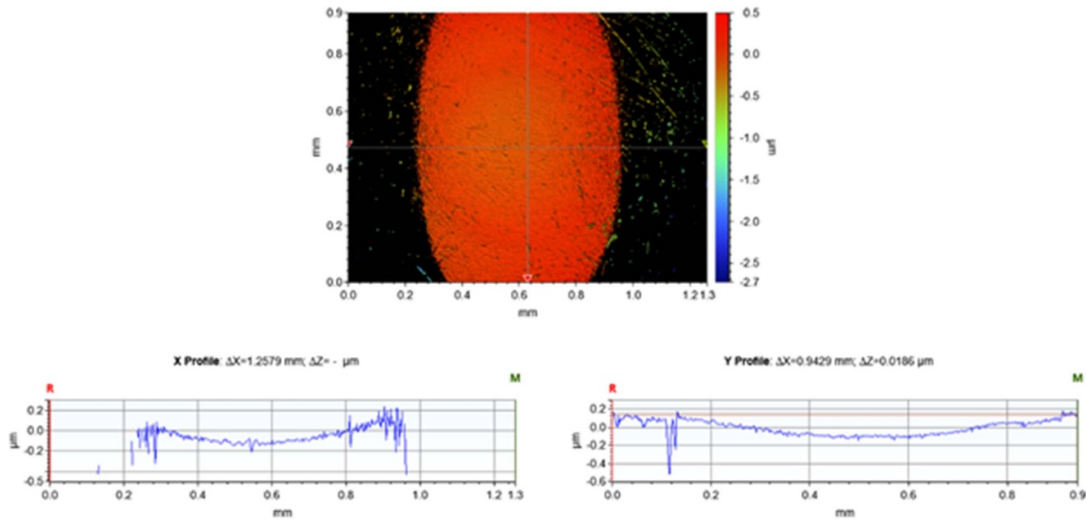


Figure 5. Topographic scan of a smooth sphere.

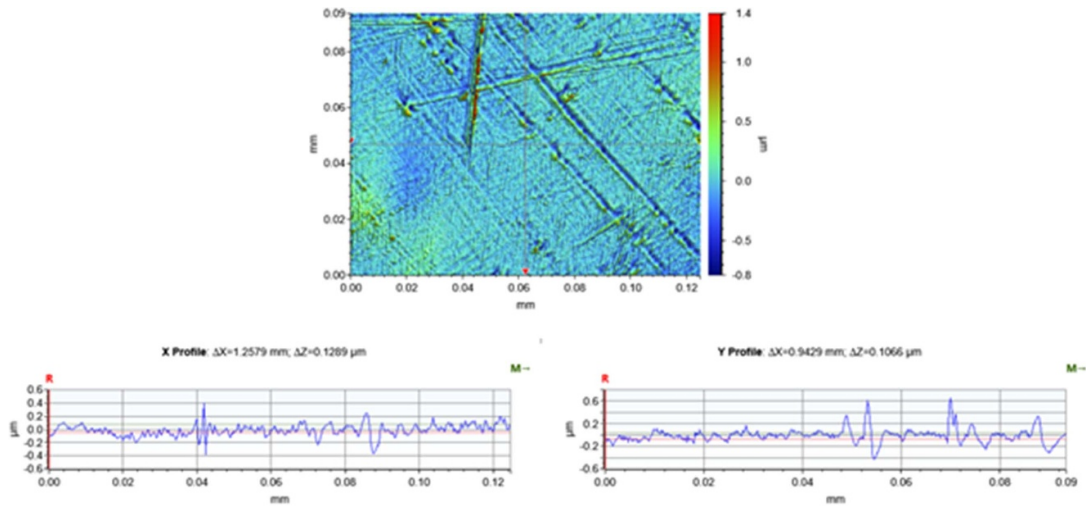


Figure 6. Topographic scan of a smooth sphere using green rather than white light (magnified 50×).

previous discussion, where we stated that phase-shifting interferometry only becomes ineffective when height discontinuities between adjacent pixels approach one quarter of the wavelength, which would be a difference of around 135 nm for green light. The arithmetical mean height and the root mean square height are similar in both cases, for example. The maximum pit height differs significantly, but this can be attributed to local differences on different portions of the sphere, presence of dirt particles, and so on. On the other hand, the

sharpness of the roughness profile is three times higher in figure 5 compared to figure 6 obtained with green light.

In summary, we have confirmed that rough curved surfaces can easily be studied using white light interferometry, as long as the roughness is kept within certain limits. We would encourage further discussion amongst students of the limits at which WLI might start to break down. As emphasised before, the full mathematical treatment of this topic is complicated, but one

could next introduce the idea that the spectral density of a broadband light source takes the form of a Gaussian distribution, whereas a narrowband monochromatic light source does not take this form and so is harder to model from the mathematical point of view.

### Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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