Chapter 1

How the Wyko Surface Profilers Work

This chapter explains how Wyko surface profilers measure both smooth and rough surfaces. It also discusses system performance, and provides a list of additional technical references.

Theory of Operation

Wyko surface profiler systems are non-contact optical profilers that use two technologies to measure a wide range of surface heights. Phase-shifting interferometry (PSI) mode allows you to measure smooth surfaces and small steps, while vertical scanning interferometry (VSI) mode allows you to measure rough surfaces and steps up to several millimeters high.

PSI Mode

Phase-shifting interferometry (PSI) is not a new technique. Wyko has used it for several years to accurately measure smooth surfaces. In phase-shifting interferometry, a white-light beam is filtered and passed through an interferometer objective to the test surface. The interferometer beamsplitter reflects half of the incident beam to the reference surface within the interferometer. The beams reflected from the test surface and the reference surface recombine to form interference fringes. These fringes are the alternating light and dark bands you see when the surface is in focus. Figure 1-1 shows a diagram of an interference microscope.

During the measurement, a piezoelectric transducer (PZT) linearly moves the reference surface a small, known amount to cause a phase shift between the test and reference beams. The system records the intensity of the resulting interference pattern at many different relative phase shifts, and then converts the intensity to wavefront (phase) data by integrating the intensity data.

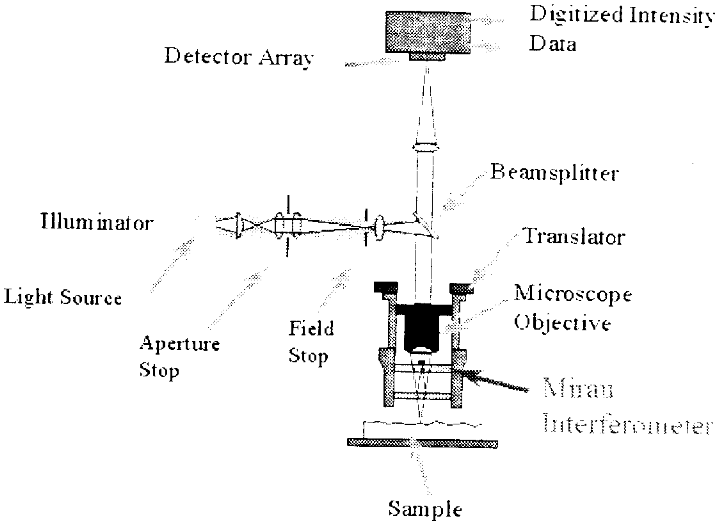

Figure 1-1. An Interference Microscope

The phase data are processed to remove phase ambiguities between adjacent pixels, and the relative surface height can be calculated from the phase data as follows:

$$h(x, y) = \frac{\lambda}{4\pi}\phi(x, y)$$

where λ is the wavelength of the source beam, and $\phi(x,y)$ is the phase data.

This technique for resolving surface heights is reliable when the fringe pattern is sufficiently sampled. When the surface-height difference between adjacent measurement points is greater than $\lambda/4$, height errors in multiples of $\lambda/2$ may be introduced and the wavefront cannot be reliably reconstructed. Thus, conventional phase-shifting interferometry is limited to fairly smooth, continuous surfaces. To resolve rougher surfaces, Wyko surface profilers use vertical-scanning interferometry techniques.

VSI Mode

A newer technique than PSI, vertical scanning interferometry was developed at Wyko[1]. The basic interferometric principles are similar in both techniques: light reflected from a reference mirror combines with light reflected from a sample to produce interference fringes, where the best-contrast fringe occurs at best focus. However, in VSI mode, the white-light source is filtered with a neutral desnity filter, which preserves the short coherence length of the white light, and the system measures the degree of fringe modulation, or coherence, instead of the phase of the interference fringes.

1. Patent Numbers 5,133,601; 5,204,734; 5,355,221

In VSI, the irradiance signal is sampled at fixed intervals as the optical path difference (OPD) is varied by a continuous translation of the vertical axis through focus. Low-frequency components are first removed from the signal; the signal is rectified by square-law detection, then filtered. Finally, the peak of the low-pass filter output is located and the vertical position that corresponds to the peak is recorded. To increase the resolution of the measurement beyond the sampling interval, a curve-fitting interpolation technique is used.

The interferometric objective moves vertically to scan the surface at varying heights. A motor with feedback from an LVDT (linear variable differential transformer) precisely controls the motion. Because white light has a short coherence length, interference fringes are present only over a very shallow depth for each focus position. Fringe contrast at a single sample point reaches a peak as the sample is translated through focus. As seen in Figure 1-2, the fringe contrast, or modulation, increases as the sample is translated into focus, then falls as it is translated past focus.

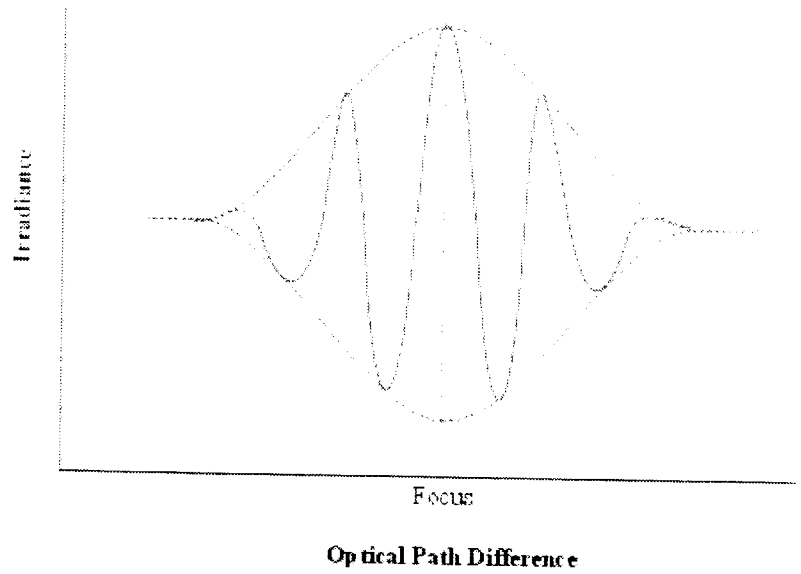

Figure 1-2. Fringe Contrast through Focus

The system scans through focus (starting above focus) as the camera captures frames of interference data at evenly-spaced intervals. As the system scans downward, an interference signal for each point on the surface is recorded. The system uses a series of advanced computer algorithms to demodulate the envelope of the fringe signal. Finally the vertical position corresponding to the peak of the interference signal is extracted for each point on the surface. A block diagram of the algorithm used in VSI is shown in Figure 1-3.

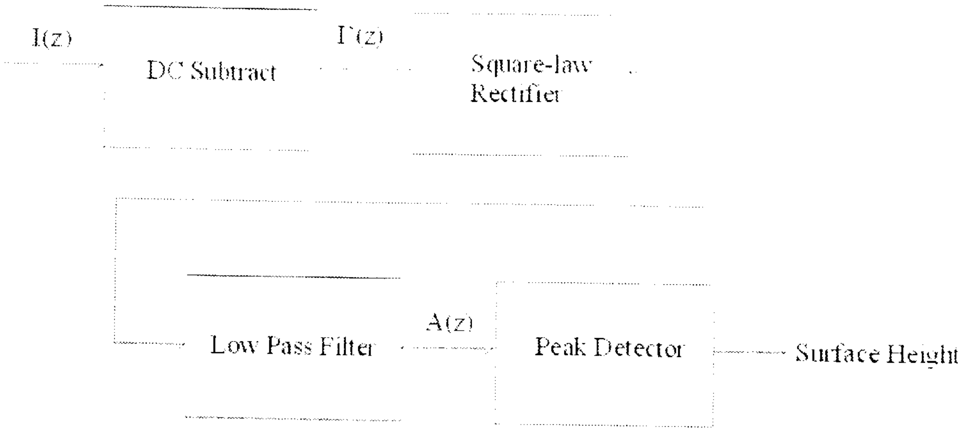

Figure 1-3. VSI Algorithm

Operational Differences Between PSI and VSI

It is important that you understand the differences between the two measurement techniques so you know when and how to use each technique.

The differences between VSI and PSI mode are summarized below. The significance of these differences is explained in the sections following the summary.

Table 1-1. Operational Differences Between PSI and VSI Measurement

VSI	PSI
Neutral Density filter for white light	Narrow bandwidth filtered light
Vertically scans — the objective actually moves through focus	Phase-shift at a single focus point — the objective does not move
Processes fringe modulation data from the intensity signal to calculate surface heights	Processes phase data from the intensity signal to calculate surface heights

Why Do VSI and PSI Use Different Types of Light?

The light for both techniques originates from a white-light source; however, it is filtered during PSI measurements to produce red light at a nominal wavelength of 632 nm. VSI measurements use a neutral density filter, preserving the short coherence length of the white light.

Because white light has a short coherence length, the fringe contrast is highest at best focus but falls off rapidly as you move away from focus. *A white-light source works best for vertical-scanning interferometry* because the technique requires high modulation at a precise focus point.

On the other hand, white-light focusing does not work well for phase-shifting interferometry. If you were to use white light during a measurement, a single high-contrast fringe (the zero order fringe) would fill most or all of the array. Because the contrast drops off rapidly on either side of this fringe, the intensity modulation would be low in some regions when phase-shifting occurs. ***A filtered light source works best for phase-shifting interferometry*** because it has a longer coherence length than white light, so high-contrast fringes are present through a larger depth of focus. This increases the accuracy of your measurements, especially when the objective has a short depth of focus or the sample has tilt that cannot be removed easily.

☞ You can experiment with different types of light while focusing and finding fringes. If you have trouble finding fringes, use red light so more fringes will be visible. If you want to verify the precise focus location, use white light and center the highest-contrast fringe. Be certain to return to the proper measurement filter before taking the measurement.

How Do Scanning and Focusing Differ for PSI and VSI?

In phase-shifting interferometry, the objective does not move through focus. Instead, you focus on the sample so the region of interest is at precise focus, then you make the measurement. During the measurement, the PZT causes a slight shift between the reference and sample beams. The measurement is very quick.

You can find precise focus by using unfiltered white light and looking for the zero-order fringe. When you center this high-contrast fringe, you are at precise focus. (Be certain to switch to filtered light to make the measurement.)

In vertical-scanning interferometry, the internal optical assembly and the magnification objective move through focus in a controlled manner. The detector measures the modulation corresponding to every focus point on the surface as the objective moves vertically. Before you start the measurement, you position the objective at or slightly above focus. After starting the measurement, the system scans downward a specified amount. You must make sure this amount covers the vertical distance you want to scan. The measurement takes a few seconds.

As the system scans through focus, you will see how the focus of the image changes. The plane in which the highest-contrast fringe is visible is the plane at which focus is the most precise, and this plane changes as the surface is scanned. Figure 1-4 shows how fringes would look on various samples as the system moves downward through focus. The top frame shows focus on the highest features; the bottom frame shows focus on the lowest features.

☞ In PSI mode, you can use the **Autofocus** option to automatically focus the objective on the sample. During an autofocus measurement, the objective moves up a specified distance from rough focus, then scans down through focus (up to 100 μm) until the highest-contrast fringe is detected. Since the focal plane changes during a VSI measurement, Autofocus is unnecessary.

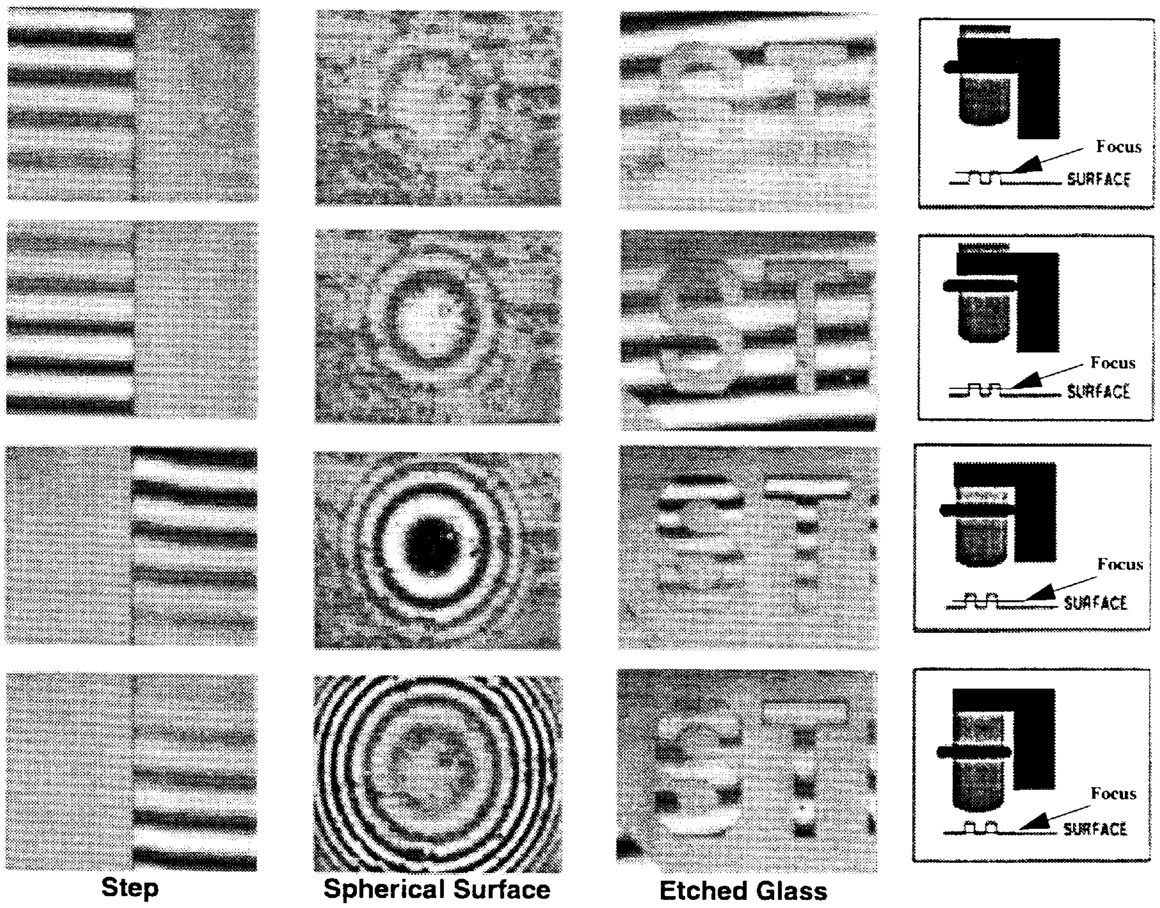

Figure 1-4. Fringe Progression on Various Samples

VSI + PSI

For some samples with both smooth and rough surface features, you can use the two modes together in the same measurement. The combined measurement mode is VSI + PSI mode. VSI + PSI mode works well for samples such as step heights, where the vertical resolution of VSI is required to measure the abrupt height change, and the lateral resolution of PSI is required to resolve the fine features on the surface of the step. VSI + PSI mode is intended for samples in which the height change between adjacent pixels is greater than 160 nm—it does not work for samples with gradual surface height changes.

When you measure a step height sample with VSI + PSI mode, the system first makes a PSI measurement to resolve the surfaces of the steps. Then the system automatically switches to VSI mode and makes another measurement to determine the relative heights of the steps. The program performs a step height adjustment on the PSI data according to the VSI step height data, then discards the VSI data. The result is accurate and repeatable step height and surface roughness data.

System Performance

The following sections briefly describe the range, resolution, and accuracy of your profiler system.

The performance of you system depends to some extent on your measurement technique. To obtain optimum system performance, always use a well-calibrated system and consistent measurement techniques.

Range

Range refers to the greatest vertical distance the profiler can accurately measure. The limits of dynamic range for each mode are listed in Table 1-2. These two modes allow you to measure a wide range of smooth and rough surfaces.

In PSI, six intensity frames of data are recorded as the PZT is moved a distance of $\pi/2$, or $\lambda_0/4$[2], between each frame. The system determines phase data from the intensity data, then calculates surface heights. The surface height data is then integrated to remove 2π effects. If the surface is smooth and continuous, such that integration errors are not encountered, the resulting data is used directly to generate the surface map.

PSI is reliable for smooth surfaces in which the height change between two adjacent points is not more than approximately 160 nm ($\lambda_0/4$ for a nominal measurement wavelength of 640 nm). If you try to use PSI mode for higher steps, you will see integration errors (lines of discontinuity) in your data.

Table 1-2. Measurement Range for PSI and VSI Measurements

Mode	Range
PSI	160nm
VSI	2mm

(2000 µm)

2. λ_0 is the center wavelength of the bandpass filter, usually approximately 632 nm.

VSI is reliable for rougher surfaces, because the range is limited only by the scan length allowed by the internal linear translator.

Resolution

Resolution refers to the smallest distance the Wyko surface profilers can accurately measure. It can be in terms of lateral or vertical resolution.

Lateral Resolution

Lateral resolution is a function of the magnification objective and the detector array size you choose. Each magnification objective has its own optical resolution based on the magnification and numerical aperture (NA) of the objective. Optical resolution refers to the smallest surface feature the objective can distinguish.

If you select an objective and array configuration in which the detector sampling interval is much smaller than the optical resolution, you will be *oversampling* the surface. In this case, the resolution is optically limited. The resulting surface map may show blurry images because the features cannot be resolved optically. Generally, you should select a configuration in which the detector sampling interval is larger than the optical resolution. In this case, the resolution is limited by the detector. However, if the detector sampling interval is considerably larger than the optical resolution, you will be *undersampling* the surface, which could result in undetected surface features.

Vertical Resolution

Each mode has different resolution limits. Resolution values for PSI and VSI are listed in Table 1-3. The values are in terms of R_q and are based on measurements of a smooth surface (R_q of 1.5Å or less).

Table 1-3. Vertical Resolution of PSI and VSI

Mode	Vertical Resolution: Single Measurement	Vertical Resolution: Multiple Measurements (Averaged)
PSI	3 Å	1 Å
VSI	3 nm	<1 nm

When you consider resolution, you must also consider the techniques you use when making the measurement. As you can see in Table 1-3., you get better resolution when you average multiple VSI measurements.

You can determine the vertical resolution of you system by taking the difference of two measurements from the same location on the sample. The resolution data is essentially the noise limit of you system, or the lowest vertical resolution you can obtain at that time. It should be a near-flat profile with an R_q value approaching the non-averaged values in Table 1-2.

☞ Making a difference measurement is sometimes referred to as "checking the repeatability." If the result shows a significant difference, the two measurements are not very repeatable.

To get the best resolution from your Wyko surface profiler, always use consistent and correct measurement techniques. Also make sure environmental noise is minimized by setting up the system as described in your operator's guide.

Accuracy

Accuracy refers to how closely a measured value matches the true value. It is determined relative to a known, traceable standard. You can check your system's accuracy by measuring a standard (such as a step height standard) and comparing the result to the true value. Veeco recommends you use a known standard that is traceable by NIST.

Accuracy can be compromised by measurement technique, miscalibration, and aberrations in the interferometer's optics. Make sure your system in well-calibrated by checking the calibration periodically and recalibrating if necessary. During VSI calibration, the measured value of a known step height standard is compared to the true value of the step height. If there is a deviation, the scanning mechanism corrects itself accordingly. During PSI calibration, a super-smooth mirror is measured to verify that the PZT is shifting the correct amount.

To correct for aberrations in the interferometer's optics, you can generate a measurement of the internal reference mirror and subtract it from your measurements. This removes aberrational effects, which are significant for very smooth surfaces. (In VSI mode, the option to subtract a reference is not available because the coarser vertical resolution masks the effects of optical aberrations in the system. Guidelines for determining when reference subtraction is beneficial are provided in Table 4-1, later in this manual. For more information about generating and subtracting a reference file. see the Setup Guide for your system.