Basic SPM Training Course

004-131-000 (standard)
004-131-100 (cleanroom)

Document Revision History: Basic SPM Training Course

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Chapter 1 Product Introduction

1.1 Introduction

This chapter provides the history of Scanning Probe Microscopy (SPM), the forms it takes, and relevant definitions. The following topics are addressed:

1.1.1 Definitions of Scanning Probe Microscopy (SPM)

Scanning Probe Microscopy consists of a family of microscopy forms in which a sharp probe is scanned across a surface and some probe-sample interaction(s) are monitored.

Primary Forms of SPM

- Scanning Tunneling Microscopy (STM)
- Atomic Force Microscopy (AFM), known as Scanning Force Microscopy (SFM)

Primary Modes of AFM

- Contact Mode AFM
- Non-contact Mode AFM
- TappingMode™ AFM

STM and AFM are the primary detection methods used by the instrument to allow the probe to follow the surface features.

Other Forms of SPM:

- Lateral Force Microscopy (LFM)
- Force Modulation Microscopy
- Magnetic Force Microscopy (MFM)
- Electric Force Microscopy (EFM)
- Surface Potential Microscopy
- Phase Imaging
- Force Volume
- Electrochemical STM & AFM (ECM)
- Scanning Capacitance Microscopy (SCM)
- Scanning Thermal Microscopy (SThM)
- Near-field Scanning Optical Microscopy (NSOM or SNOM)
- Tunneling AFM (TunA)
- Scanning Spreading Resistance (SSRM)

Note:
These other forms of SPM are all secondary signals used to characterize other properties of a sample during surface scanning. The capability of an SPM system is constantly expanding. This is an example of measurements that are regarded as other forms of microscopy.

1.2 Instrument Overview

1.2.1 Primary Components of the SPM

A complete NanoScope SPM system consists of a control system connected to a microscope system. The control system can operate all types of Microscope systems. The NanoScope control software is set to operate the particular microscope that is connected to the controller (See Figure 1.2a).

Control System

The control system includes: a computer, control monitor, display monitor, SPM control electronics and software.

Microscope System

The Microscope system includes: a sample stage, piezo electric scanner and SPM detection electronics.

1.2.2 Basic Types of Microscope Systems

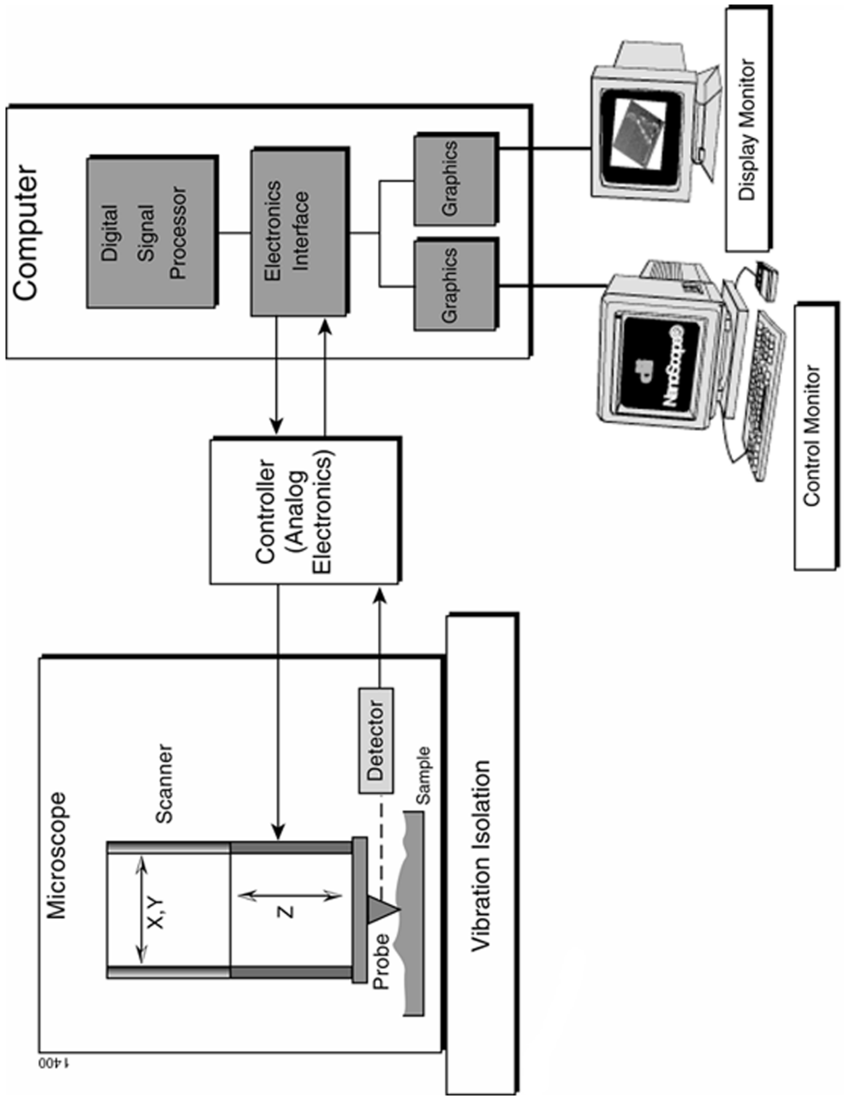
Small Sample Systems

STM, Contact AFM, LFM, Multimode™ AFM are the systems originally designed, before the Dimension series of stage-based SPMs, by Digital Instruments. They are structurally rigid enough to resolve detail on surfaces down to sub-nanometer resolution. The sample size is limited to 1/2” diameter by ~2mm thickness.

Large Sample Stage Systems

The Dimension 3000/3100, Dimension 5000, Dimension 9000, Dimension 9300 have motorized stages that allow samples up to 300mm (Dimension 9300) to be scanned. The detector and Piezo scanner are contained in a single unit that is fixed over the sample. This type of microscope system contains progressively more advanced automated features. These features mainly revolve around automated sample positioning and automated scanning software routines. The microscope systems are capable of operating in all the scanning modes of the small sample systems with the benefit of large sample handling. The limit to this type of system is its mechanical rigidity. They are more susceptible to external vibration and acoustic noise.

Figure 1.2a Basic SPM Components



Chapter 2 General SPM Training

2.1 Introduction

This chapter overviews software and operational theory/procedures:

2.2 Theory of Operation

The NanoScope control system performs two main functions:

- Generates drive voltages to control the X-Y scans of the SPM probe by way of a piezoelectric transducer.
- Maintains an incoming analog signal from the microscope detection circuitry at a constant value.

A closed-loop feedback control system performs the second function.The signal from the microscope detection circuit changes as the probe scans over the sample surface. The signal from the microscope is compared to a fixed level signal generated by the control system (setpoint). The resulting differential voltage is read by the computer through an analog to digital (A/D) converter.

The computer is programmed to keep the two inputs equal (0 volts).

An output voltage generated by the computer moves the piezoelectric transducer in the Z direction to correct for differences read into the A/D converter. This closed-loop feedback control is the heart of the imaging portion of the control station.

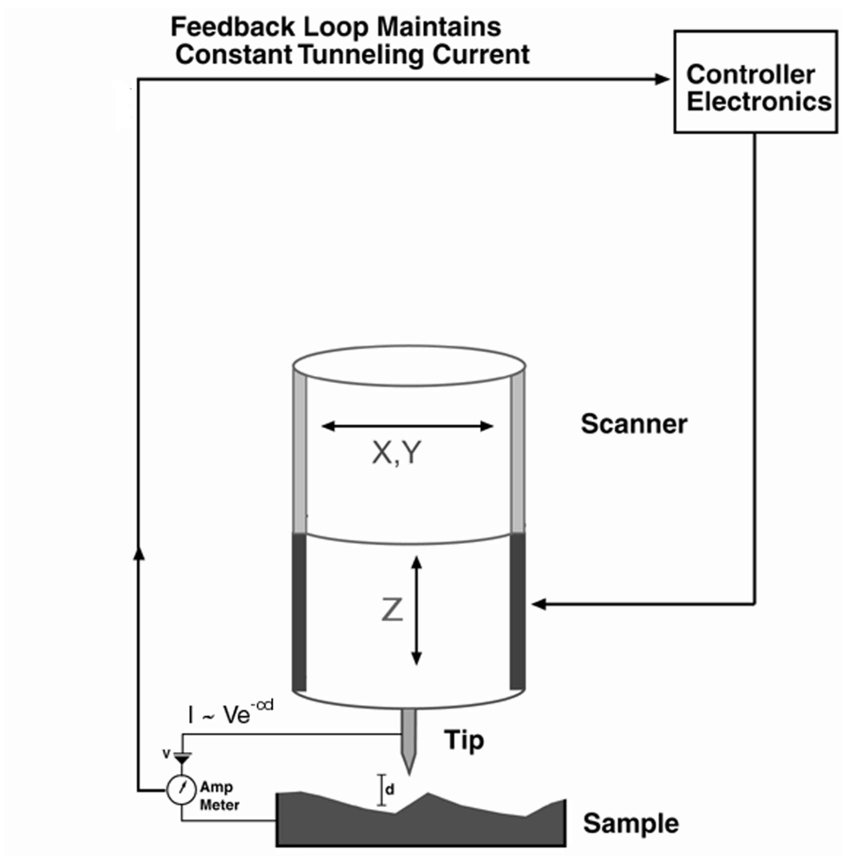
STM and AFM are the two basic detection methods. The STM method moves the probe across the sample surface while maintaining a constant current flow between the sample and the SPM probe. The AFM method uses an optical positioning system that monitors the position of the SPM probe. The probe is deflected by changes in surface height as it is scanned across the sample surface.

The following pages illustrate the SPM system using these detection methods.

2.3 Scanning Tunneling Microscopy (STM)

STM is based on the tunneling current between a conductive tip and sample (See Figure 2.3a). As the tip scans the sample surface, it encounters sample features of different heights, resulting in an exponential change in the tunneling current. A feedback loop maintains a constant tunneling current during scanning by vertically moving the scanner at each (x,y) data point until a set current is reached. The computer stores the vertical position of the scanner at each (x,y) data point to form the topographic image of the sample surface. This technique is limited to conductive and semiconducting surfaces.

Figure 2.3a Scanning Tunneling Microscope

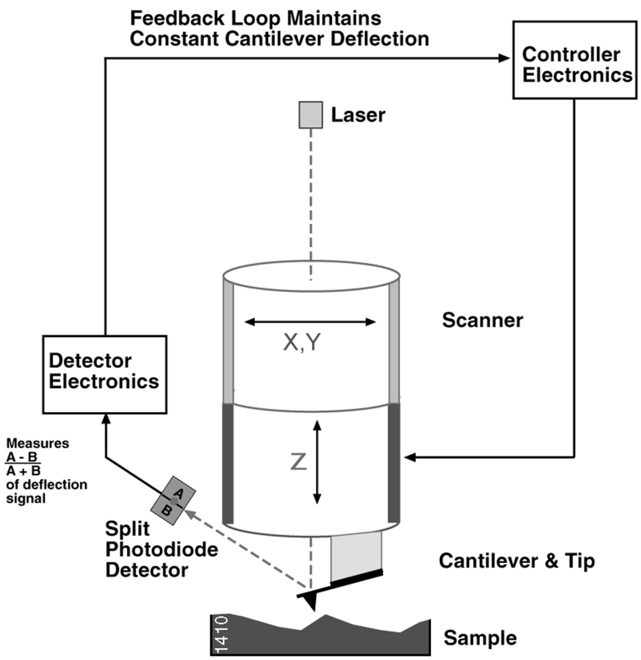


2.4 Contact Mode AFM

Contact mode AFM operates by scanning a tip attached to the end of a cantilever across the sample surface while monitoring the change in cantilever deflection with a split photodiode detector.

The tip contacts the surface through the adsorbed fluid layer on the sample surface (See Figure 2.4a).

Figure 2.4a Contact Mode AFM



A feedback loop maintains a constant deflection between the cantilever and the sample by vertically moving the scanner at each (X,Y) data point to maintain a set deflection.

By maintaining a constant cantilever deflection, the force between the tip and the sample remains constant.

The computer stores the distance the scanner moves vertically at each (x,y) data point to form the topographic image of the sample surface. Operation can take place in ambient and liquid environments.

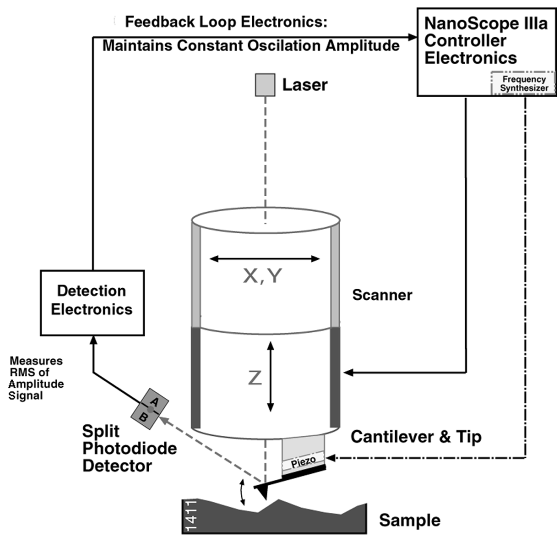
2.5 TappingMode™ AFM

TappingMode™ AFM operates by scanning a tip attached to the end of an oscillating cantilever across the sample surface.

The cantilever oscillates at or near its resonance frequency with an amplitude ranging typically from 20nm to 100nm.

The tip lightly taps the sample surface during scanning, contacting the surface at the bottom of its swing (See Figure 2.5a).

Figure 2.5a TappingMode AFM



A feedback loop maintains a constant cantilever oscillation by vertically moving the scanner until a set amplitude is achieved.

The computer stores the vertical position of the scanner at each (x,y) data point in order to form the topographic image of the sample surface.

Operation can take place in ambient and liquid environments. In liquid, the oscillation need not be at the cantilever resonance.

2.6 Advantages and Disadvantages of Contact Mode AFM and TappingMode AFM

2.6.1 Contact Mode AFM

Advantages

- High scan speeds (throughput)
- Contact mode AFM is the only AFM technique which can obtain atomic resolution images.
- Rough samples with extreme changes in vertical topography can sometimes be scanned more easily in contact mode.

Disadvantages

- Lateral (shear) forces can distort features in the image.
- The forces normal to the tip-sample interaction can be high in air due to capillary forces from the adsorbed fluid layer on the sample surface.
- The combination of lateral forces and high normal forces can result in reduced spatial resolution and may damage soft samples (i.e., biological samples, polymers, silicon) due to scraping between the tip and sample.

2.6.2 TappingMode AFM

Advantages

- Higher lateral resolution on most samples (1 nm to 5 nm).
- Lower forces and less damage to soft samples imaged in air.
- Lateral forces are virtually eliminated, so there is no scraping.

Disadvantages

- Slightly slower scan speed than contact mode AFM.

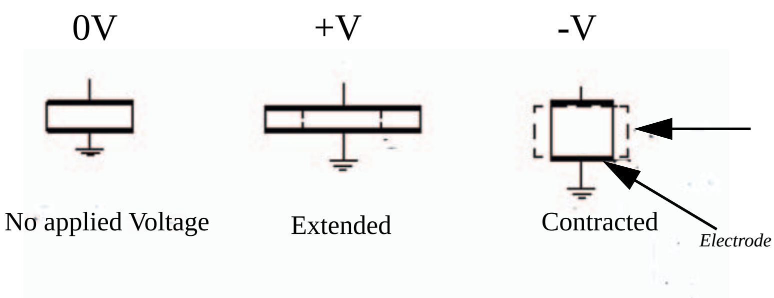
2.7 Piezoelectric Scanners

2.7.1 Piezoelectric Scanners Overview

SPM scanners are made from piezoelectric material, which expands and contracts proportionally to an applied voltage.

Whether they elongate or contract depends upon the polarity of the voltage applied.

Figure 2.7a Effect of Applied Voltage on Piezoelectric Materials

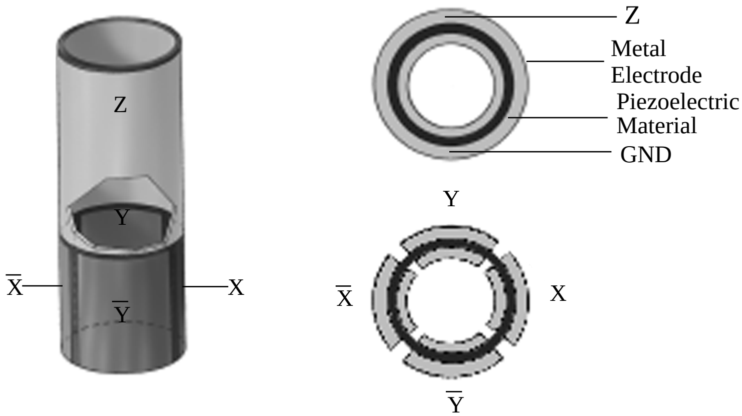


To construct the scanner, we combine independently operated piezo electrodes for X, Y, & Z into a single tube, forming a scanner which can manipulate samples and probes with extreme precision in 3 dimensions.

In some models (e.g., MultiMode SPM) the scanner tube moves the sample relative to the stationary tip. In other models (e.g., STM, Dimension Series SPMs) the sample is stationary while the scanner moves the tip.

Figure 2.7b shows typical scanner piezo tube and X-Y-Z configurations. AC Signals applied to conductive areas of the tube create piezo movement along the three major axes.

Figure 2.7b Typical Scanner Piezo Tube and X-Y-Z Configurations



Voltages applied to the different electrodes of the piezoelectric scanner produce a scanning raster motion in X and Y. There are two segments of the piezoelectric crystal for X (X & X) and Y (Y & Y).

Figure 2.7c Voltages Applied to Electrodes of Scanner

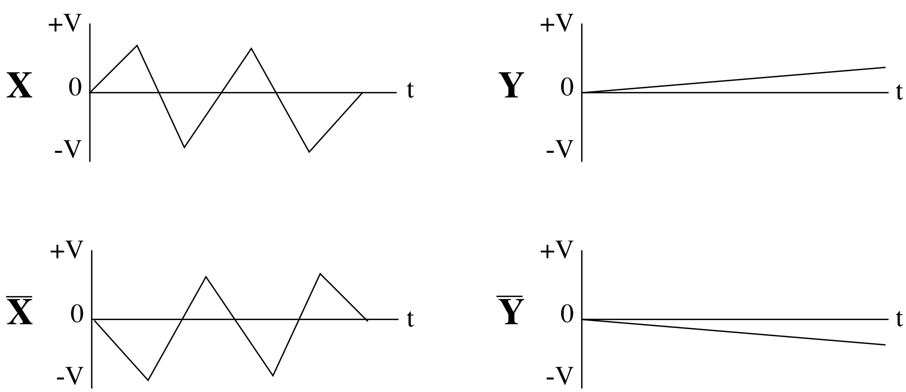
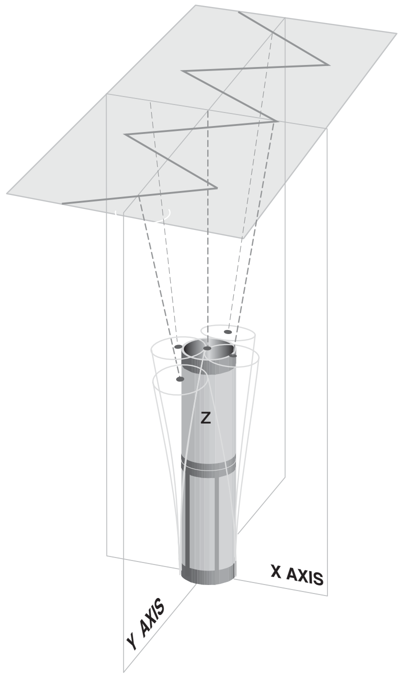


Figure 2.7d Waveforms Applied to the Piezo Electrodes During a Raster Scan with the X Axis Designated as the Fast Axis (Scan Angle = 0°)



Schematic of piezo movement during a raster scan. Voltage applied to the X- and Y-axes produce the scan pattern.

2.7.2 Piezoelectric Scanners: Hysteresis and Aging

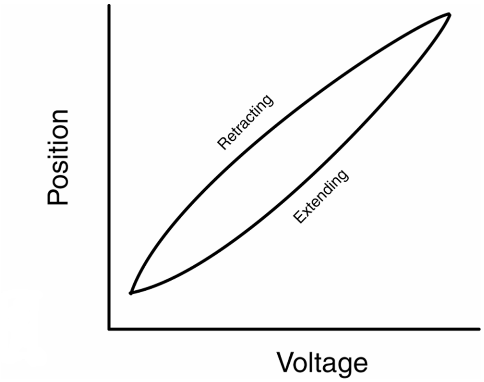
Hysteresis

Because of differences in the material properties and dimensions of each piezoelectric element, each scanner responds differently to an applied voltage.

This response is conveniently measured in terms of sensitivity, a ratio of piezo movement-to-piezo voltage (i.e., how far the piezo extends or contracts per applied volt).

Sensitivity is not a linear relationship with respect to scan size. Because piezo scanners exhibit more sensitivity (i.e., more movement per volt) at the end of a scan line than at the beginning, the relationship of movement vs. applied voltage is nonlinear. This causes the forward and reverse scan directions to behave differently and display hysteresis between the two scan directions.

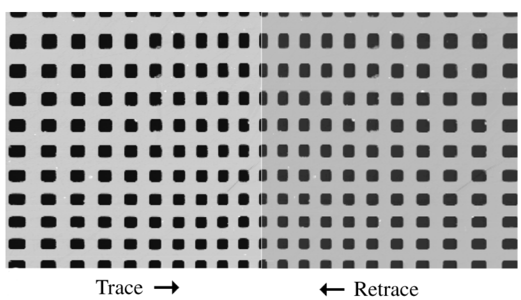
Figure 2.7e Ratio of Piezo Movement to Piezo Voltage



The curve in Figure 2.7e demonstrates the effect of nonlinearity and hysteresis. As the piezo extends and retracts throughout its full range, it moves less per applied volt at the beginning of the extension than near the end. The same is true when the piezo is retracting - the piezo moves less per applied volt at the beginning of its extension than near the end.

Nonlinearity and hysteresis can cause feature distortion in SPM images if not properly corrected. Figure 2.7f shows 100µm x 100µm scans in the forward (trace) and reverse (retrace) directions of a two-dimensional 10µm pitch grating without linearity correction. Both scans are in the down direction. Notice the differences in the spacing, size and shape of the pits between the bottom and the top of each image. The effect of the hysteresis loop on each scan direction is demonstrated.

Figure 2.7f Trace and Retrace Scans



This nonlinear relationship is corrected during the calibration routine by applying a nonlinear voltage to produce a linear scan in X and Y in both trace and retrace scan directions.

Figure 2.7g shows nonlinear waveform (solid line) applied to the piezo electrodes to produce linear scanner movement. The unaltered triangular waveform (dashed line) is included for reference.

Figure 2.7g Nonlinear Waveform (Solid Line)

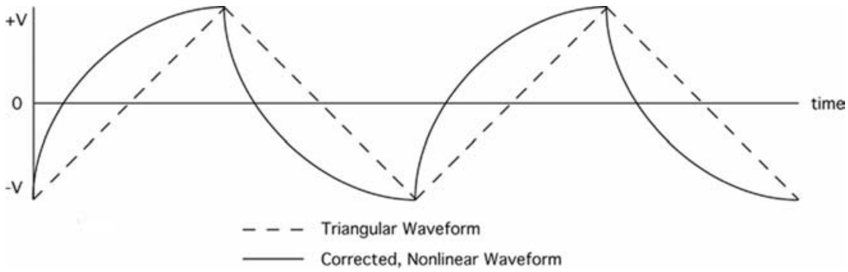
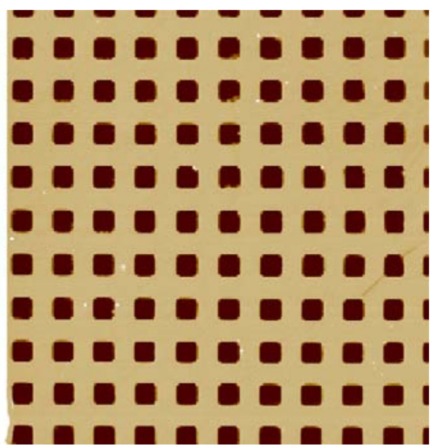


Figure 2.7h shows a 100μm x 100μm scan of the same two-dimensional 10μm pitch calibration grating with a nonlinear scan voltage. Notice the equal spacing between all pits and the consistent shape and size of pits throughout the image.

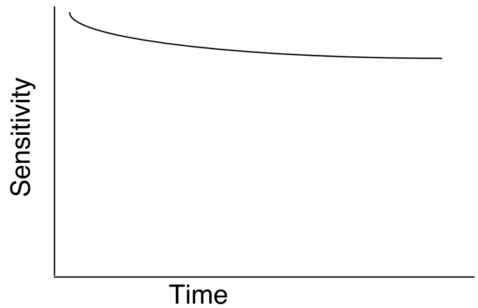
Figure 2.7h Scan, Two-Dimensional Calibration Grating



Aging

The sensitivity of piezoelectric materials decreases exponentially with operation time. This causes most of the change in the sensitivity to occur at the beginning of a scanner's life (See Figure 2.7i).

Figure 2.7i Aging



Scanners run approximately 48 hours before shipment from the factory to get the scanner past the point where the sensitivity changes dramatically over short periods of time. As the scanner ages, the sensitivity changes less with time, and eventually reaches the point where it seldom needs recalibrating. This occurs after approximately 6 months of typical use.

2.7.3 Piezoelectric Scanners: Creep and Bow

Creep

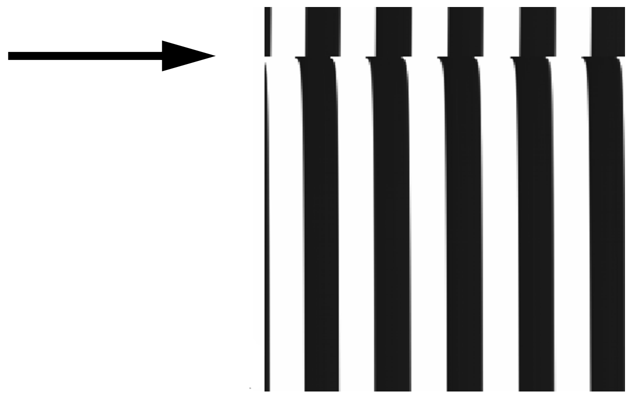
Creep is the drift of the piezo displacement after a DC offset voltage is applied to the piezo.

This may occur with large changes in X and Y offsets, and when using the frame up and frame down commands when the piezo travels over most of the scan area to restart the scan.

When performing a large offset, the scanner stops scanning and a DC voltage is applied to the scanner to move the requested offset distance. However, the scanner does not move the full offset distance all at once. It initially moves the majority of the offset distance quickly, and then slowly moves over the remainder. The scanning resumes after a majority of the offset distance has been moved although the scanner is still slowly moving in the direction of the offset. Creep is the result of this slow movement of the piezo over the remainder of the offset distance once scanning has resumed.

Creep appears in the image as an elongation and stretching of features in the direction of the offset for a short period of time after the offset. An example of creep is shown in the image of a calibration grating (See Figure 2.7j). The tip was scanning from top to bottom and an offset of 10μm in the X direction was performed near the beginning of the scan (indicated by the arrow). The slight bending of the lines which occurs directly after performing the offset are due to creep. The creep settles out by the end of the scan.

Figure 2.7j Creep



When creep appears in the image, it often settles out by the end of the scan to allow the next image may be capture. For very large offsets (>50μm), it may take longer than 1 scan for the creep to settle out. You may reduce creep by offsetting beyond the desired point and then offsetting back to the desired point.

Bow

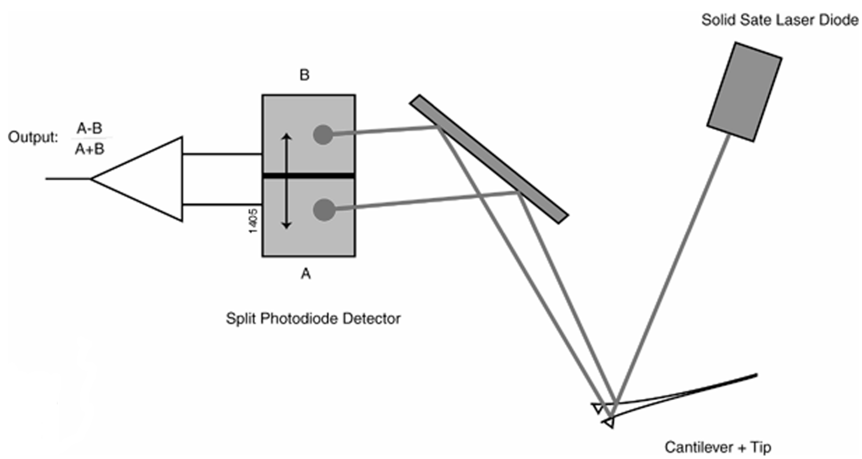
Because scanners are attached at one end and move the sample or tip on the other, the free end does not move in a level plane. The mechanical properties of the piezo, as well as the kinematics of motion, often result in 2nd order or 3rd order curvatures from an ideal plane. This is commonly called Bow, which increases with scan size. You may remove bow from a captured image by using software filters after the data is collected.

2.8 AFM Detection Optics

2.8.1 Atomic Force Microscopy- Beam Deflection Detection

- Laser light from a solid state diode is reflected off the back of the cantilever and collected by a position sensitive detector (PSD) consisting of two closely spaced photodiodes whose output signal is collected by a differential amplifier.
- Angular displacement of cantilever results in one photodiode collecting more light than the other photodiode, producing an output signal (the difference between the photodiode signals normalized by their sum) which is proportional to the deflection of the cantilever (See Figure 2.8a).

Figure 2.8a Beam Deflection



2.8.2 SPM Configurations

Figure 2.8b Scanned Tip SPM

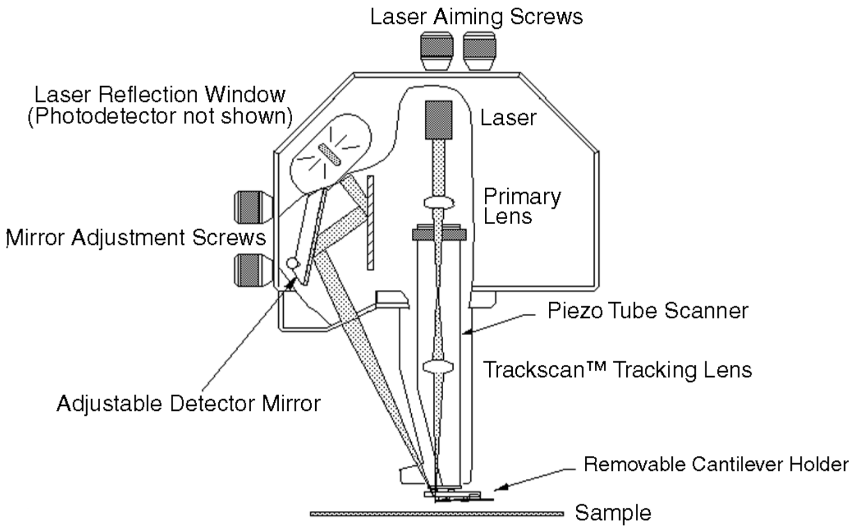
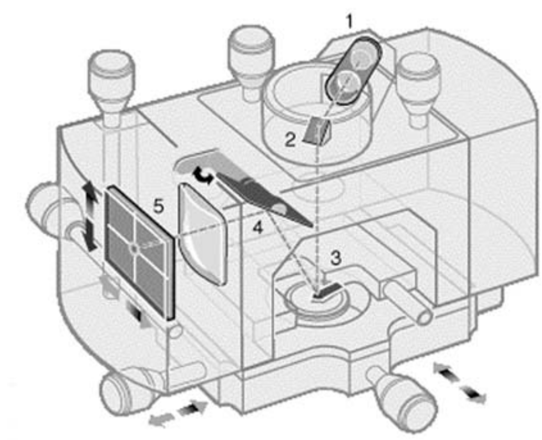


Figure 2.8c Scanned Sample SPM



Labels:
1. Laser
2. Mirror
3. Cantilever
4. Tilt Mirror
5. Photodetector

2.9 AFM Probe Overview

Outside sources manufacture AFM probes for Digital Instruments Veeco. There are two basic types of probes, referred to by their respective material types: Silicon Nitride or Silicon.

2.9.1 AFM Probe's Three Major Components

Substrate

The substrate is the body of the probe. It is the portion of the probe handled by the tweezers during installation into the cantilever holder.

Cantilever

The cantilever is the portion of the probe that projects off of the end of the substrate. The tip mounts on the end of the cantilever.

Tip

The tip is the portion of the probe that comes in proximity to the sample surface. The tip is usually a four-sided pyramid that comes to a point. The point of the tip has a radius of curvature from 5nm to 50nm depending on the type.

2.9.2 Silicon Nitride Probes

We use Silicon Nitride probes primarily for Contact AFM. and for **TappingMode** in fluids.

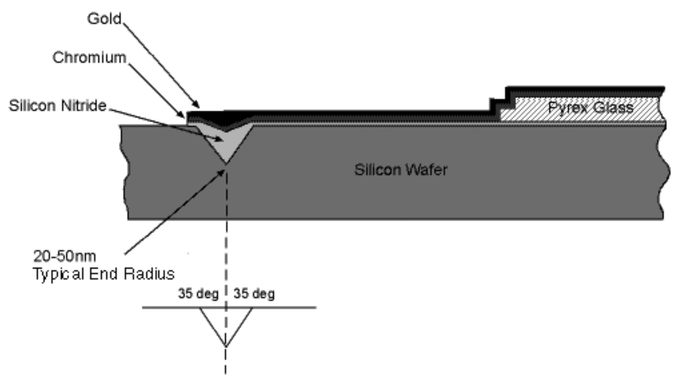
Manufacture

The manufacturing process of silicon nitride probes begins with application of a photomask containing 4μm square holes is to a bare silicon wafer. The silicon wafer is then etched (See Figure 2.9a).

The etching process creates a square pyramid shaped pit in the silicon. The wafer is coated with a layer of Silicon Nitride. A photomask containing four different shaped levers is applied to the silicon nitride coated wafer.

The levers have two legs that join at one end to form a triangle. The apex of the triangle positions over the pit in the silicon. The surface of the wafer is etched, to remove the silicon nitride not covered by the photomask. A disk of Pyrex glass that has been sawed into strips is bonded to the wafer. The glass forms the substrate component of the probe. The etching process removes the silicon wafer, revealing the tip and the cantilever. The upper surface of the cantilever and the substrate is coated with a layer of chromium. The chromium functions to flatten the cantilever and to act as a bonding interface for the reflective gold coating. Internal stress in the silicon nitride causes the levers to curl or twist. The thickness of the chromium flattens the cantilever. The last process is to add a layer of gold. The gold reflects the laser light to the photo detector.

Figure 2.9a Silicon Nitride Probe Manufacture



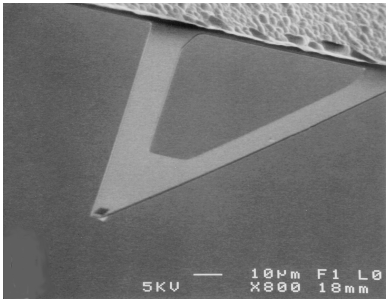
Characteristics of the standard silicon nitride probes (Models NP and DNP) are listed below:

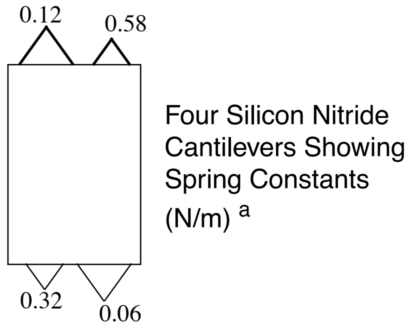
Table 2.9a: Silicon Nitride Probe Characteristics

Spring Constant (k)	0.58, 0.32, 0.12, 0.06 N/m [a]
Nominal Tip Radius of Curvature	20 - 50 nm
Cantilever Lengths	100 & 200 μm
Cantilever Configuration	V-shaped
Reflective Coating	Gold
Sidewall angles	35° on all 4 sides

a. Calculated spring constant values are based on the 0.6μm silicon nitride thickness; however, this value can actually vary from 0.4μm to 0.7μm. Thickness is cubed in the spring constant calculation, thus, actual values can vary substantially.

Figure 2.9b Silicon Nitride Cantilevers





2.9.3 Silicon Probes

Silicon probes are used primarily for TappingMode applications.

The tip and cantilever are an integrated assembly of single crystal silicon, produced by etching techniques.

Only 1 cantilever and tip are integrated with each substrate.

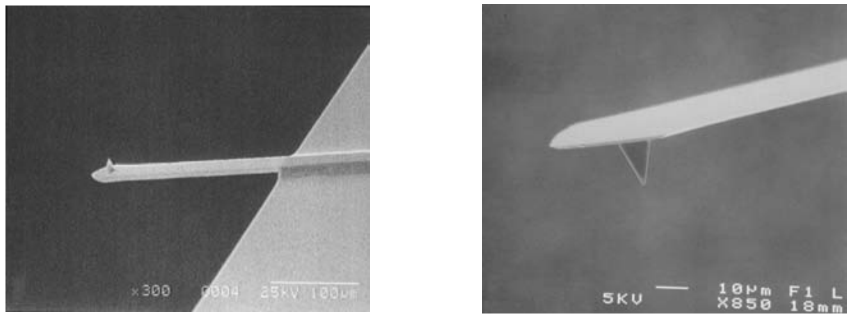
These probes can be much stiffer than the silicon nitride probes, resulting in larger force constants and resonant frequencies.

Table 2.9b lists the characteristics of the TappingMode Etched Silicon Probes (Model TESP).

Table 2.9b: TappingMode Etched Silicon Probe (TESP) Characteristics

Spring Constant (k)	20 - 100 N/m
resonance frequency	200 - 400 kHz
Nominal Tip Radius of Curvature	5 - 10 nm
Cantilever Length	125 μm
Cantilever Configuration	Single Beam
Reflective Coating	Uncoated, Optional Al Coating

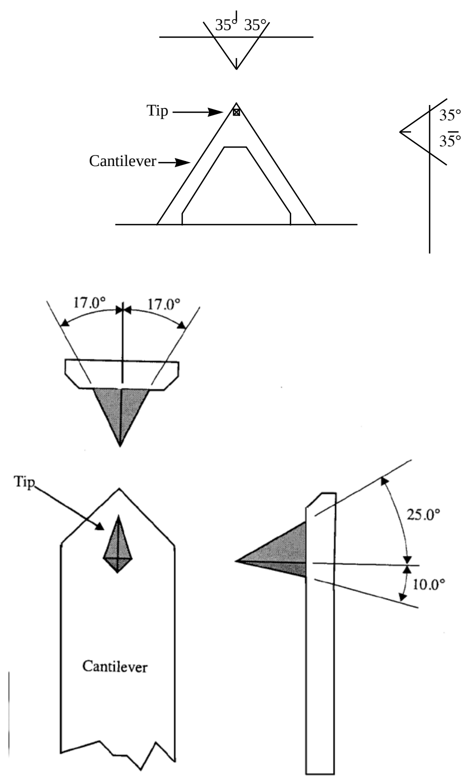
Figure 2.9c Scanning Electron Microscope (SEM) Silicon Cantilever and Tip



Tip Sidewall Angles

The sidewall angles of the tip determine the ability to image steep sidewalls on a sample surface (See Figure 2.9d).

Figure 2.9d Tip Sidewall Angles of Silicon Nitride Probes



2.10 Imaging Artifacts

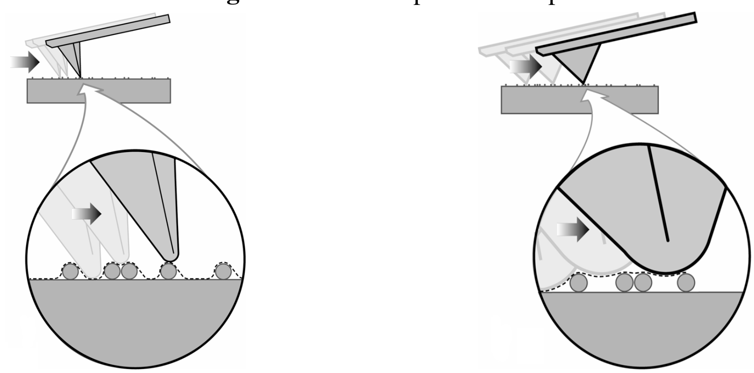
2.10.1 Tip Shape Issues

The SPM image is a result of the interaction of the tip shape with the surface topography.

There are two primary features of the tip which affect the SPM image: the radius of curvature and the tip sidewall angles.

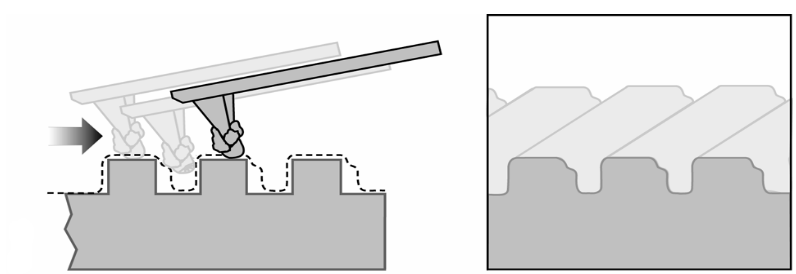
The smaller the radius of curvature, the smaller the feature that can be resolved. A sharper tip will be able to laterally resolve smaller features than a dull tip with a larger radius of curvature. See Figure 2.10a, which shows schematics and image profiles of spheres scanned with a sharp (left) and dull (right) probe.

Figure 2.10a Sharp vs. Dull Tip



The accumulation of debris on the end of the tip can dull the tip, resulting in image distortion (See Figure 2.10b).

Figure 2.10b Debris Accumulation on Tip



Note: A dull or dirty tip may not affect the measurement of the vertical dimensions of these samples.

The sidewall angles of the tip determine the ability to image steep sidewalls on a sample surface.

The tip cannot profile sides of surfaces steeper than the sidewall angle of the tip.

When scanning across features which are steeper than the sidewall angle of the tip, the sidewall angle in the images reflect the sidewall angle of the tip.

The following examples show the resulting angles and image profiles of silicon nitride and silicon tips scanned over trenches with 90° sidewall angles.

The tip mounts in the cantilever at ~10°, so the angles measured with the front and back sides of the tip will be skewed by ~10°. Figure 2.10c shows Sidewall Angle Measurements of Trench with Vertical Sidewalls Acquired with Silicon Nitride Probe. Figure 2.10d shows Sidewall Angle Measurements of Trench with Vertical Sidewalls Acquired with Silicon Probe.

Figure 2.10c Silicon Nitride Tip Sidewall Interaction

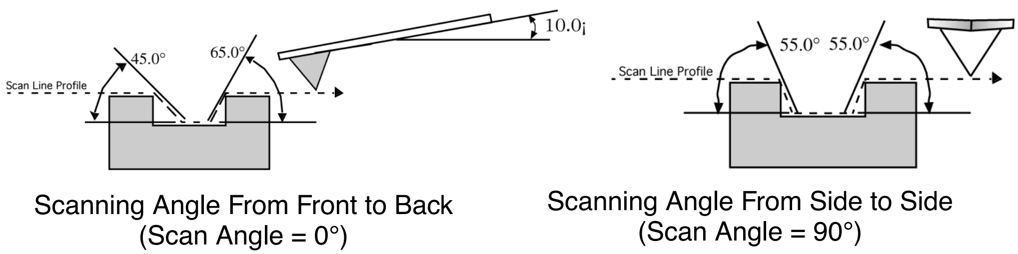
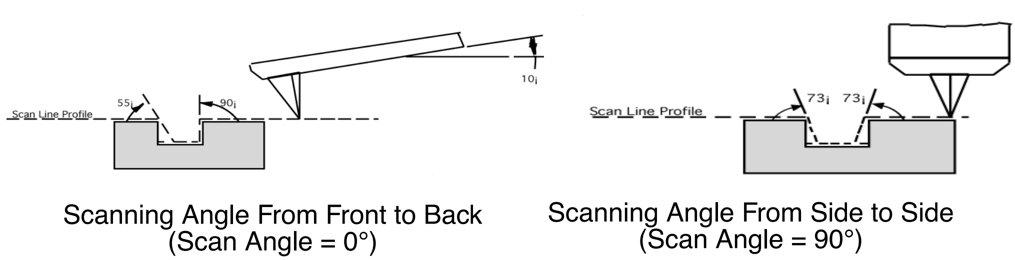


Figure 2.10d Etched Silicon Tip Sidewall Interaction



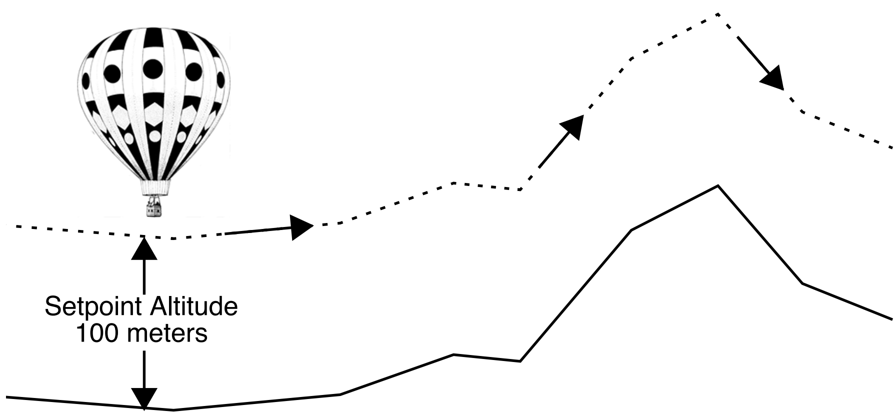
2.11 Feedback Gains

The feedback system used to control tip-sample interactions and render images must be optimized for each new sample, by adjusting various gains in the SPM feedback circuit. This section discusses gains and how to use them to obtain images.

2.11.1 Proportional and Integral Gain—An Analogy

To better understand gains and how they control SPM probes, consider the analogy of a hot air balloon carrying three balloonists. Each rider controls a separate valve on the balloon's gas burner. The valves are mounted in parallel, such that if any one valve is open, gas flows to the burners, causing the balloon to rise. Similarly, each balloonist may turn their burner off to reduce altitude. Mounted beneath the balloon's gondola is a camera, which automatically takes a photograph of the ground below. The balloon's objective is to obtain detailed photographs of the surface. To obtain the highest resolution images, the balloon must track the surface as closely as possible without crashing into it. This poses a challenge to the balloonists: how to tightly control the balloon's position relative to the ground.

Figure 2.11a Setpoint Altitude



Because the balloon drifts slightly up and down due to the effects of wind and temperature, the balloonists must establish some minimum altitude as a safety zone. Let us call this the **Setpoint Altitude**, and let us assume that it is set at an altitude of 100 meters.[1]

When the terrain is flat, the problem is simplified. The balloonists need only ensure a constant supply of gas is supplied to the balloon's burners to keep the balloon aloft. As the terrain becomes hilly, the task becomes more complex. If the terrain rises, the balloonists must respond by firing the burners to lift the balloon. As the balloon clears the hill and terrain drops away, the balloonists must turn the burners off to reduce height and continue tracking the terrain. The type and intensity of the balloonists' responses to terrain can be modeled in terms of three types of feedback: proportional, integral and LookAhead™.

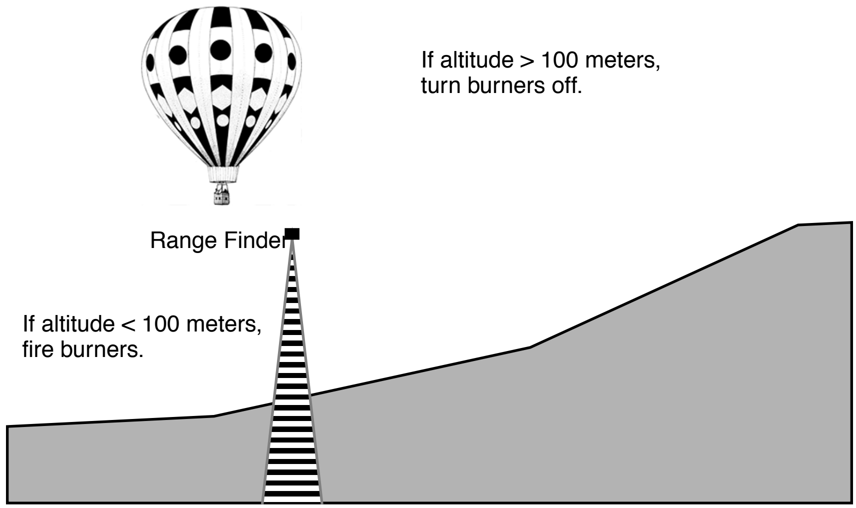
2.11.2 Proportional Gain

Proportional gain means that something is done proportionally in response to something else. In the case of our first balloonist, Peter, this means producing hot air in proportion to the balloon's altitude above the terrain. Where the terrain rises sharply, Peter uses large amounts of gas to lift the balloon; where the terrain is relatively flat, Peter supplies a small, steady amount of gas to maintain the **Setpoint Altitude** above the surface.

A simple feedback loop emerges in this analogy: let us say Peter uses a range finder every 30 seconds to determine the distance between the balloon and ground. If the balloon is below its **Setpoint Altitude**, he fires the burners. If the balloon is above its **Setpoint Altitude**, he turns off the burners to lower the balloon. The higher the proportional gain, the more Peter reacts to changes in altitude. For example, at a proportional gain of 1, if the balloon is 25 meters too low, he opens his valve at 10 liters per second; if the balloon is 50 meters too low, he opens his valve at 20 liters per second. The **Proportional Gain** value serves as a multiplier such that at a **Proportional Gain** of 2, the gas flow rates are doubled from a **Proportional Gain** of 1, and so on. Although this sort of feedback gain works well for simple, linear models, it does not function as well for nonlinear models. There remains always some residual error which causes the system to approach, but not quite reach, the target state.

1. For the sake of simplicity, **Setpoint** in this analogy applies to the balloon's altitude; however, **Setpoint** in SPM is applied to tip-sample forces, *not* the tip's height above the surface.

Figure 2.11b Proportional Gain



Assuming that the balloonists want to get as close as possible without crashing, the response will depend upon, among other things, the balloon's speed over the terrain. When the balloon is being carried swiftly, it is necessary to apply feedback earlier to compensate. (That is, they must use more gas earlier.) On the other hand, if there is little or no wind, the balloon may achieve a closer tracking of the terrain. There may also be sufficient knowledge of the terrain to anticipate its rises and falls. In order to compensate for these effects, you may employ **Integral** and **LookAhead Gain** feedbacks. These are discussed next.

2.11.3 Integral Gain

Integral Gain corrects the cumulative error between a system and its target state. In the case of the balloon, it is not enough to use only **Proportional Gain**. The balloon maintains a constant error around the **Setpoint Altitude** if it relies on **Proportional Gain** alone. It is also necessary to consider whether the total error between the balloon's actual altitude and its **Setpoint Altitude** is increasing or decreasing over some interval of time. To correct for cumulative error, our second balloonist, Irene, utilizes integral gain.

Let us assume that Peter announces the balloon's altitude every 30 seconds from his range finder. Irene uses a stopwatch and clipboard to record the amount of error at each measuring interval, averaging the error over a preceding interval of time (e.g., 3 minutes). Irene fires the burners based upon her observations: if she notices that the running average error puts the balloon below the **Setpoint Altitude**, she fires the balloon's burners, if she notices that the average error puts the balloon above the setpoint, she turns the burners off.The effect of **Integral Gain Feedback** is to reduce total error by addressing error over a longer period of time. This tends to smooth out the short-term, fluctuating effects of proportional gain while narrowing the error closer to the setpoint value. If the integral gain is set too high, there is a tendency to overshoot the setpoint. Therefore, **Integral Gain** is highly sensitive and must be used carefully.

2.11.4 LookAhead™ Gain

Finally, the third balloonist, Larry, employs yet another type of gain to ensure optimal tracking over the terrain: **LookAhead Gain**. For our example, Larry uses a map to anticipate the rise and fall of the terrain. When his map indicates a mountain, he opens his valve to fire the burners and lift the balloon. When a valley is indicated on the map, he turns his burner off to lower the balloon. The effect of **LookAhead Gain** is to keep the balloon within the proper altitude zone so that proportional and integral gains will perform better by maintaining the balloon closer to its proper **Setpoint Altitude**. When the terrain is comprised of regular rises and falls, the **LookAhead** balloonist is at his best, easily anticipating rises and falls. In these instances, you can maximize **LookAhead Gain**. Conversely, when the terrain is rough and broken, the **LookAhead** balloonist must struggle with the balloon's sluggish response to anticipate every irregular rise and fall, and may actually make control of the balloon more difficult. In these instances, **LookAhead Gain** should be minimized or turned off.

2.11.5 Completing the Analogy—Feedback Gains in SPM

Feedback Gains used to control an SPM's probe tip are not far removed from those controlling a hot air balloon. In the case of a probe tip, the objective is quite similar. The operator assigns a setpoint value corresponding to a certain amount of tip-sample force, then adjusts gains to track the surface as closely as possible while maintaining the setpoint. Instead of gas-fired burners, however, the Z-axis piezo crystal uses voltage to retract and lower the probe. In addition, such parameters as **Scan Rate** must be figured in. Just as a balloonist would find it difficult to closely track rough terrain in a fast-moving balloon, the microscopist must frequently adjust **Scan Rate** and setpoint to track samples successfully.

2.11.6 Setpoint

In our ballooning example, setpoint referred to the target altitude to be maintained. In scanning probe microscopy, setpoint refers to how much tip-sample force is maintained. There are two ways of defining setpoint, depending upon whether one is referring to contact AFM or TappingMode. In contact AFM, the amount of cantilever flexion determines the setpoint—as the setpoint increases, the cantilever flexes more and tip-sample forces increase. In TappingMode, the RMS amplitude of the oscillating tip determines the setpoint—as setpoint decreases, RMS amplitude decreases, but tip-sample forces increase[1].

2.11.7 SPM Electronic Feedback Loop

Just as the balloonists in Section 2.11.1 want to get close to the ground without crashing into it, the SPM tightly controls the tip's position relative to the sample surface. In the case of contact AFM, this means applying a very light force to the tip—just enough to trace surface features, but not so much force that the tip is broken off or the surface damaged. In the case of TappingMode, it holds the tapping force (measured in terms of the oscillating probe's amplitude) to the setpoint level.

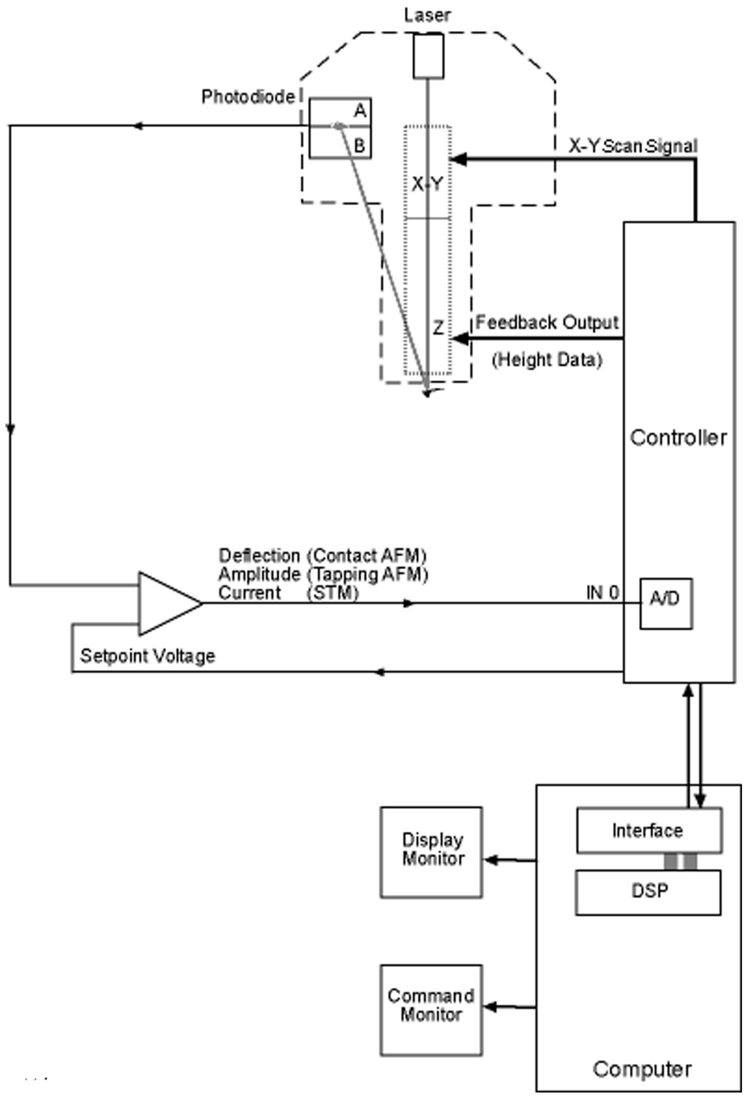
2.11.8 Data Type of Image

SPM technology has rapidly grown beyond its scanning tunneling roots to encompass numerous types of microscopy. This includes: ECSTM, contact AFM, ECAFM, TappingMode in air, TappingMode in fluids, amplitude and phase magnetic force microscopy (MFM), surface potential and field gradient electric force microscopy (EFM), lateral force microscopy (LFM), force modulation imaging, scanning capacitance microscopy (SCM), thermal imaging, and force volume imaging. In addition, there are numerous variations and combinations of the above; new types of SPM are added continually as the field expands. Each of these variations reveals something unique by using a feedback system to process and extract signals in slightly different ways.

1. At first glance, this may seem counterintuitive. However, recall that an oscillating tip in TappingMode attains its fullest amplitude when it is in free air and not interacting with a sample. As the oscillating tip is brought against the sample, its RMS amplitude decreases due to damping effects. The harder the tip is pressed into the sample, the more RMS oscillation is reduced. Thus, requesting a setpoint of 0.00 in TappingMode commands the system to press the tip against the sample so hard that the cantilever cannot oscillate at all. In TappingMode, reducing setpoint increases tip-sample forces, which is the opposite of contact AFM.

The NanoScope system allows three simultaneous image channels, plus auxiliary channels. Each of the three image **Channel** control panels contains a **Data Type** parameter, specifying the type of image shown on that channel. The **Data Type** is determined by the currently selected microscope (**Real-time/ Microscope / Select**) and AFM mode shown on the **Other Controls** panel. For example, although **Height** data can be displayed for most types of imagery, only TappingMode displays **Amplitude** data. And only contact AFM displays **Deflection** data.

Figure 2.11c Dimension Feedback Loop Block Diagram



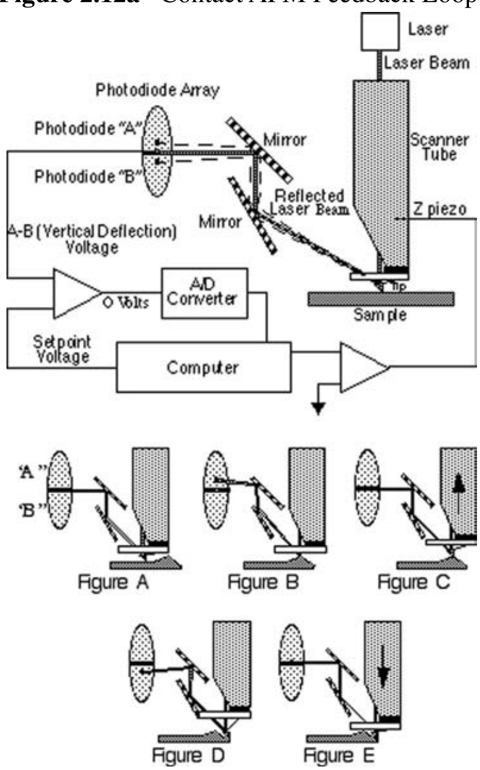
2.12 Contact AFM Operation

2.12.1 General Operating Concepts

The AFM system has two main components: the scanner and the AFM detection system. The scanner houses the piezoelectric transducer. The piezo element physically moves the sample in the X, Y and Z direction. The detection system consists of a laser, which generates a spot of light that is reflected off of a microfabricated cantilever onto a mirror and finally into a pair of photodiodes (See Figure 2.12a). Circuitry determines the position of the spot which generates a voltage from the difference between the two photodiodes (A-B). The circuit outputs a voltage ranging from +10V to -10V depending on the position of the spot on the two photodiodes.

The AFM system maintains the tip at the end of the cantilever in contact with the sample surface. The sample is scanned under the tip in X and Y. Features on the sample surface deflect the cantilever, which in turn change the position of the laser spot on the photodiodes. The feedback loop reads this position change. The feedback loop moves the sample in Z to restore the spot to its original position. Refer to Figure 2.12a.

Figure 2.12a Contact AFM Feedback Loop



2.12.2 Contact AFM Concept

(Figures A—E explained, Figure 2.12a)

a. The tip scans a flat portion of the sample surface left-to-right, maintaining the laser beam at the center of the photodiode array.

b. As the tip encounters a raised feature, the cantilever is pushed up, deflecting the laser beam upward onto the A portion of the array. With the A photodiode receiving an increased portion of the laser light, its voltage increases while portion B's decreases (A > B).

c. The feedback electronics detect Vertical Deflection (A-B) voltage differential, causing a dropped voltage to the Z piezo crystal—the piezo retracts. As the Z piezo retracts, the cantilever re-centers the laser beam onto the photodiode array (A = B).

d. As the tip encounters a decline in the sample topology, the tip drops. This directs more of the beam onto the B portion of the photodiode array. With the B photodiode receiving an increased portion of the laser light, its voltage increases while portion A's decreases (A < B).

e. The feedback electronics sense the Vertical Deflection (A-B) voltage differential, increasing voltage to the Z piezo crystal—the piezo extends. As the Z piezo extends, the tip is pushed down until the laser beam re-centers on the photodiode array (A = B).

The AFM always first engages in the repulsive region of its operating range. The cantilever needs to exert a positive pressure on the sample surface. The AFM block diagram shows the relationship between the cantilever movement and the laser spot on the photodiode array.

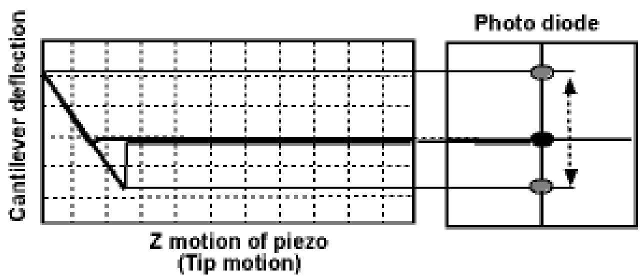
The diagram shows that the spot moves up (more on A) when the cantilever is pushed up. The initial setup is to have the Vertical Deflection (A-B) voltage about 2-3 volts more negative than the setpoint voltage. Veeco recommends starting with the setpoint voltage set to 2 volts and the Vertical Deflection (A-B) set to 0 volts. 0 volts is the middle of the control range. The indication of a good engagement is a jump of approximately 1V from the Vertical Deflection (A-B) voltage to the setpoint voltage.

2.13 Force Calibration Curves

2.13.1 Overview

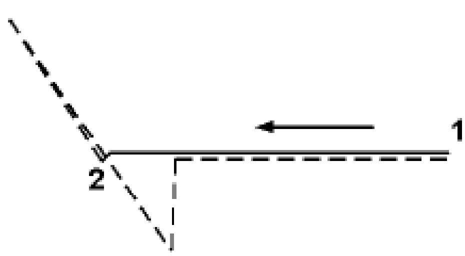
During scanning, the feedback loop tries to make the photodiode voltage equal to the setpoint voltage. The initial setpoint voltage is typically greater than the photodiode voltage. Changing the relationship between the two voltages indirectly causes the feedback loop to change the tip's tracking force. During feedback as the system scans the sample, it may be necessary to change the setpoint voltage to change the tracking force. A graph called the force calibration curve plots the deflection of the cantilever (A-B signal) versus the tip/sample separation. This is a typical example of a force curve plot. The voltage produced by the photo diode assembly can be compared to the force curve data (See Figure 2.13a).

Figure 2.13a Force Curve Plot

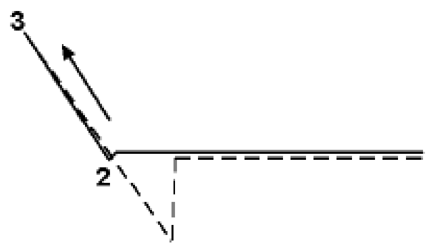


The force curve plot is read as a cycle of the tip's motion toward the away from the sample surface. To better understand the meaning of the plot, each segment of the cycle is described in the following paragraphs.

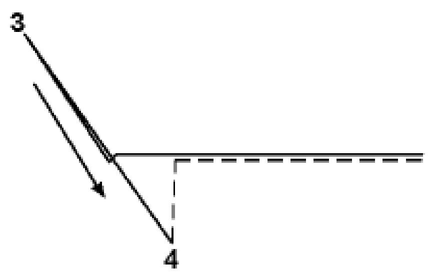
Segment 1 to 2 shows the tip moving toward the sample. The small downward dip at the end of the segment represents the tip being pulled to the surface when the adsorbed fluid layers on the tip and the sample combine.



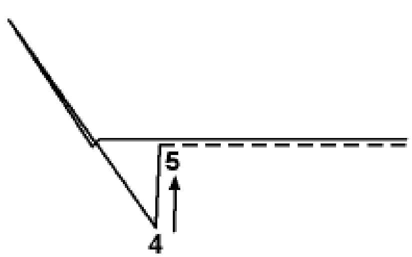
Segment 2 to 3 shows the cantilever bending up as the tip is pushed into the sample surface.



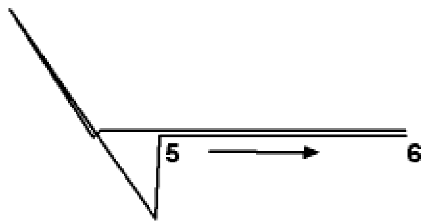
Segment 3 to 4 shows the cantilever moving down as the tip is pulled away from the surface. Note that the cantilever bends down further than it the level between segments 1-2. This is due to the adhesion between the tip and the sample being stronger than the spring tension of the cantilever.



Segment 4 to 5 shows the point where the tip detaches from the sample surface. As the tip is being pulled away from the surface, the negative stress in the cantilever overcomes the adhesion between the tip and the sample. The cantilever immediately pulls free from the sample. Position 4 on the plot is the point where the pulling force of the cantilever is in balance with the adhesion between the tip and the sample. This is the point we define as having zero force between the tip and the sample.



Segment 5 to 6 shows the cantilever position has returned as the tip is no longer influenced by the sample.



2.13.2 Main controls

There are four main software controls used to position the tip motion and to change the deflection data on the plot.

Ramp Size – Ramp size controls the amount of tip travel. The typical range is 500nm – 1μm.

Scan Start – Scan start controls the position where the tip pulls away from the sample. The scan start acts as an offset control to the Ramp size control. Making small positive incremental adjustments to the scan start lowers the tip to the surface.

Ramp rate – Ramp rate controls the frequency of the tip motion away and toward the sample. The typical setting is 2-5Hz.

Deflection Setpoint – Deflection Setpoint controls the vertical position of the force curve data. Changing the Deflection Setpoint voltage establishes a different tracking force when you return to scanning on the surface.

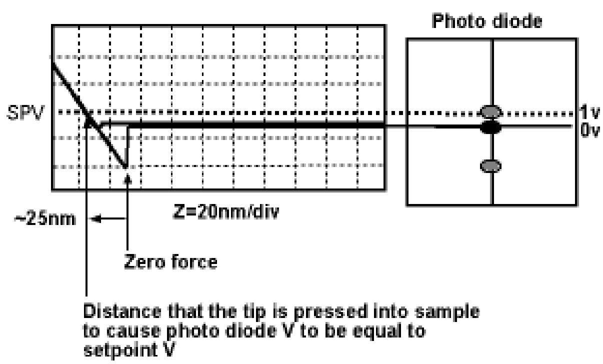
2.13.3 Using the controls to get a force curve

1. Engage the AFM in contact mode.
2. Enter the force calibration software routine by selecting View-force mode-calibrate
3. Press the Setpoint zero button to center the force curve data on the graph.
4. Set the Ramp Size to at least 500nm
5. Use the right arrow key to increase the Scan Start. Make the adjustment until the force curve data appears centered on the graph
6. Adjust the Deflection Setpoint voltage until the desired force is achieved.

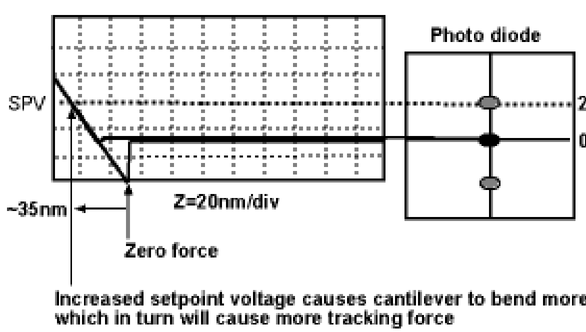
2.13.4 Determining the tip force

Raising the setpoint voltage relative to the photodiode voltage indirectly causes more force. Knowing how much force is applied to the sample is determined by using the force calibration curve. Measuring the distance between the point on the graph where the tip is at zero force and where the set point voltage crosses over the deflection voltage indicates how much the cantilever is bent during feedback. Using hooks law, (F=K*X) the basic tip tracking force is determined by multiplying the spring constant of the cantilever (K) by the distance the tip is pressed into the sample (X).

Below is an example of how to measure and change the tracking force



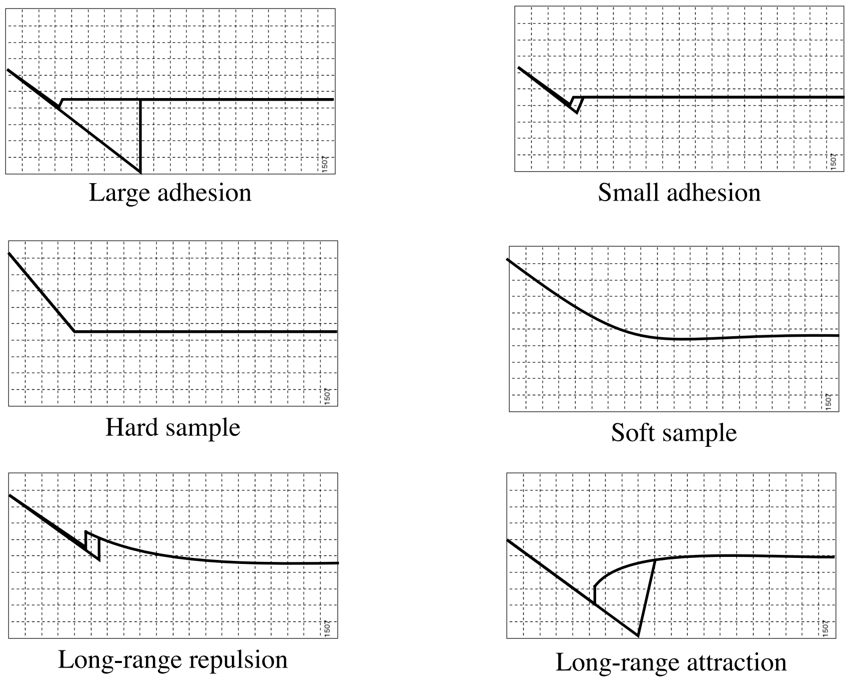
Increase the Deflection Setpoint voltage to the desired tracking force



2.13.5 Other uses of the force curve

An examination of force curves can prove useful in determining adhesion and hardness characteristics of samples. The examples in Figure 2.13b represent some of the general variations in force curves.

Figure 2.13b Force Curve Examples



2.14 TappingMode AFM Operation

2.14.1 General Operating Concepts

One advantage of TappingMode AFM is an absence of lateral forces which exert torque on the cantilever. Unlike traditional contact AFM, the feedback loop keeps a vibrating cantilever at a constant amplitude. (Rather than keeping a cantilever at a constant deflection.)

The tip on the cantilever is modulated through mechanical excitation at its resonance. A laser beam reflects off of a microfabricated cantilever, onto a mirror, then reflects onto a photodiode array. The laser spot oscillates vertically across the array as a result of the vibrating cantilever. The signal from the photodiodes rectifies, then passes through a lowpass filter into a DC voltage (RMS Ampl.). The magnitude of RMS amplitude is proportional to the amount of cantilever motion.

The feedback system compares the RMS amplitude to the setpoint voltage. Controlling the amount of cantilever movement keeps two voltages equal. The sample surface is in close proximity to the cantilever. The distance assures that the tip touches the surface only at the lowest point of its oscillation.

The feedback loop moving the tip into the sample reduces the RMS voltage to the setpoint voltage. The sample restricts the cantilever movement until the desired RMS voltage is reached. The damping of the cantilever is held constant by moving the tip in Z as it is simultaneously translated in X and Y.

The engagement of TappingMode AFM requires that the setpoint voltage be smaller than the RMS voltage. The tip is lowered until the RMS reaches the setpoint.

Figure 2.14a shows the relationship between the RMS and the setpoint voltage during the engage cycle. The computer determines the initial setpoint voltage, rather than the user.

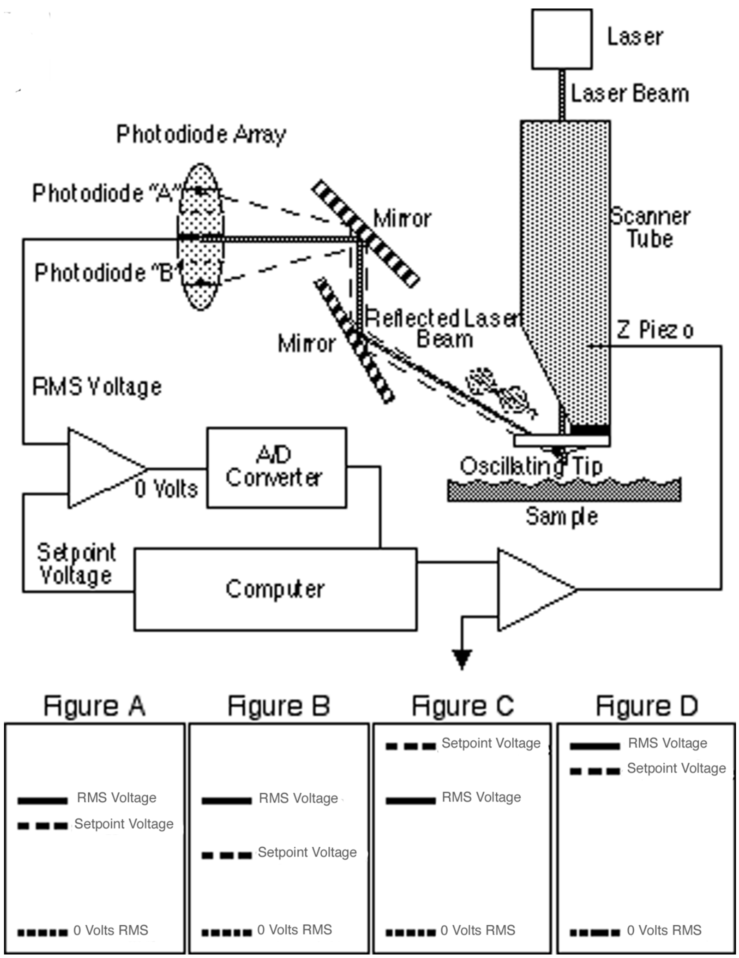
The computer sets the setpoint equal to 90 percent of the RMS amplitude. The tip is then lowered until the RMS matches the setpoint. The computer then tests for true engagement as follows:

1. The motor halts the tip’s descent.
2. The setpoint lowers slightly (2% typically).
3. The feedback control monitors movement of the Z piezo.

Depending upon the tip's relationship to the sample, one of these two conditions result:

- **A small Z piezo movement**. This indicates that the cantilever is engaged with the sample surface.
- **A large Z piezo movement**. This indicates that the cantilever is damped by air trapped between the cantilever and sample surface (not in contact with the actual, solid surface)—this is a false engagement condition. The setpoint is readjusted and the engage cycle repeated until the computer reads a small change in Z when the setpoint voltage is lowered further. One symptom that this condition is occurring is when the "tip travel μm" display stops momentarily, then starts again.

Figure 2.14a TappingMode AFM Concepts



Figures A through D illustrate the relationship between the RMS and the setpoint voltages. There are some basic rules to remember:

- The setpoint voltage is always lower than the RMS voltage (Figure A).
- The difference between the RMS voltage when the tip is off the surface and the setpoint voltage dictates the amount of damping or "tapping force." The larger the difference, the greater the tapping force (Figures A and B).
- The RMS voltage controls the amount of energy that is in the cantilever (Figures A and D). This is important to note because some samples are stickier than others. The tip may stick and hold to the sample surface if the RMS amplitude is too small. Increasing the RMS amplitude and the Setpoint voltage may relieve this problem.

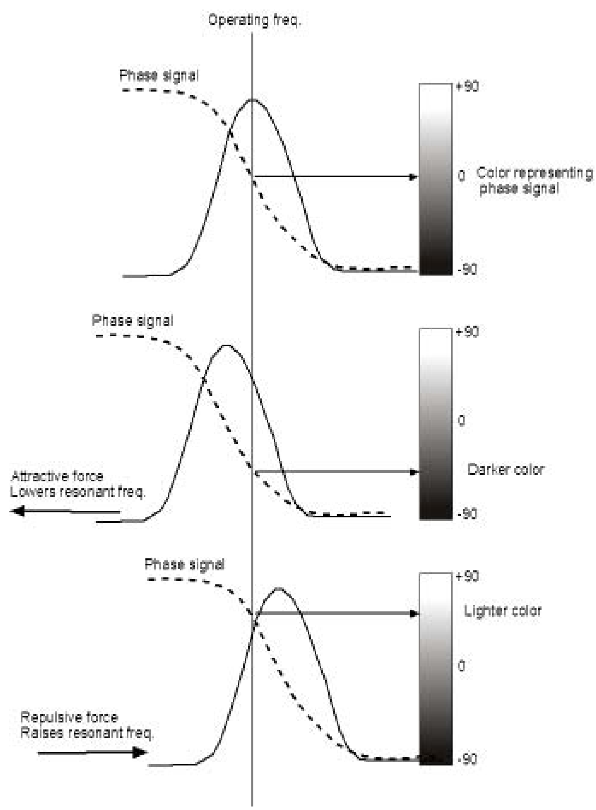
2.15 The Phase Signal

The phase signal refers to the timing of the mechanical vibration of the cantilever relative to the movement of the cantilever substrate. The phase of the AC waveform from the photo diode assembly is compared to the drive signal applied to the tapping piezo on the cantilever holder.

Monitoring the phase of the cantilevers vibration allows the microscope to record mechanical as well as electrical changes on the sample during scanning. In some experiments that are performed, (EFM or MFM) a specialized tip that is coated with a conductive or a magnetic material causes an attractive or a repulsive force to exist between the tip and the sample. The force causes the resonant frequency to change, which in turn causes the phase of the cantilever vibration to change.

Attractive forces on the cantilever lower the resonant frequency. Repulsive forces on the cantilever raise the resonant frequency.

The illustration below shows how the color scale represents the change in the phase signal.



2.16 Real-time Plane Fit Filters

2.16.1 Real-time Planefit

Real-time **Planefit** applies a software leveling plane to each Real-time image. This removes first-order tilt. Five types of planefit are available to each Real-time image shown on the display monitor.

Note: This function does not apply to captured data, but is offered only to improve the user's Real-time image.

Range or Settings

- **None**— Only raw, unprocessed data displays.
- **Offset**— Takes the Z-axis average of each scan line, then subtracts it from every data point in that scan line.
- **Line**— Takes the slope and Z-axis average of each scan line and subtracts it from each data point in that scan line. **This is the default mode of operation; use it unless there is a specific reason to do otherwise.**
- **AC**— Takes the slope and Z-axis average of each scan line across one-half of that line, then subtracts it from each data point in that scan line.
- **Frame**— The entire Real-time image is leveled based on a best-fit plane calculated from the most recent Real-time frame performed with the same frame direction (up or down).
- **Captured**— The entire Real-time image is leveled based on a best fit plane calculated from a plane captured with the **Capture Plane** command in the **Real-time/ Capture** menu. This selection will not appear until a valid plane is captured.

Note: The **Real-time Planefit** is applied only to display data at the time of the scan and does not apply to captured data. To planefit captured data, use the **Off-line Planefit** parameter.

2.16.2 Off-line Planefit

Off-line planefit applies a software "leveling plane" to each off-line image for removing first-order tilt. Five types of planefit are available to each off-line image.

Range or Settings

- **None**— Only raw, unprocessed data is displays.
- **Offset**— Captured images have a DC offset removed from them, but they are not fitted to a plane.
- **Full**— A best-fit plane which is derived from the data file is subtracted from the captured image. **This is the default mode of operation. Use it unless there is a specific reason to do otherwise.**
- **Captured**— Captured images have a best-fit plane which is calculated from an image previously collected with the Real-time **Capture / Capture Plane** command subtracted from them.

The **None** option should only be used in special cases. The **Offset** and **Full** options provide greater dynamic range in the data to reduce round-off and other errors in subsequent calculations.

Use the **Off-line / Modify / Flatten** and **Planefit** commands to level the data after it has been captured.The **Captured** option does not appear in the control panel until you use the **Capture Plane** command to collect a plane.

2.17 Captured Data Filters

There are a wide range of modification functions found in the **Modify** menu that you may apply to an image after capture. The *Command Reference Manual explains* these functions in detail.

When using any modification functions, you change the data which may affect the measurements of interest. Modify the image as little as possible, and understand how the applied function affects the image and measurements.

2.17.1 Flatten

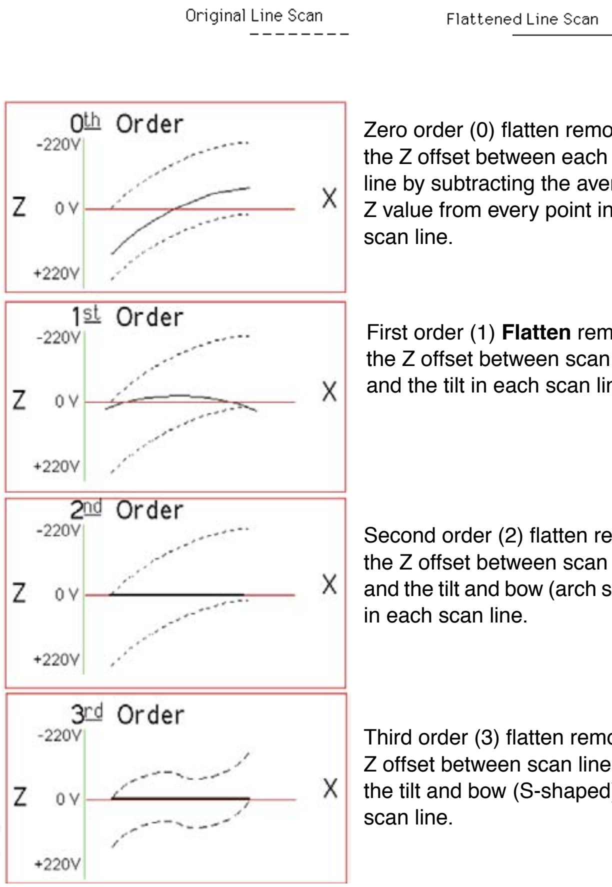
Flatten allows the user to remove image artifacts due to vertical (Z) scanner drift, image bow, skips and anything resulting in a vertical offset between scan lines.

Flattening modifies the image on a line-by-line basis. It consists of removing the vertical offset between scan lines in the fast scan direction (X at 0° scan angle) by calculating a least-squares fit polynomial for a scan line, and subtracting the polynomial fit from the original scan line.

This makes the average Z value of each scan line equal to 0V out of the +/-220V Z-range.

Flattening is performed by applying a 0th, 1st, 2nd, or 3rd order polynomial fit to each scan line. Figure 2.17a is a schematic showing the effects of flattening order on two scan lines in X acquired at different locations in Y in the image.

Figure 2.17a Schematic Showing Effects of Flattening



Zero order (0) flatten removes the Z offset between each scan line by subtracting the average Z value from every point in the scan line.

First order (1) **Flatten** removed the Z offset between scan lines, and the tilt in each scan line.

Second order (2) flatten removes the Z offset between scan lines, and the tilt and bow (arch shaped) in each scan line.

Third order (3) flatten removes the Z offset between scan lines, and the tilt and bow (S-shaped) in each scan line.

Flattening is a powerful filter often used. It is important to understand how flattening can affect subsequent measurement.When removing the vertical offset between each line scan, you remove the information in the Y direction. Applying **Flatten** on very smooth surfaces has a negligible effect on the roughness measurements.

Measuring Feature Heights

To measure feature heights, scan across these features in the fast direction. If you need to perform a **Flatten**, it will not adversely affect your measurements (See Figure 2.17b).

Figure 2.17b Effect of Flattening on Image Measurements

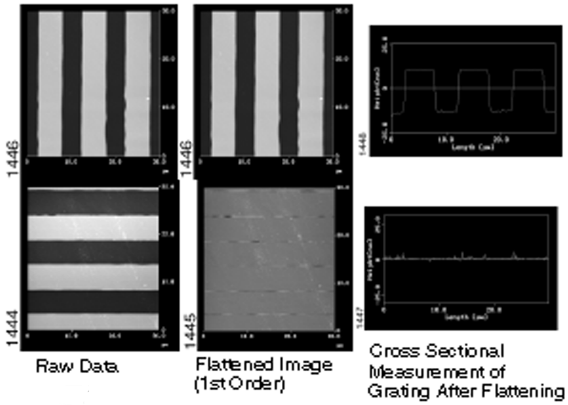


Figure 2.17b displays the structures oriented to be scanned in the fast scan direction (at a 0° scan angle, this is the X scan direction) in order to make accurate cross sectional measurements on the grating after flattening.

If the features of interest are not oriented perpendicular to the fast axis, rotate the scan with the **Scan Angle** parameter, or rotate the sample.

Flattening an image which consists of a flat plane with "bumps" or "pits" on it results in the flat area next to the features (along the X direction) appearing lower with respect to the **Flatten** scan lines without raised or depressed features. Refer to Figure 2.17c which shows cross sections of first order flattened image of cells on a smooth glass substrate, demonstrating how flattening can cause the distortion of the plane next to a raised feature in the fast direction.

Figure 2.17c Cross Sections on First Order Flattened Image of Cells

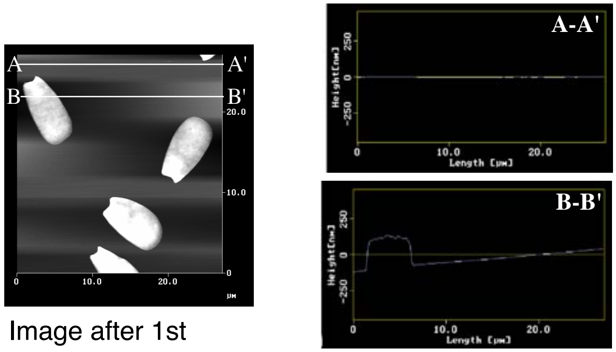
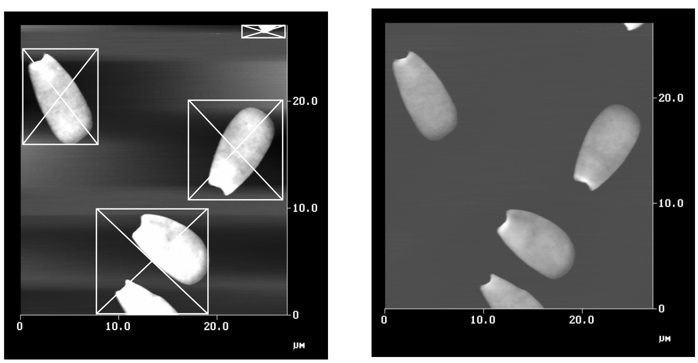


Image after 1st
Order **Flatten**

To remedy this problem, exclude the raised or depressed features from the **Flatten** calculation by drawing boxes around them with the cursor before executing the **Flatten**.

Figure 2.17d Flattening an AFM Image of Cells on a Smooth Glass Substrate



Use Boxes to Exclude
Raised Features from the
Flatten Calculation

Image After 1st Order Flatten

2.17.2 Planefit Auto

We commonly use **Planefit** to remove tilt or bow from images.

Planefit calculates a single polynomial fit for the entire image, then subtracts the polynomial fit from the image.

Planefit is applied by calculating a 1st, 2nd, or 3rd order polynomial fit to the image in the X or Y directions.

- 1st order planefit removes tilt.
- 2nd order planefit removes tilt and an “arch-shaped” bow.
- 3rd order planefit removes tilt and an “S-shaped” bow.

Extreme variations in the sample topography can alter the planefit, leaving a slight tilt in the image.

To remove the tilt select only flat portions of the image to determine the planefit. Perform the calculation using only the chosen areas, and the planefit is extrapolated on to rest of the image.

Draw a box or boxes on the image to choose the areas to be part of the planefit calculation (See Figure 2.17e).

Note: For examples of 2nd and 3rd order bow removal, see Section 2.18.5.

Figure 2.17e First Order Planefit Using Selected Areas on a Smooth Glass

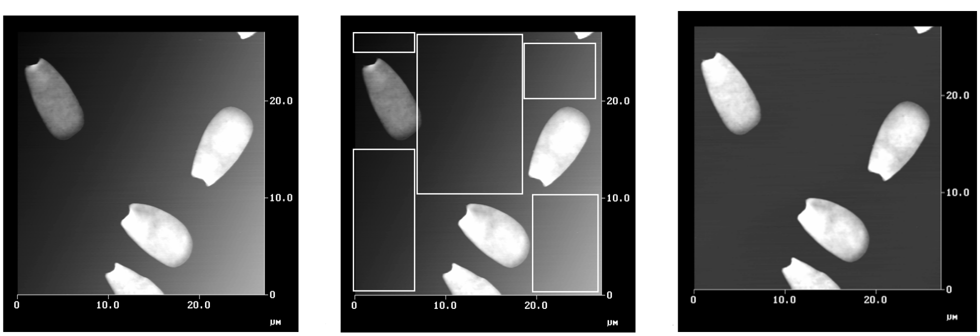


Image before Planefit

Use cursor to select areas to be included in planefit calculation.

Image After 1st Order Planefit in X and Y Using Selected Areas

2.17.3 Resolution Issues

Consider the resolution of AFM images in terms of lateral (X,Y) resolution and vertical (Z) resolution.

Lateral Resolution Issues

1. Tip Shape

As discussed in the previous section on tip shape effects, the radius of curvature of the end of the tip determines the highest lateral resolution obtainable with a specific tip. The sidewall angles of the tip also determines its ability to probe high aspect ratio features.

2. Pixelization - Z Limit Parameter

The **Samples/ Line** parameter in the Real-time menu determines the number of data points present in the image in the X and Y scan direction. These data points are commonly called "pixels." Available choices are 512, 256 and 128.

Pixelization affects resolution in that you cannot resolve features smaller than the pixel size of the image.

For example, if you are acquiring a 50μm x 50μm image with the Samples/ line parameter set to 512, then the pixel size is 98nm (50μm÷512=0.098μm or 98nm). Thus, you cannot resolve features smaller than 98nm at a 50μm scan size.

To see 10nm sized features, choose a scan size <5.12μm (preferably 1 or 2μm) since 5.12μm÷512=0.010μm or 10nm.

Regardless of the pixel size, the feedback loop samples the topography many times at each pixel. The data displayed at each pixel is the average of the sampling iterations by the feedback loop over the pixel area.

Vertical Resolution Issues

1. Scanner

Tip shape does not determine the resolution in the vertical direction; it is primarily determined by the resolution of the vertical scanner movement which is <1Å.

2. Pixelization

As in the lateral dimension, the number of data points in the vertical direction limits the size of the smallest resolvable height change.

The conversion of 16 bits over the full vertical range of the scanner (440V) determines the number of data points in the vertical dimension.

Use the Z-limit parameter to increase the sampling resolution in the vertical dimension to image sub-angstrom height changes with large Z range scanners.

Noise

The overall system noise is the primary limiting factor in the highest obtainable vertical resolution acquirable with your SPM. This may be a result of combined effects from electrical, mechanical and acoustic noise sources.

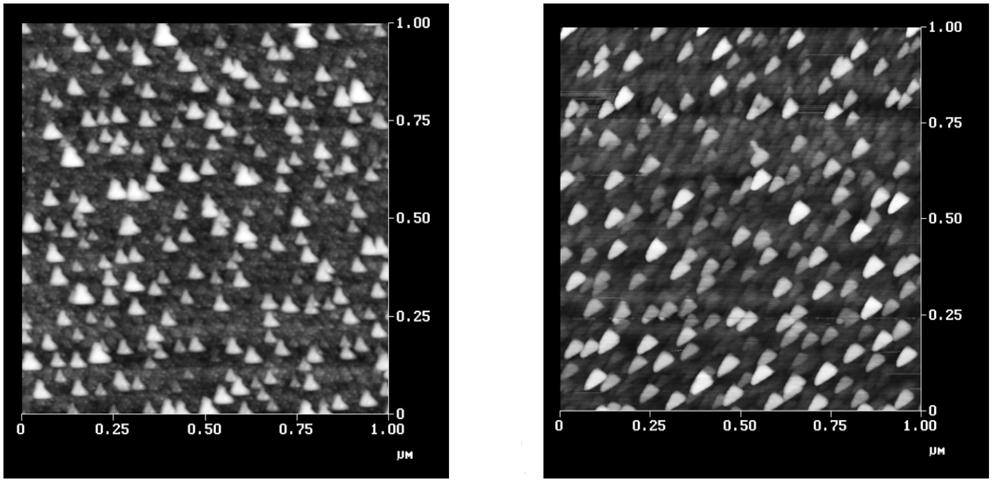
Noise levels of 0.3 to ~1Å RMS are typical depending on the type of SPM and environment.

2.17.4 Examples of Typical Image Artifacts

Dull or Dirty Tip

If the tip becomes worn or if debris attaches itself to the end of the tip, the features in the image may all have the same shape. A dull or dirty tip images the worn shape of the tip or the shape of the debris, not the morphology of the surface features.

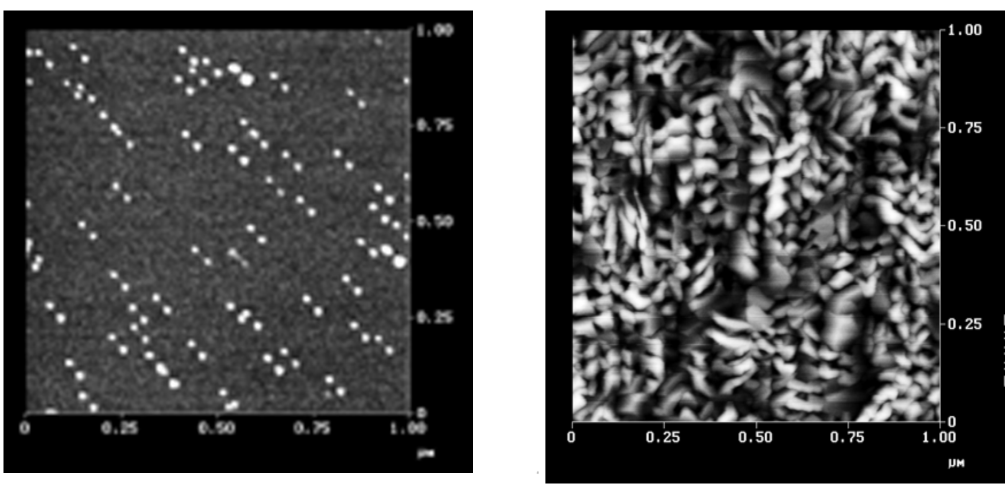
Figure 2.17f Dull or Dirty Tip



Double or Multiple Tip

Double or multiple tip images form when a tip with two or more end points contacts the sample while imaging.

Figure 2.17g Double or Multiple Tip



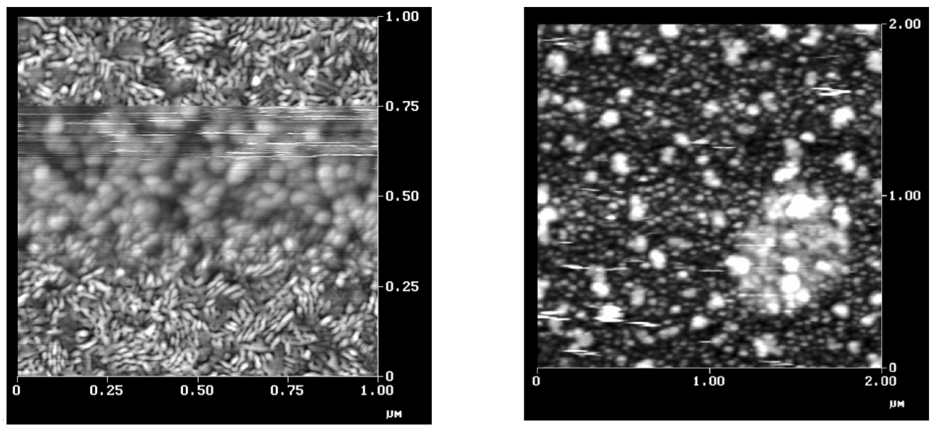
Contamination from Sample Surface

Loose debris on the sample surface can cause loss of image resolution and can produce streaking in the image (See Figure 2.17h). The image on the left shows loss of resolution caused by build up of contamination on the tip when scanning from bottom-to-top. The small elongated features become represented as larger, rounded features until the debris detaches from the tip near the top of the scan. The image on the right shows skips and streaking caused by loose debris on the sample surface.

A few scans sweep loose debris out of the image, making it possible to acquire a relatively clean image.

The **Erase Scan Lines** function removes Skips from a captured image.

Figure 2.17h Contamination from Sample Surface



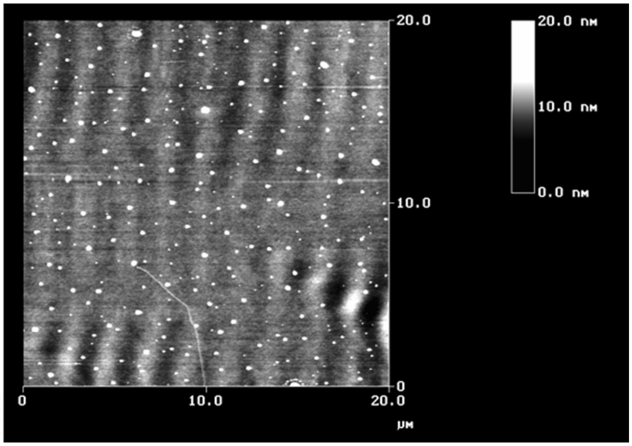
Optical Interference

Interference between the incident and reflected light from the sample surface can produce a sinusoidal pattern on the image with a period typically ranging between 1.5-2.5μm (See Figure 2.17i).

This artifact often appears in Contact Mode on highly reflective surfaces, and occasionally appears in TappingMode.

Attempt correction by adjusting the laser alignment, so that more light reflects off the back of the cantilever and less off the sample surface.

Figure 2.17i Optical Interference



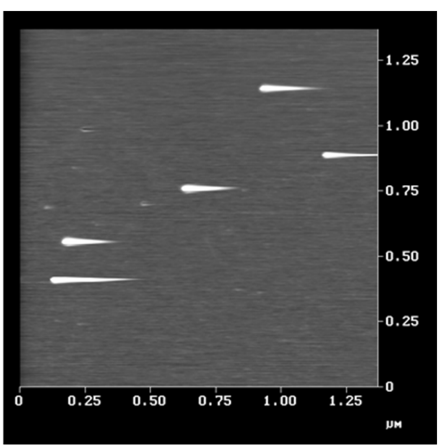
Not Tracking

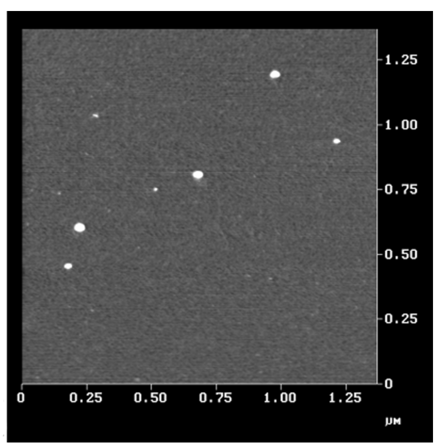
Adjust feedback parameters properly, or the tip will not trace down the back side of the features in TappingMode (See Figure 2.17j).

The image on the left was scanned from left-to-right (trace) producing "tails" on the colloidal gold spheres.

The image on the right is the same area imaged with a lower setpoint voltage, increased gains, and slower **Scan Rate**.

Figure 2.17j Not Tracking



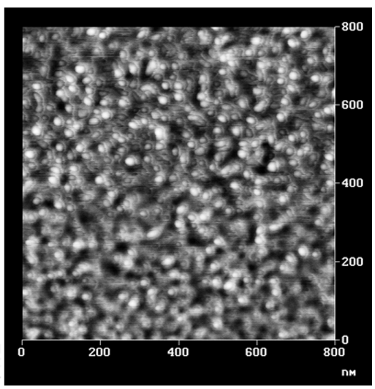


Rings During High Frequency Operation

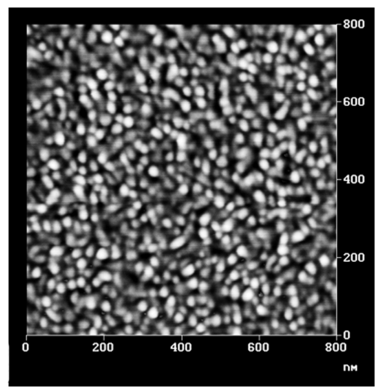
In TappingMode, when operating on the high frequency side of the resonance peak, rings may appear around raised features, making them appear as if surrounded by water (See Figure 2.17k). The image of the Ti grains on the left is an example. Decreasing the **Drive Frequency** during imaging eliminates this artifact, as shown on the right.

Note: When reducing the **Drive Frequency**, reduce the setpoint voltage as well, if necessary. Set the **Peak Offset** parameter in the **Cantilever Tune** controls to 5 percent to automatically lower the **Drive Frequency** as part of the SPM initial setup.

Figure 2.17k Rings During High Frequency Operation



Example of Rings Around Raised Features in High Frequency Operation

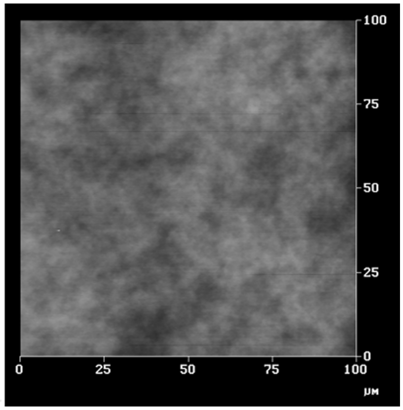


After Reducing Drive Frequency

Second Order Bow

The arch shaped bow in the scanner becomes visible at large scan sizes (See Figure 2.17l). Perform a **2nd Order Planefit** in X and Y (right) to remove the bow in the left image. (Data Scale = 30 nm.)

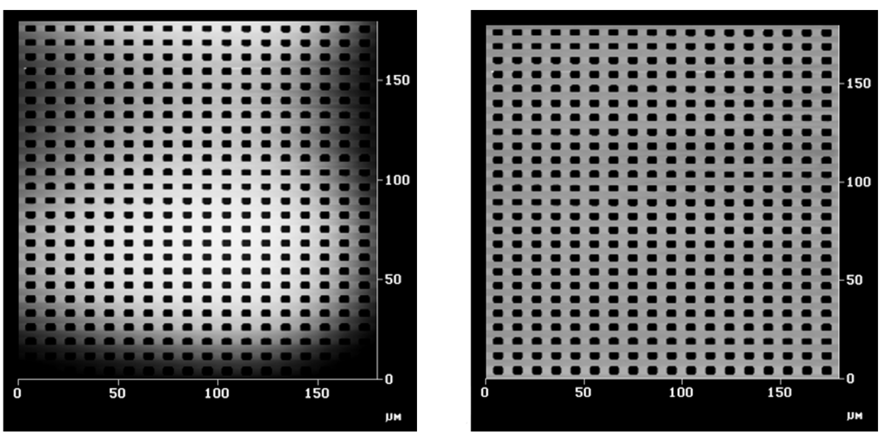
Figure 2.17l Second Order Bow



Third Order Bow

At large scan sizes, the bow in the scanner may take on an S-shaped appearance (See Figure 2.17m). Perform a **3rd Order Planefit** in X and Y (right) to remove The bow in the left image.
(Data Scale = 324 nm.)

Figure 2.17m Third Order Bow



Chapter 3 Dimension AFM System

3.1 Introduction

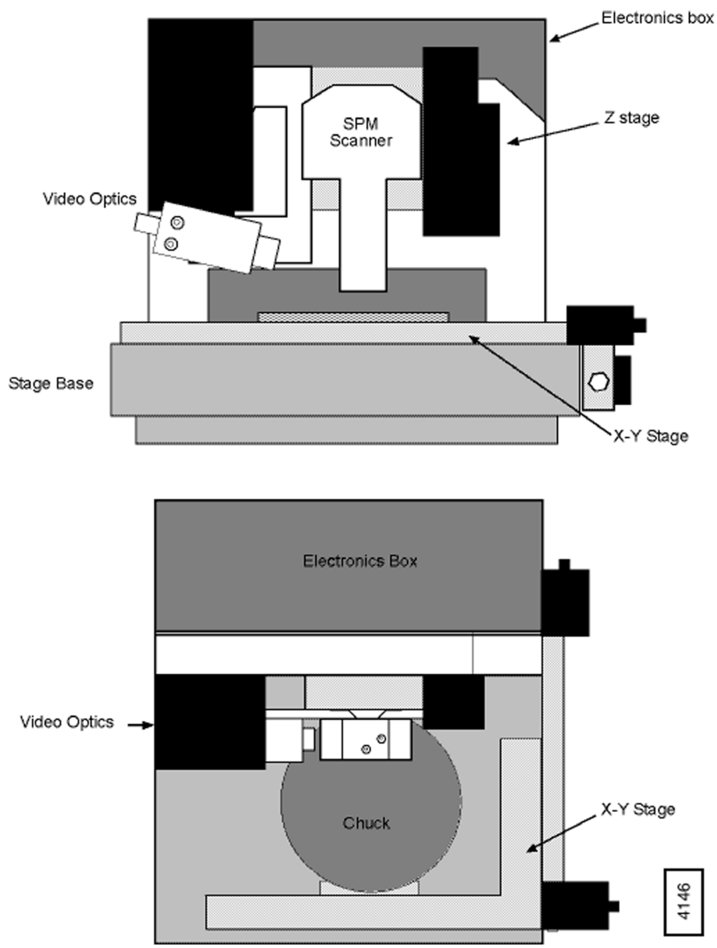
This chapter addresses the following topics:

The Dimension model series of Scanning Probe Microscope (SPM) systems have motorized stages that allow scanning of samples up to six inches in diameter and one-half inch in thickness. The detector and piezo scanner are contained in a single piece that is fixed over the sample. The microscope system can operate in all the scanning modes with the benefit of large sample handling. The limit to this type of system is its mechanical rigidity. They are more susceptible to external vibration and acoustic noise.

3.2 System Components

The main components of the Dimension model series of SPM systems are the stage base, X-Y stage assembly, Z stage assembly, video optics system, SPM electronics box and the Dimension SPM scanner (See Figure 3.2a).

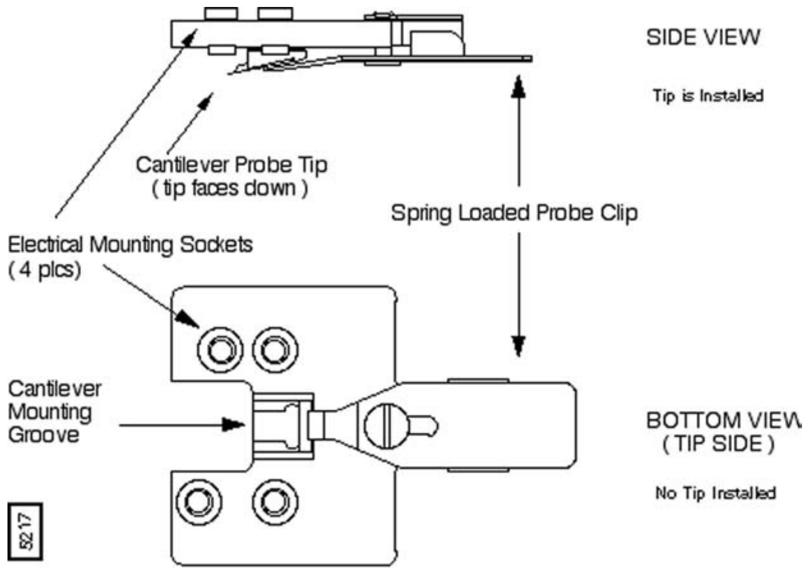
Figure 3.2a Dimension 3100 Overview



3.3 Probe Installation

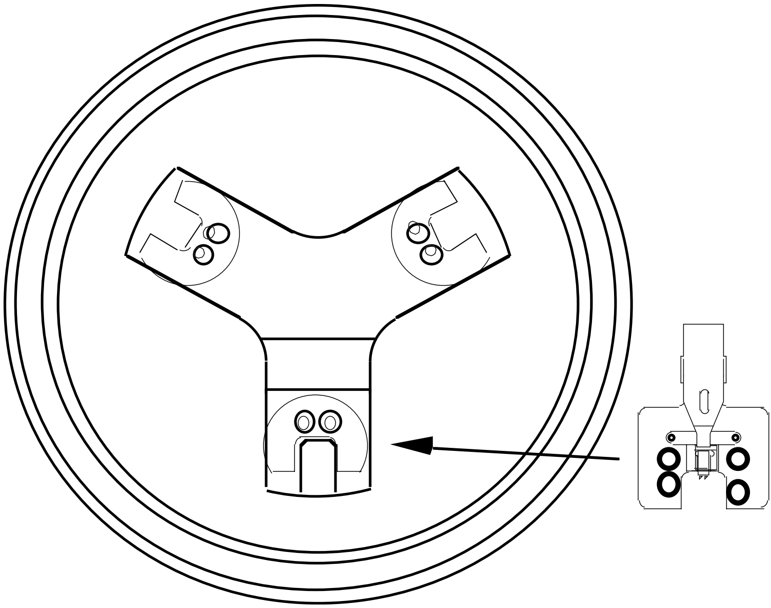
The cantilever holder for the Dimension scanner has a spring loaded clip that holds the probe by clamping on to the probe's substrate. The holder contains sockets that allow electrical signals to be applied to the tip as well as provide connection to the tapping piezo element.

Figure 3.3a Standard AFM Tip Holder



Due to the physical size of the cantilever holder, we provide a fixture that holds the cantilever holder while the probe is being installed. The fixture is a metal block with gold pins pointing up. There are three positions on the fixture that will hold the cantilever holder. The position that has the raised ledge in between the pins is the most commonly used for the standard cantilever holder.

Figure 3.3b View of Cantilever Installation Fixture



Install an AFM probe into the holder by:

1. Attach the cantilever holder to the fixture by aligning the sockets on the holder to the pins on the fixture.

2. Carefully push the end of the cantilever holder spring clip down. The opposite end of the spring clip will tilt up.

3. Pick up a new AFM probe by the edge of the substrate with tweezers.

4. Gently slide the probe substrate under the spring clip.

5. Release the spring clip and allow the cantilever substrate to be captured.

6. Gently push the cantilever substrate back until it hits the back of the groove. The spring clip will allow the substrate to slide while still providing good clamping force.

7. Remove the cantilever holder from the fixture after the probe is installed.

8. Attach the cantilever holder to the end of the Dimension scanner alignment pins.

3.4 Dimension Laser Alignment

3.4.1 Overview

The optical detection system inside the Dimension scanner begins with a solid state laser diode that sends a focused spot of light down the center of the piezo tube. The spot is positioned to reflect off of the back of the SPM cantilever. The reflected light from the cantilever enters the left side of the scanner body where it reflects off of a mirror and onto the photodiode assembly (See Figure 3.4a).

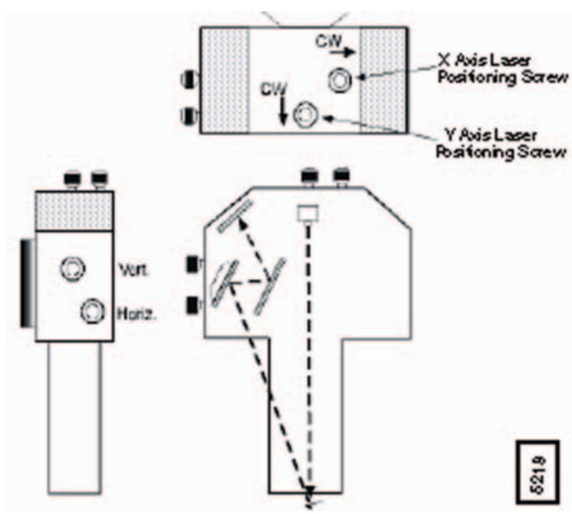
There are four knobs on the Dimension scanner. The knobs located on the top of the scanner move the laser diode assembly. The knobs on the left side of the scanner body move the mirror that redirects the light to the photodiode assembly.

Align the laser spot in the detector system as follows:

1. Align the laser so that it reflects off of the back of the cantilever.

2. Adjust reflected light onto the photodiode assembly.

Figure 3.4a Dimension Scanner



3.4.2 Align the Laser Spot on the Cantilever

1. Hold the Dimension scanner in your hand while pointing the scanner down toward the stage.
   - You will see the laser beam on the stage if the SPM probe does not obstruct it.

2. While looking at the unobstructed laser spot on the stage, prepare to make adjustments to the laser positioning screws as follows:

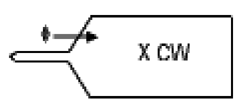
   a. Load a new probe in the holder and attach it to the end of the scanner.
      - Note the orientation of the cantilever with respect to the scanner as viewed from above. The cantilever substrate is on the right and the cantilever points toward the left.

   b. Hold the scanner in your hand while is connected to the stage electronics box.

   c. Point the scanner down at a small piece of paper laying on the stage. You will see an oval red spot. This is the laser spot coming from the diode assembly.

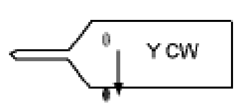
3. Move the laser spot toward the cantilever substrate by turning the laser positioning screw that moves the laser in the X direction. Move the knob clockwise until the spot disappears.

Figure 3.4b Laser Off of Substrate



4. Move the Y axis laser positioning screw clockwise until the light reappears.

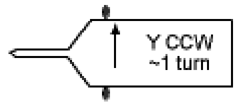
Figure 3.4c Laser on Front Edge of Substrate



5. Move the Y axis laser screw counter-clockwise. The light disappears. Continue turning the screw until the light reappears.

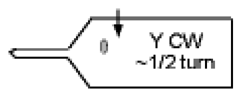
- Note the amount of motion that was required to do this. The screw should have turned about 1 revolution. You can repeat Step 4 and Step 5 to confirm the motion of the screw.

Figure 3.4d Laser Moved to Rear of Substrate



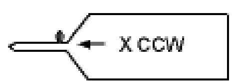
6. Position the laser spot in the center of the substrate by moving the Y axis screw half the distance that it was moved during Step 5.

Figure 3.4e Laser Centered on Substrate



7. Slowly turn the X axis laser screw counter-clockwise until the laser light appears. This moves the light toward the cantilever.

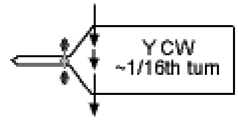
Figure 3.4f Laser Moved Toward Cantilever



8. Slowly turn the Y axis screw clockwise.

   - You might notice that the light briefly disappears and then reappears. If this happens, you just moved the spot across the cantilever.
   - If you do not see the interruption of the laser spot within one turn of clockwise motion, try turning the Y axis screw counter-clockwise.
   - This step sweeps the laser spot across the cantilever. You passed across the cantilever if the total range of motion of the Y axis adjustment screw is about 1/16 of a turn.

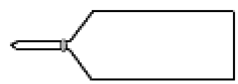
Figure 3.4g Laser Moved Across Cantilever



Note: You see two interruptions of the laser spot if a silicon nitride cantilever is used, because this type of cantilever has two legs that form a triangle. Find the two legs by the method described inStep 8. Move the laser spot between the legs of the lever and proceed to Step 10.

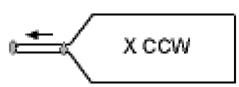
9. Position the laser on the cantilever. The laser will be on the back of the cantilever when you see the laser light dim to a dark red color.

Figure 3.4h Laser Positioned on Cantilever



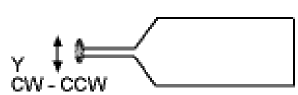
10. Slowly turn the X axis laser screw counter-clockwise until the spot starts becoming bright red again. This step moves the laser spot along the length of the lever toward the end where the tip is located.

Figure 3.4i Laser Moved Toward End of Cantilever



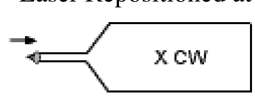
11. Slowly move the Y axis knob back and fourth to center the spot on the cantilever.

Figure 3.4j Laser Moved Across End of Cantilever



12. Move the X axis screw slightly clockwise to position the laser spot over the location of the tip.

Figure 3.4k Laser Repositioned at End of Cantilever



3.4.3 Align the Reflected Laser Spot on the Photo Detector Assembly

Adjust the photo diode adjustment screws to position the laser spot onto the photodiode assembly as follows:

Note: The display monitor shows a green square box divided into four parts (target). This is a representation of the four photodiodes in the detector assembly. The red dot on the target is a representation of the position of the laser spot on the detector.

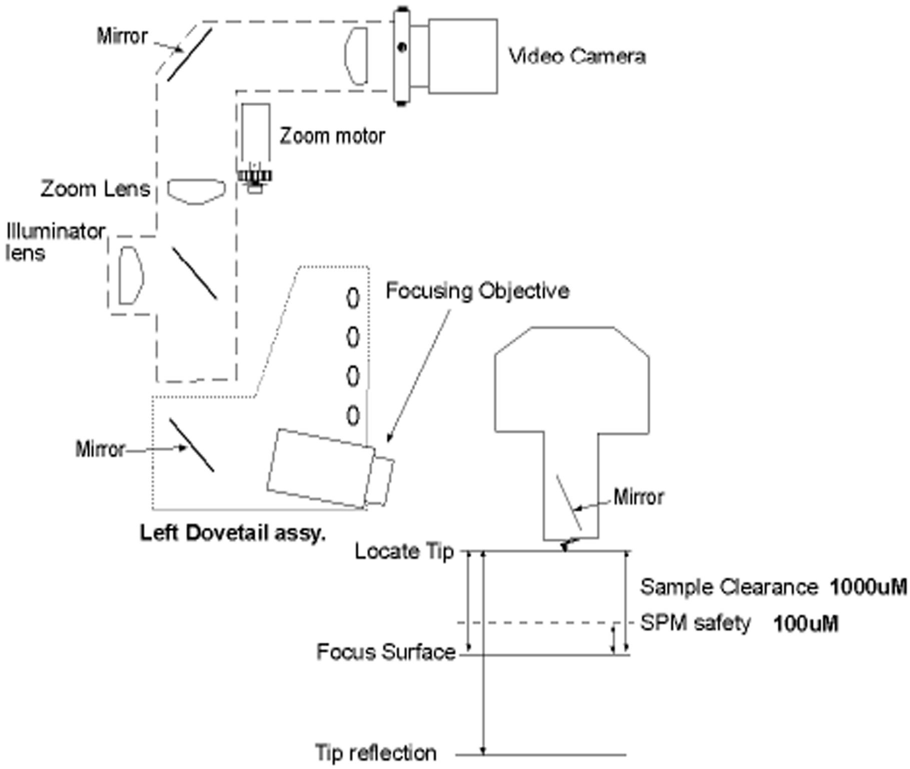
1. Turn the vertical and horizontal positioning screws located on the left side of the scanner body until the red spot on the target centers.
    - Turning the vertical adjustment screw clockwise moves the red spot down.
    - Turning the horizontal adjustment screw clockwise moves the red spot to the left.
2. Verify the SUM signal is ~2 volts for a silicon SPM probe, or ~6-8 volts for a silicon nitride SPM probe.

Note: The initial position of the red dot on the target is usually all the way on one edge. The dot will not move until the photo diode adjustment screws move the laser spot close enough to the detector.

3.4.4 Aligning the SPM Probe to the Sample

The Dimension AFM incorporates a video optics system to position the SPM probe over the desired scanning area on the sample surface. This process is accomplished by using an objective lens with a narrow depth of field (~10μm)

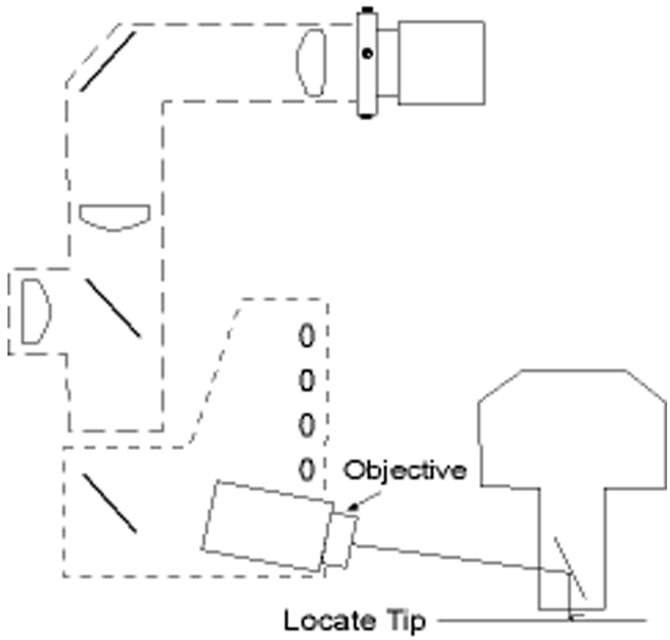
Figure 3.4l Dimension Stage Optics.



Locate Tip

The operator first teaches the software the SPM probe location by focusing the optics on the cantilever. Due to the objective's narrow depth of field, only the cantilever is in focus

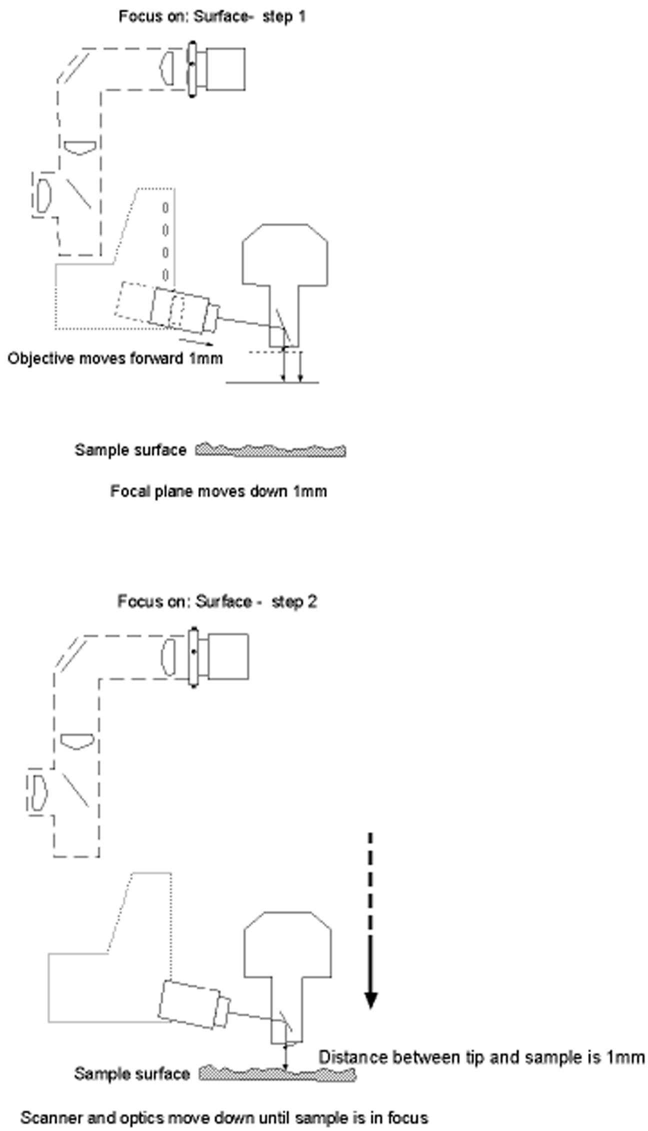
Figure 3.4m .Objective in Locate Tip Position



Focus Surface: Focus on Surface

After the tip is located, the focus surface command lowers the focal plane by moving the objective forward a controlled distance from the tip location. The distance is normally 1000 μm (1mm). The user raises or lowers the SPM system by using the Z stage assembly until the sample surface is in focus.

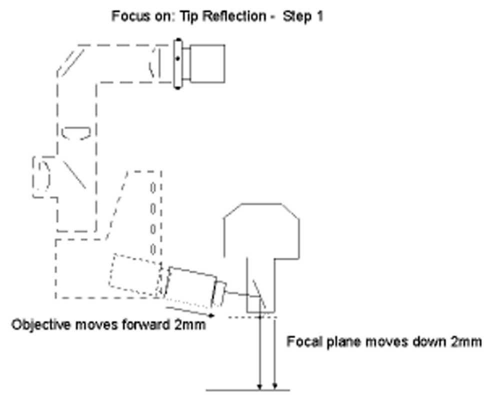
Figure 3.4n Focus Surface: Focus on Surface

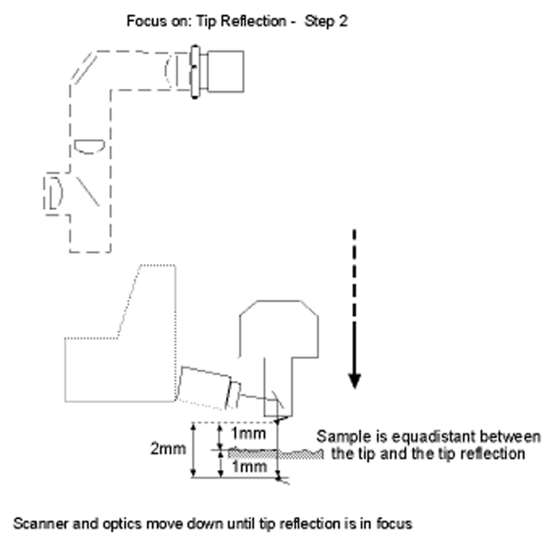


Focus Surface: Focus on Tip Reflection

An alternate method of establishing the tip/sample separation is to use the reflection of the SPM cantilever instead of focusing on the image of the sample surface. This is necessary when extremely flat or featureless samples are to be scanned. In this case, the video objective is moved forward 2000 μm (2mm) below the probe. The user raises or lowers the SPM system by the Z stage assembly until the reflection of the tip is in focus. The resulting tip/sample clearance is the same as when the Focus Surface: Focus on Surface method was used (1mm).

Figure 3.4o Focus Surface: Focus on Tip Reflection





Tip/Sample Alignment Procedure

Use the video optics to position the tip over the sample prior to engaging, as follows:

Note: The AFM laser optics should already be aligned on a new SPM probe. The AFM scanner should be locked in the Z stage.

1. Activate the **Locate Tip** by selecting **Stage/Locate Tip** on the Command screen.
2. Use the trackball to **Zoom Out** until the cantilever is in view.
3. Move the knobs on the objective to center the cantilever in the video image.
4. Use the trackball to focus the image of the tip.
5. Use the trackball to **Zoom In** approximately 50% of the range.
6. Exit the **Locate Tip** routine.

   Note: This saves the position of the cantilever in the software.

7. Activate the **Focus Surface** software routine by selecting **Stage/Focus Surface** on the Command screen.
8. Select to either focus on the surface or tip reflection.

   Note: The default is focus on Surface.

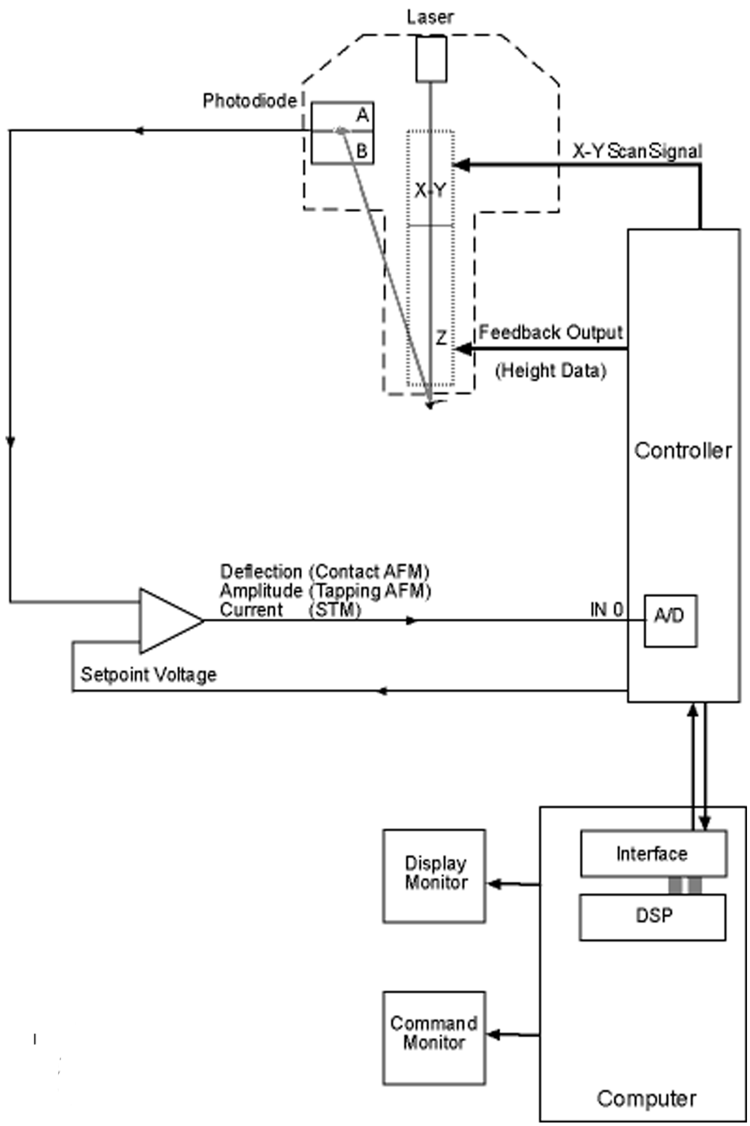
9. Use the trackball to move the X-Y stage until the cantilever is over the sample surface.
10. Use the trackball to raise or lower the SPM until the cantilever is approximately 1mm above the sample surface.
11. Use the trackball to bring either the sample surface or the tip reflection into focus in the video image.
12. Use the trackball to move the X-Y stage until the desired scan area is in the center of the video image.

    Note: The sample surface can only be viewed if the focus on surface is selected.

3.5 Feedback Loop

This block diagram illustrates the signal path of the feedback loop of the Dimension series SPM.

Figure 3.5a System Block Diagram



3.6 Abbreviated Instructions for the Dimension Series AFMs

3.6.1 Mode of Operation

1. In the **Other Controls** panel, set the **AFM Mode** to Tapping or Contact.

2. Mount the probe into the cantilever holder. Verify there is a firm contact with the end of the groove.

   - **Tapping**: Use an etched single crystal silicon probe (TESP).

   - **Contact**: Use a silicon nitride probe (DNP).

3. Mount the cantilever holder onto the end of the scanner head.

3.6.2 Align Laser

1. Adjust the laser so that it is on the cantilever using the two screws on the top of the scanner.

   - **Tapping**: Verify the Sum signal is approximately 2 volts.

   - **Contact**: Verify the Sum signal is 4-6 volts.

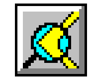
3.6.3 Adjust Photodetector

1. Using the two screws on the side of the scanner, adjust the photodetector so that the red dot moves towards the center of the square.

   - **Tapping**: Center the red dot and set the vertical deflection (**Vert Defl**) to a value close to 0.0 volts.

   - **Contact**: **Horiz Defl** should be about 0.0 volts, and **Vert Defl** should be approximately -2.0 volts.

3.6.4 Locate Tip

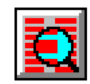


1. Using the mouse, select **Stage/Locate Tip** (or click on the **Locate Tip** icon).

2. Center the tip on the cantilever under the cross hairs using the two adjustment screws to the left of the optical objective on the microscope.

3. Focus on the tip end of the cantilever using the trackball while holding down on the bottom left button.

3.6.5 Focus Surface



1. Select **Stage/Focus Surface** (or click on the **Focus Surface** icon). The optics move to a focus position approximately 1mm below the tip.

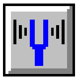
2. Focus on the sample surface by rolling the trackball up or down while pressing the bottom-left button.

Note: This adjustment raises or lowers the vertical engage stage on which the SPM and optics are mounted.

CAUTION: Take care when making this adjustment to ensure that the tip does not hit the sample surface.

3. Without holding down any of the buttons, move the desired measurement point under the cross hairs with the trackball.

3.6.6 Cantilever Tune (TappingMode Only)



1. Click on **View/Cantilever Tune** (or on the **Cantilever Tune** icon).

   a. For **Auto Tune Controls**, make sure the **Start Frequency** is at 0 kHz and the **End Frequency** is at 400 kHz.

   b. Verify the **Target Amplitude** is 2-3 volts. Click on **Auto Tune**. A “Tuning...” sign appears and disappears once Auto Tune completes.

2. When complete, quit the **Cantilever Tune** menu.

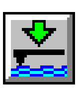
3.6.7 Set Initial Scan Parameters

1. In the **Scan Controls** panel, set the initial **Scan Size** to 1 μm, **X** and **Y Offsets** to 0, and **Scan Angle** to 0.

   - **Tapping**: In the **Feedback Controls** panel, set **Integral Gain** to 0.5, **Proportional Gain** to 0.7, and **Scan Rate** to 1 Hz.

   - **Contact**: In the **Feedback Controls** panel, set the **Setpoint** is to +1.0 volts, **Integral Gain** to 2.0, **Proportional Gain** to 3.0, and **Scan Rate** to 2 Hz.

3.6.8 Engage

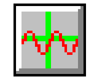


1. Select **Motor/Engage** (or click the **Engage** icon).

3.6.9 Adjust Scan Parameters

Tapping

1. Select **View/Scope Mode** (or click the **Scope Mode** icon).



2. Verify **Trace** and **Retrace** are tracking each other well (i.e. look similar).

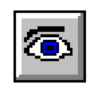
    - If they are tracking, the lines look the same, but do not necessarily overlap each other, either horizontally or vertically.
    - If they are tracking well, then your tip is scanning on the sample surface.

    a. To keep a minimum force between the tip and sample, click on **Setpoint** and use the right arrow key to increase the **Setpoint** value gradually, until the tip lifts off the surface. (At this point the Trace and Retrace will no longer track each other.)

    b. Decrease the **Setpoint** with the left arrow key until the **Trace** and **Retrace** follow each other again.

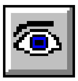
    c. Decrease the **Setpoint** one or two arrow clicks more to make sure that the tip continues to track the surface.

    d. Choose **View/Image Mode** (or click on the **Image Mode** icon) to view the image.



    - If they are not tracking well, adjust the **Scan Rate**, **Gains** and/or **Setpoint** to improve the tracking.
    - If **Trace** and **Retrace** look completely different, decrease the **Setpoint** one or two clicks with the left arrow key until they start having common features in both scan directions. Then, reduce **Scan Rate** to the lowest speed with which you feel comfortable.
    - For scan sizes of 1-3μm try scanning at 2Hz; for 5-10μm, try 1Hz; and for large scans, try 1.0-0.5Hz.
    - Next, try increasing the **Integral Gain** using the right arrow key.

- While increasing the **Integral Gain**, increase the **Proportional Gain** as well (**Proportional Gain** can usually be 30-100% more than **Integral Gain**.) The tracking should improve as the gains increase, although you will reach a value beyond which the noise will increase as the feedback loop starts to oscillate. If this happens, reduce the gains until the noise goes away.



- If **Trace** and **Retrace** still do not track satisfactorily, reduce the **Setpoint**. Once the tip is tracking the surface, choose **View/Image Mode** (or click on the Image Mode icon) to view the image.

Contact

1. Once engaged, increase the **Setpoint** by using the right arrow key and observe the **Z-Center Position**.

    a. If the line in the **Z-Center Position** moves far to the extended end, the tip false engaged. Increase the **Setpoint** by +2 volts and execute the engage command again.

    b. If the **Z-Center Position** does not change greatly, you are probably on the sample surface. Go to **View/Scope Mode** to see how well **Trace** and **Retrace** are tracking each other.

2. Adjust the **Gains**, **Scan Rate**, and **Setpoint** if needed.

    - Remember that in **Contact** mode, increasing the **Setpoint** increases the force on the sample. Minimizing the imaging force is recommended for most applications.

3.6.10 Set Desired Scan Size, Scan Angle and Offsets

Once the scan parameters are optimized, adjust scan size and other features for capturing images for analysis. When changing the scan size value, the scan rate must be lowered for larger scan sizes.

Chapter 4 Small Sample SPM Systems

4.1 Introduction

This chapter discusses the hardware and operating procedures of the small sample microscope, with emphasis on preparation for scanning. This chapter addresses the following subjects:

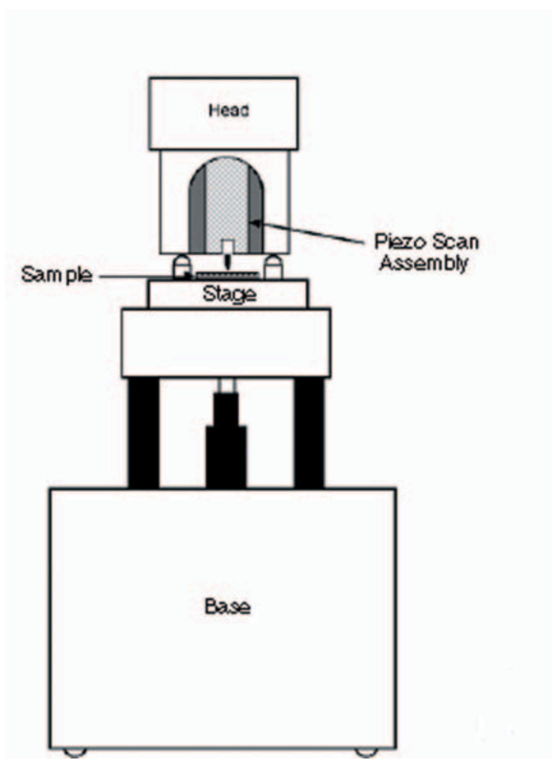
4.2 Hardware Overview

The small sample systems were the first types of instruments manufactured by Digital Instruments Veeco. As a new measurement method was discovered, Digital Instruments Veeco created a new type of instrument. Consequently, there are a variety of products that make up the current product line, but the basic format of each instrument is similar. A small sample system consists of three main components: the head, the scanner and the base.

4.2.1 Scanning Tunneling Microscope (STM) Systems

The first small sample system created performs STM *only*. The configuration of this system includes a base which houses a stepper motor for engaging and withdrawing the probe. A sample mounting stage sits in a recessed area on top of the base. The head of the STM system houses the piezo scanning equipment and preamplifier for converting the current to voltage. The STM probe scans over the sample with the sample fixed to the stage.

Figure 4.2a Small Sample STM System



4.2.2 Atomic Force Microscope (AFM) Systems

There are currently three types of AFM systems: Contact AFM, LFM and MultiMode. The form of each is the same. A separate assembly houses the Piezo scan element used on all three systems.

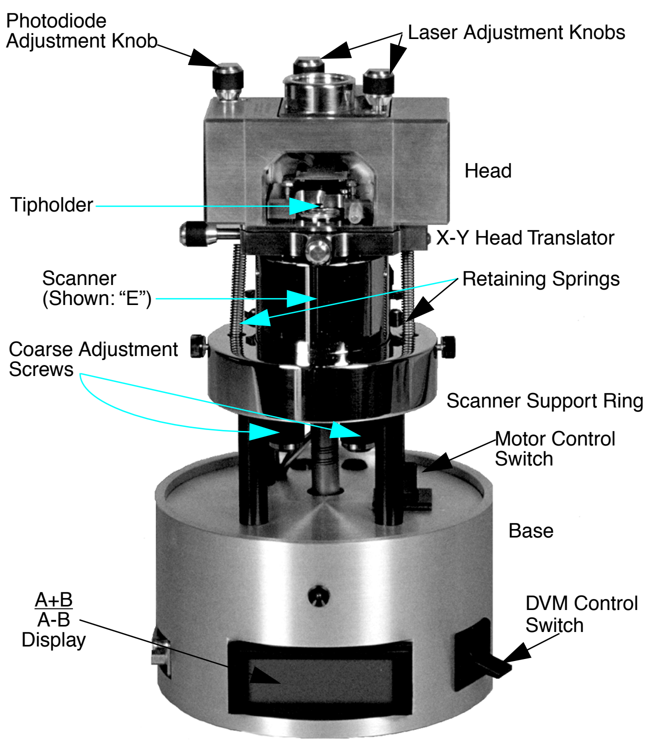
The AFM head houses the AFM probe and the optical detection electronics. The base includes electronics which create A-B/A+B signal and subtract the setpoint voltage from the A-B signal. A stepper motor in the base moves the head to engage and withdraw the AFM probe. The scanner, fitted into the upper portion of the base, moves the sample under while the AFM probe is stationary in the head.

4.2.3 Small Sample STM System

Contact AFM System

This small sample system performs contact AFM *only*.

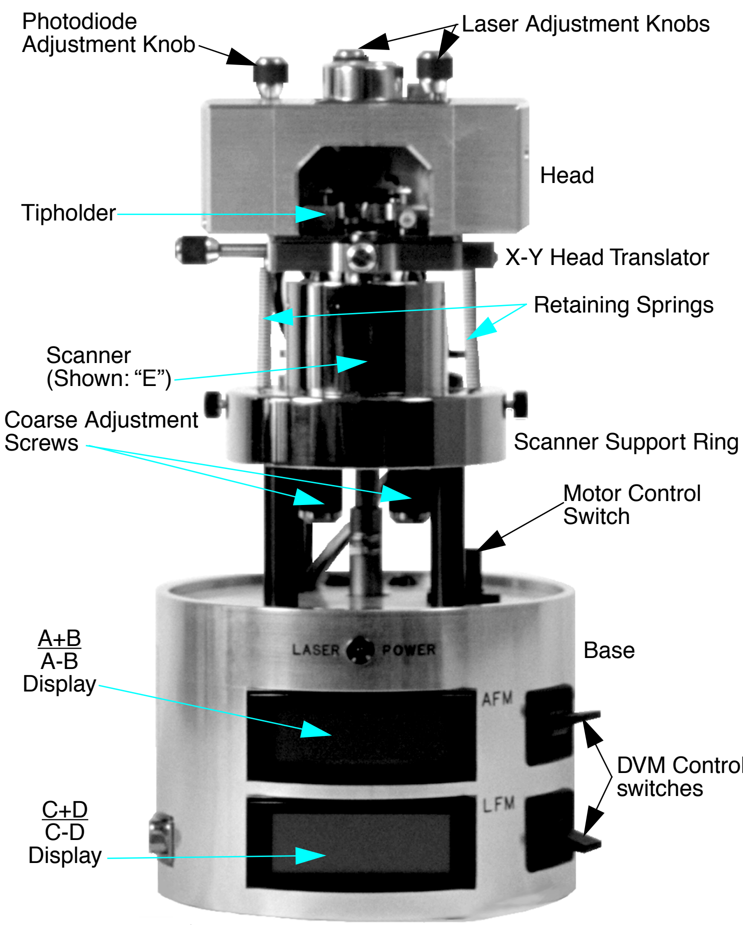
Figure 4.2b AFM



LFM System

The LFM system measures lateral forces exerted on the cantilever while performing contact AFM.

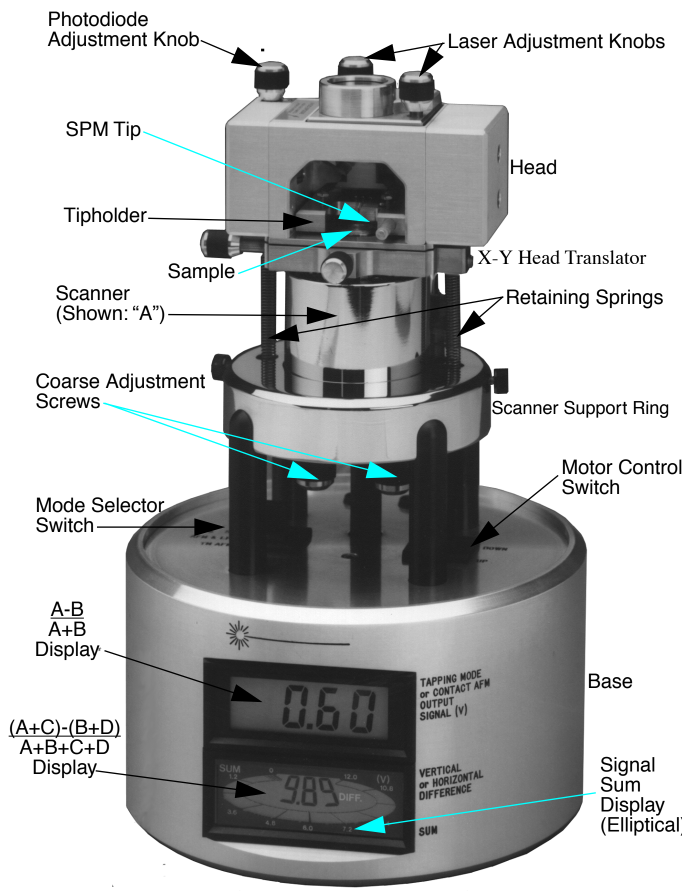
Figure 4.2c LFM



MultiMode AFM System

The Multimode AFM system performs contact AFM and LFM measurements, and is capable of TappingMode™ AFM. This system is configured to work with or without the Phase Extender electronics module. Figure 4.2a illustrates the standard small sample configurations.

Figure 4.2d MultiMode AFM

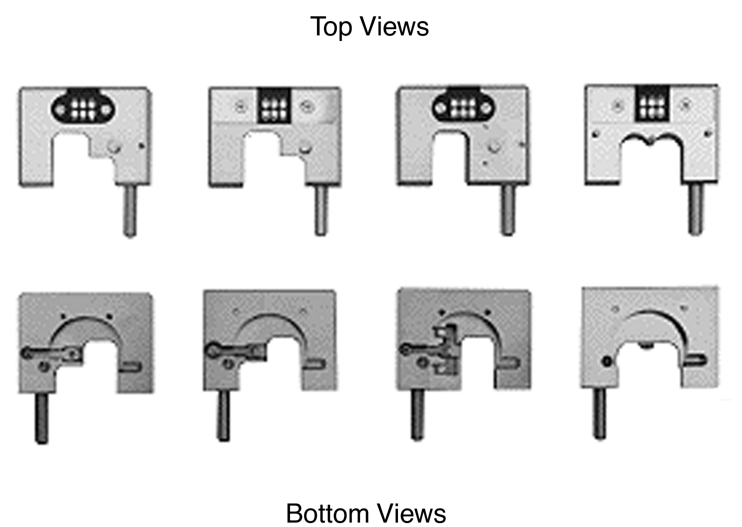


4.3 Accessories for Small Sample Systems

4.3.1 Tipholders for Small Sample SPM Systems

The sample and mode of SPM to be performed dictate the choice of tip and tipholder. For example, if using contact AFM for imaging, typically we choose a silicon nitride cantilever mounted in a standard tipholder. If using TappingMode for imaging a biological specimen in fluid, we use a special fluid cell. STM utilizes a special tipholder, with a tiny tube holder adapted for holding wire tips. Figure 4.3a displays examples of each tipholder.

Figure 4.3a Various Tipholders Used with MultiMode SPM

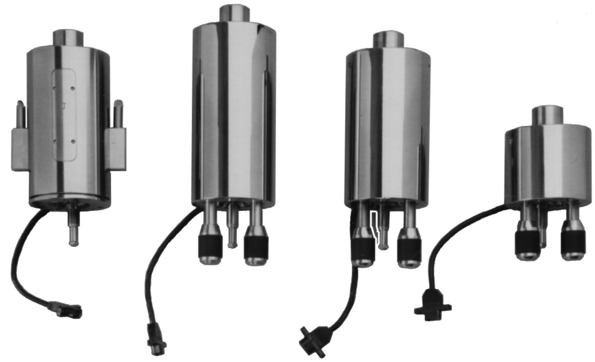


4.3.2 Scanners

Figure 4.3b shows the various, interchangeable scanners. The maximum scan size and resolution of images depend upon the choice of scanner (See Table 4.3a).

Longer scanners (e.g., type J) yield larger scan sizes. Shorter scanners (e.g., type A) offer smaller images down to the atomic-scale. Smaller scanners tend to be more noise-free at acoustic frequencies because of their compact size and rigidity. Larger scanners offer wider scans while requiring extra noise dampening precautions at smaller scan sizes of high resolution.

Figure 4.3b Various Scanners Available with the AFM



Note: Left-to-right: AS-130V (vertical “J”); AS-200 (“K”); AS-130 (“J”); AS-0.5 (“A”). Not shown: AS-12 (“E”) All scanners are interchangeable.

Scanner Parameter Files

Because each scanner exhibits its own unique piezo properties, each has its own parameter file. When changing scanners, you must change the parameter file for the new scanner to ensure maximum accuracy at any scan size. Loading new parameter files requires only a few seconds. The table below describes the range capabilities of each SPM scanner (See Table 4.3a).

Table 4.3a: Scanner Parameters

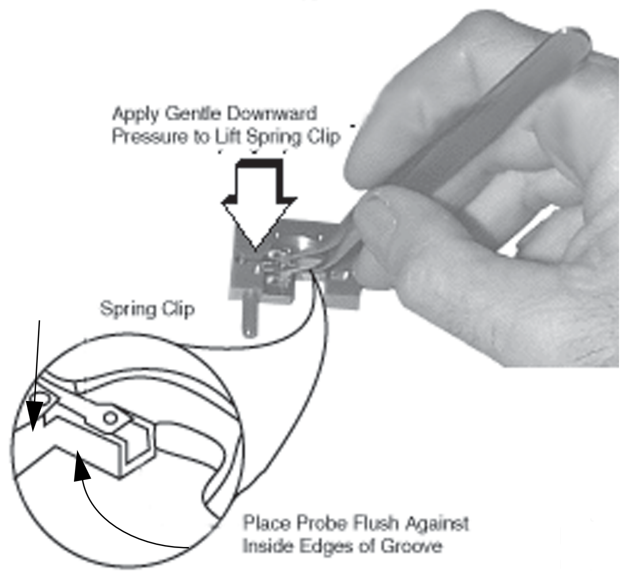
Model	Scan Size	Vertical Range
AS-0.5 (“A”)	0.4μm x 0.4μm	0.4μm
AS-12 (“E”)	10μm x 10μm	2.5μm
AS-12V (“E” vertical)	**10µm x 10µm**	**2.5µm**
AS-130 (“J”)	125μm x 125μm	5.0μm
AS-130V (“J” vertical)	125μm x 125μm	5.0μm
AS-200	200μm x 200μm	8.0μm

The AS-130V and AS-12V vertical scanners incorporate a new design for vertical motion, which eliminate tilt and lateral movement of the cantilever during engage. They are fully motorized and computer controlled, and require no manual adjustments.

4.4 AFM Probe Installation

The cantilever holder for the small sample system is a square metal part with a "U" shaped cut out. The cantilever is fitted in a groove in the holder. A spring clip located on the underside of the holder retains the cantilever in the holder. A small button located on the top of the cantilever holder moves the spring clip to allow the cantilever to be exchanged.(See Figure 4.4a).

Figure 4.4a AFM Probe Installation



1. Remove the cantilever holder from the head assembly
2. Place the cantilever holder upside down on a solid surface.
3. Grasp the cantilever holder and press down. This will cause the button on the cantilever holder to raise the spring clip.
4. Pick up a new AFM probe with a pair of tweezers.
5. Gently slide the substrate of the probe under the spring clip.
6. Gently release the cantilever holder and allow the spring clip to apply clamping pressure to the probe substrate.
7. Use tweezers to gently push the substrate fully into the groove in the cantilever holder
8. Install the cantilever holder into the head assembly.

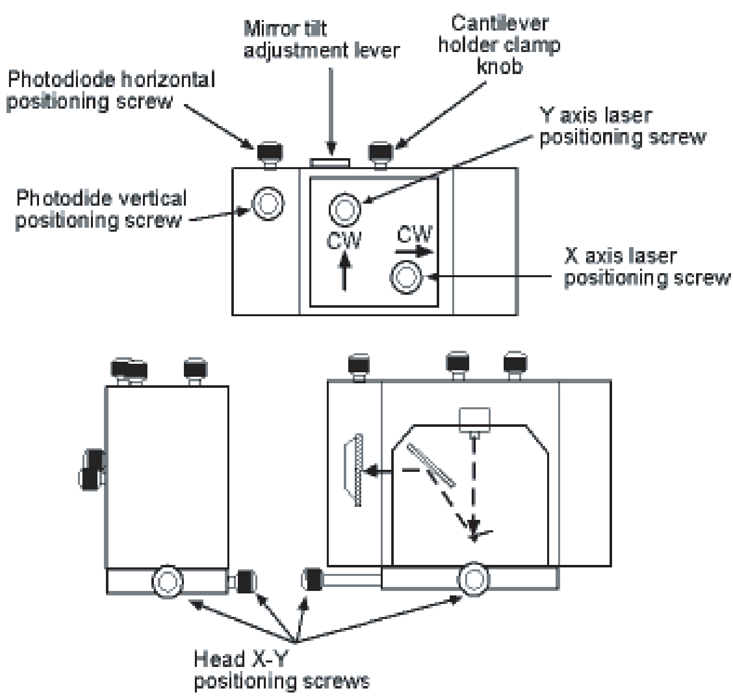
4.5 AFM Laser Alignment

4.5.1 Overview

The optical detection system inside the small sample AFM head begins with a solid state laser diode that sends a focused spot of light down toward the AFM probe. The user positions the spot to reflect off of the back of the cantilever. The reflected light from the cantilever reflects off of a mirror and onto the photodiode assembly.

There are four knobs on the AFM head. The knobs located on the top center of the head move the laser diode assembly. The knobs on the left side of the head move the photodiode assembly (See Figure 4.5a).

Figure 4.5a Laser Alignment Knobs



4.5.2 Align the Laser Spot on the Cantilever

To align the laser onto the back of the cantilever, perform the following procedure (See Figure 4.5b):

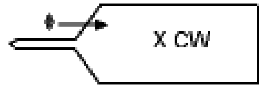
1. Load a new probe in the cantilever holder (See Section 4.4).
2. Insert the cantilever holder into the AFM head.
3. Clamp the holder to the head by turning the knob on the back of the head, bringing the clamp assembly down.
4. Note the orientation of the cantilever with respect to the head as viewed from above. The cantilever substrate is on the right and the cantilever points toward the left.
5. Hold the head in your hand while still connected to the AFM base. Point the head down at a small piece of paper. You will see an oval shaped red spot. This is the laser spot coming from the diode assembly.

Figure 4.5b Projecting Diffraction Patterns Downward with Head Removed

Note: Microscope shown is a MultiMode™ AFM, however, procedure applies to all current models of small sample microscopes.

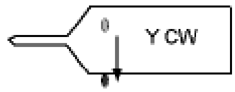
6. Move the laser spot toward the cantilever substrate by turning the X direction laser positioning screw. Move the knob *clockwise* until the spot disappears.

Figure 4.5c Laser Off of Substrate



7. Move the Y axis laser positioning screw *clockwise* until the light reappears.

Figure 4.5d Laser on Front Edge of Substrate

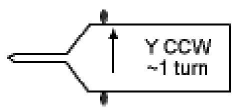


8. Move the Y axis laser screw *counter-clockwise*.

   a. The light disappears. Continue to turn the screw until the light reappears.

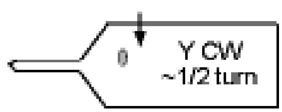
   b. Note the amount of motion that was required to complete Step a. The screw should have turned approximately 1 revolution. Repeat Step 4 and Step 5 to confirm the motion of the screw.

Figure 4.5e Laser Moved to Rear of Substrate



9. Position the laser spot in the center of the substrate by moving the Y axis screw half the distance that it was moved during Step 5.

Figure 4.5f Laser Centered on Substrate



10. Slowly turn the X axis laser screw *counter-clockwise* until the laser light appears.

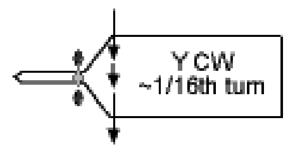
Note: This step moves the light toward the cantilever.

Figure 4.5g Laser Moved Toward Cantilever

11. Slowly turn the Y axis screw *clockwise*.

    - You might notice that the light briefly disappears and then reappears. If this happens, you just moved the spot across the cantilever.
    - If you don't see the interruption of the laser spot within one turn of clockwise motion, try turning the Y axis screw counter-clockwise, to sweep the laser spot across the cantilever.
    - You have passed across the cantilever if the total range of motion of the Y axis adjustment screw is about 1/16 of a turn.

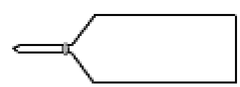
Figure 4.5h Laser Moved Across Cantilever



Note: You will see two interruptions of the laser spot if using a silicon nitride cantilever. This is because this type of cantilever has two legs that form a triangle. Find the two legs by the method described in Step 8. Move the laser spot between the legs of the lever and proceed to Step 10.

12. Position the laser on the cantilever. The laser is on the back of the cantilever when you see the laser light dim to a dark red color.

Figure 4.5i Laser Positioned on Cantilever



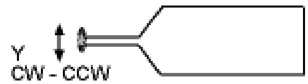
13. Slowly turn the X axis laser screw counter-clockwise until the spot starts to become bright red again.

    - This step moves the laser spot along the length of the lever toward the end where the tip is located.

Figure 4.5j Laser Moved Toward End of Cantilever

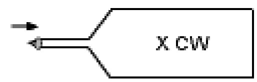
14. Slowly move the Y axis knob back and fourth to center the spot on the cantilever.

Figure 4.5k Laser Moved Across End of Cantilever



15. Move the X axis screw clockwise slightly to position the laser spot over the area where the tip is located.

Figure 4.5l Laser Repositioned at End of Cantilever



4.5.3 Align the Reflected Laser Spot on the Photo Detector Assembly

Adjust the photo diode adjustment screws to position the laser spot onto the photodiode assembly. The Digital Volt Meter (DVM) displays for the AFM, LFM and MMAFMare described below. The adjustment of the detector signal is the same for all three systems.

1. Tilt the mirror in the AFM head while monitoring the SUM signal on the DVM located on the base.

   a. Verify the SUM signal maximizes when the laser spot is in the area of the photo detectors' center.

   b. Verify the SUM signal is ~2 volts for a silicon SPM probe.

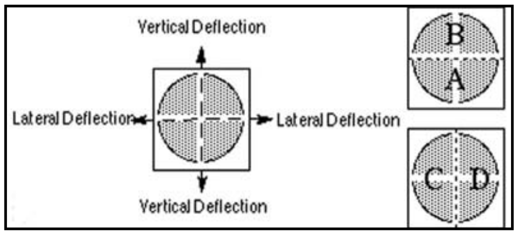
   c. Verify the SUM signal is ~6-8 volts for a silicon nitride SPM probe.

2. Adjust the A-B and C-D signals to 0 volts by moving the vertical and horizontal positioning screws located on the left side of the AFM head (for contact mode, A-B should be set to -2.0 volts).

4.6 Voltage Meter

The AFM base includes a meter which indicates voltage coming from the four-segment photodetector (See Figure 4.6a).

Figure 4.6a AFM Photodetector Array



4.6.1 AFM Voltage Meter

The AFM base has a DVM control switch to display either the SUM or the Difference (DIF) meter. The AFM's SUM meter (up position of DVM switch) indicates the voltage sum (A + B). The AFM's DIF meter (down position of DVM switch) indicates the output signal of the SPM or voltage difference (A-B).

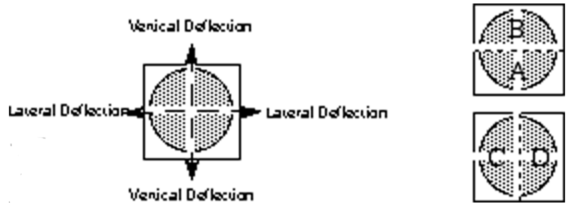
4.6.2 LFM Voltage Meter

The LFM has two volt meters on the base of the microscope. The top meter displays the same signals as the AFM, while the bottom meter displays lateral force information. The LFM's SUM meter (up position of DVM switch) indicates the voltage sum of (C + D).The LFM's DIF meter (down position of DVM switch) indicates the voltage difference of (C-D).

4.6.3 MultiMode SPM Voltage Meter

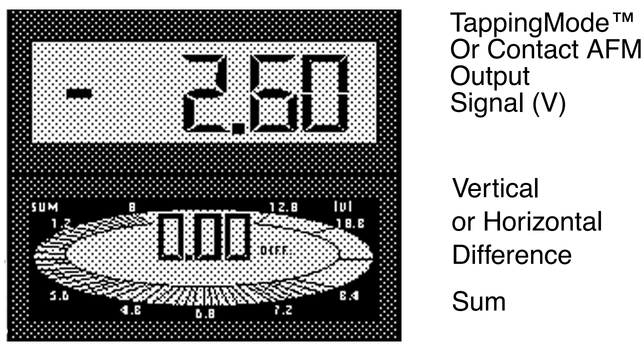
The MultiMode SPM base includes meters which indicate voltage coming from the four-segment photodetector.

Figure 4.6b SPM Photodetector Array



The MultiMode SPM's bottom, elliptical (SUM) meter 1 indicates the total voltage generated by the photodetector. (The combined voltage of photodetector segments.) This displays during all modes (except STM when all meters are off).

Figure 4.6c Sum Meter Display



The bottom digital meter reads differences in voltage between various segments of the photodetector. With the **MODE** switch toggled to **AFM and LFM**, it indicates the voltage difference (C - D) the left segments minus the right segments. With the **MODE** switch toggled to **TM AFM** (TappingMode), it indicates the voltage difference (A - B), that is, the bottom segments minus the top segments.

The top digital meter indicates the output signal of the SPM. Depending upon the mode selected, the top meter reads either the (A - B) voltage difference (**MODE** switch toggled to **AFM** and **LFM**), or the RMS voltage (**MODE** switch toggled to TM AFM).

4.7 AFM Tip / Sample Alignment

Position the SPM probe and the sample surface for engagement as follows:

1. Lower the head to slowly bring the AFM probe to the sample surface.

2. Lower the AFM head using the two coarse adjust screws and the motor drive screw in the scanner body.

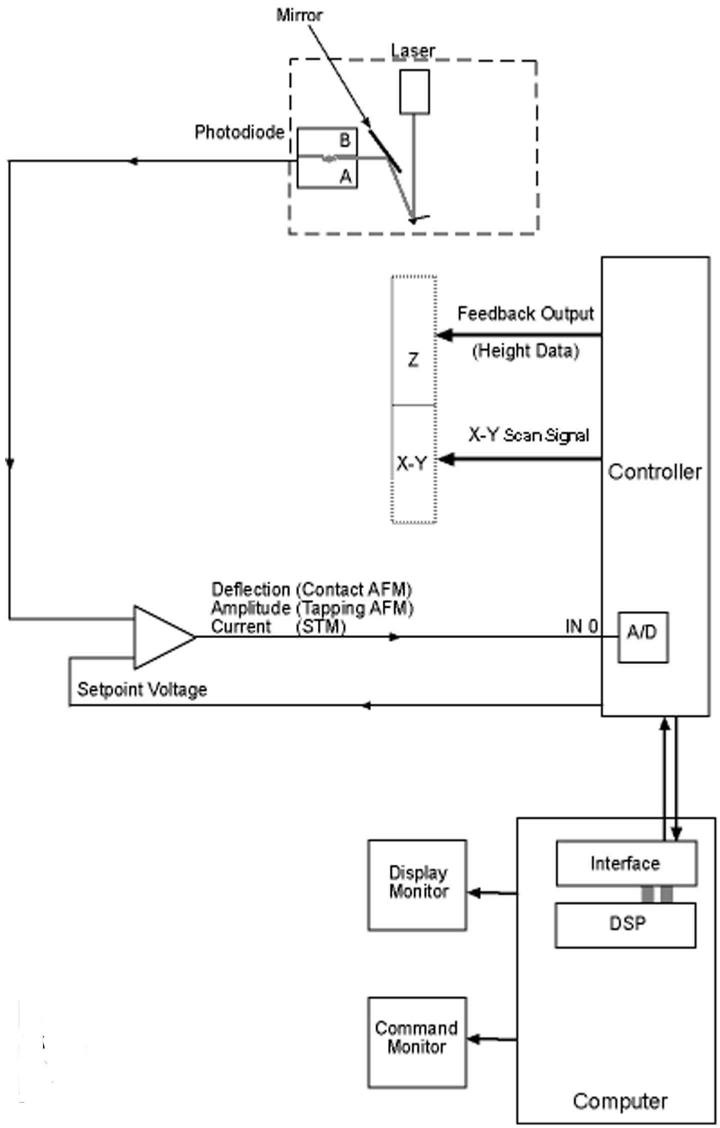
3. View the tip/sample area optically using the 40X monocular that is supplied with the AFM system.

4. Verify the tip is within 100 microns of the sample surface before the system can engage the tip.

5. Judge the distance by comparing the length of the cantilever with the separation between the probe and the sample surface.

Verify the head is level with respect to the scanner body by confirming that the gap between the top of the scanner body and the bottom of the AFM head is the same.**Small Sample SPM Feedback**

Figure 4.7a Small Sample AFM Feedback Loop Block Diagram



1.

4.8 Abbreviated Instructions for the MultiMode™ AFM

4.8.1 Mode of Operation

In the **Other Controls** panel, set **AFM Mode** to **Tapping**, **Contact**, or choose the appropriate profile and change the **MODE** switch on the base to TMAFM or AFM and LFM mode, respectively.

4.8.2 Mount Probe

1. Mount a probe into the cantilever holder. Be sure that it is in firm contact with the end of the groove (See Section 4.4).
    - **Tapping**: Use an etched single crystal silicon probe (TESP).
    - **Contact**: Use a silicon nitride probe (NP).
2. Put the cantilever holder in the optical head. Secure the holder by tightening the screw in the back of the optical head.

4.8.3 Select Scanner

1. Choose a scanner (A, E or J).
2. Mount and plug the scanner into the base.
3. Attach the corresponding springs to the microscope base.
4. In the software, choose the appropriate scanner parameters with **Microscope/Select**.

4.8.4 Mount Sample

1. Mount a sample on a metal disk with a sticky-tab (sample width should be limited to the disk's 15mm diameter).
2. Mount the disk and sample on top of the scanner.

4.8.5 Align Laser and Tip-Sample Approach (2 Methods)

Direct View Method

Follow the procedures described in Section 4.5 through Section 4.7 of this chapter.

Optical Viewing Microscope Method

1. Place the microscope on the optical microscope positioning stage.
2. Turn on the monitor and the light source.
3. Focus on the cantilever. Zoom out, if using optical microscope equipped with zoom.
4. Use the base screws on the stage of the optical microscope to center the cantilever in the field of view.
5. Lower the focus of the optical microscope to the sample surface.

    a. Look for an out of focus shadow of the cantilever in the field of view. Keep the optical head level while lowering the cantilever until it is almost in the same plane of focus. Keep the shadow of the cantilever in the field of view at all times.

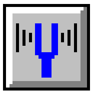
    b. Check the focus on the cantilever from time to time to see how close it is to the sample surface.

6. Once the cantilever is close to the sample surface, adjust the laser so that it is positioned over the cantilever.
7. Use the two screws at the top of the optical head to move the red laser spot onto the cantilever.
    - If necessary, change the field of view of the optical microscope initially to find the laser spot.
8. Use the "paper method" (See Step 3 under Magnifier Method) to fine position the laser spot on the cantilever.
9. Use the two screws at the base of the optical head (front and left) to position the cantilever over the area of interest on the sample.
    - As the stepper motor moves during engagement, the cantilever shifts towards the back of the microscope (except with a Vertical Engage Scanner). Place the cantilever in front of (below on the monitor) the area where you want to engage.

4.8.6 Adjust Photodiode Signal

Follow the procedure described in Section 4.5.3 of this chapter.

4.8.7 Cantilever Tune (TappingMode *Only*)



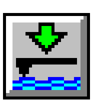
1. Click on **View/Cantilever Tune** (or on the Cantilever Tune icon).
2. For **Auto Tune Controls**, verify the following:
   - **Start Frequency** is 100 kHz
   - **End Frequency** is 500 kHz.
   - **Target Amplitude** is 2-3 volts.
3. Select **Auto Tune**. A "**TUNING**..." Prompt appears, then disappears once **Auto Tune** is complete.
4. When finished, quit the **Cantilever Tune** menu.

4.8.8 Set Initial Scan Parameters

In **Scan Controls** panel, set the initial **Scan Size** to 1 μm, **X and Y Offsets** to 0, and **Scan Angle** to 0.

- **Tapping**: In the **Feedback Controls** panel, set **Integral Gain** to 0.5, **Proportional Gain** to 0.7, and **Scan Rate** to 2 Hz.
- **Contact**: In the **Feedback Controls** panel, set the setpoint is to +1.0 volts, the **Integral Gain** to 2.0, the **Proportional Gain** to 3.0, and the **Scan Rate** to 2 Hz.

4.8.9 Engage



1. Select **Motor/Engage** (or on the **Engage** icon).

4.8.10 Adjust Scan Parameters - **See Section 3.6.9 and 3.6.10**