Ambios Technology Corporation

Operator's Manual

Q-Scope™ 250/400
Nomad™

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Table of Contents

1   Introduction

1.1   READ THIS, PLEASE…

❖Note: The probe holder at the front of the scanner is mounted at the end of a 7 cm long, thin-walled piezoelectric scan tube which is very fragile.   Even a minor bump which does not cause a visible crack may cause microscopic damage to the piezo material, and because the piezoelectric phenomenon itself is fundamentally microscopic in origin, this will degrade the performance of the scanner.   _If it is damaged it will be very expensive to repair._

Fragile
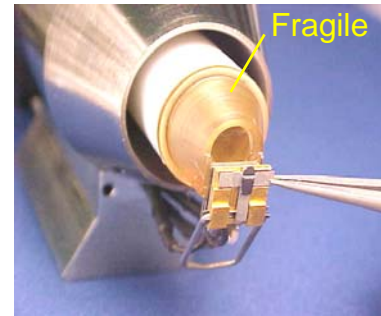
❖Note: Whenever the scanner is removed from the microscope stage be sure to protect the scan tube by placing the tip protector on the end of the scanner. _If it is damaged it will be very expensive to repair._

❖Note: If it is ever necessary to ship your scanner back to Ambios for repair be sure to protect the scan tube by placing the tip protector on the end of the scanner. Also, put the protective red plastic cap over the end of the camera tube. _If it is damaged it will be very expensive to repair._

❖Note: Always plug and unplug system's electronic cables with the EIU power switched off. Some of the electronic components are susceptible to damage if the cables are plugged or unplugged when the EIU power is on.   _If it is damaged it will be very expensive to repair._

We hope that the above warnings are sufficient to convince you that an SPM has its vulnerable points, and you should be careful in using it. Here is a final piece of useful information, which for a change will not be accompanied with the expensive repair warning. In additional to this manual, your microscope system comes with a second valuable source of information: the online software help file. If you find that you have a question about the function of a particular control in a particular window just press the F1 keyboard button and the help file will appear with information pertaining to the controls in the window. The online help file is complimentary to this manual. Some information found in the help file is not found in the manual, and vice-versa. In particular, the help file has several examples showing how to use the image processing and data analysis features of the software.

1.2   WHAT IS SCANNING PROBE MICROSCOPY?

The term 'scanning probe microscopy' (SPM) represents a family of surface measurement techniques. The list of acronyms for the imaging techniques which may be considered species within the SPM family is very long— STM, AFM, SCM, SFM, DFM, and so on. In the most general sense, these imaging techniques reveal information about the surface properties of materials by scanning or "rastering" the surface with a small probe. Information about the interaction of the probe with the surface is transmitted to a computer where an image of the surface is formed.   This section of the manual presents a simple model of the main components found inside a scanning probe microscope and a brief introduction to how the microscope works.

1.2.1 Basic Model of a Scanning Probe Microscope
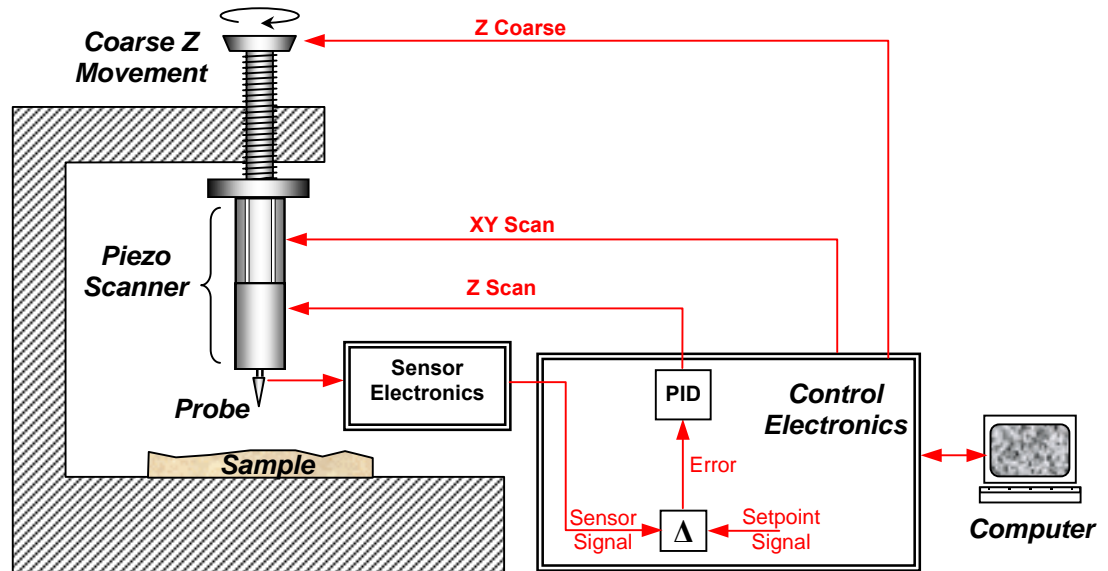
Figure 1-1 A basic model of the scanning probe microscope.

The function of the building-block components in Figure 1-1 are described below.

- The *Coarse Z Movement* mechanism acts as the "legs" of the instument. It walks the probe down to the sample surface from a position several millimeters away. The *Coarse Z Movement* has the ability to move the probe at speeds of 100's of microns per second to rapidly close the sample-probe gap, as well as the ability to take small slow steps with a resolution of about one-quarter of a micron to finely position the probe within the operation range of the *Piezo Scanner*, which is typically only a few microns.

- The *Piezo Scanner* is the "arm" of of the instrument. The top XY section moves the probe from side to side and the bottom Z section moves the probe up and down. The distances moved are very small, in the range of 10^{-10} to 10^{-5} meters.

- The *Probe* and associated *Sensor Electronics* form the "hand" of the instrument. This "feels" the sample surface beneath the probe when the *Course Z Movement* has brought the probe into surface contact. The most sensitive of the available probe types can convert changes in the probe's position as small as the size of an atom into a measurable sensor signal change.

- The *Control Electronics* provide several control functions. It coordinates the xy movement of the scanner to raster the probe over the sample surface, it performs the coarse approach operation to bring the probe into surface contact, and it produces the z feedback control to allow the probe to track the vertical profile of the surface. The *Control Electronics* also communicate with the computer, translating the SPM operator's instructions into hardware control sequences, and transfering the surface image data back up to the computer for processing and image presentation.

1.2.2 Piezo Scanner

Because of its central role in the 'scanning' part of scanning probe micrososcopy, a brief overview of the principles of operation behind the piezoelectric scanner is helpful. Piezoelectric materials have the property that they can be polorized by an electric field at high temperatures, so that when a voltage is applied to the electrodes on the piezoelectric material at room temperature it can be made to expand and contract very small distances (Figure 1-2). Any mechanical device of this sort is called a *position transducer*— a mechanical device that converts a voltage into a mechanical displacement.
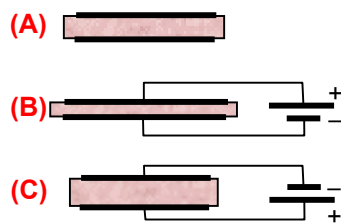
Figure 1-2   The basic concept of how a piezoelectric transducer works. (A) Side view of a thin rectangular plate of piezo material with electrodes on the top and bottom. (B)   Appling a voltage of one polarity to the electrodes causes the plate to expand horizontally. (C) Applying a voltage of the opposite polarity causes the plate to contract horizontally.

Piezoelectric material can be formed into any shape. The shape most useful for the SPM scanner is a thin walled cylinder. Imagine taking the rectangular plate in Figure 1-2 and curling it into a cylinder.   As indicated in Figure 1-3, applying a voltage between the electrodes on the inside and outside surfaces of the Z cylinder will make the cylinder expand or contract axially, which would move an attached probe up or down.

The XY motion of the piezo scanner is obtained by splitting the inside and outside electrodes on the cylinder walls into quarter sections, as shown in the righthand side of Figure 1-3. By applying equal voltages to opposing electrode pairs with reversed voltage polarity, one side of the tube can be made to stretch and the other side contract. This bends the tube sideways. The sideways bend produces the x-axis motion of the probe. The y-axis motion is produced similarly with the other two pairs of electrodes on the XY piezo.
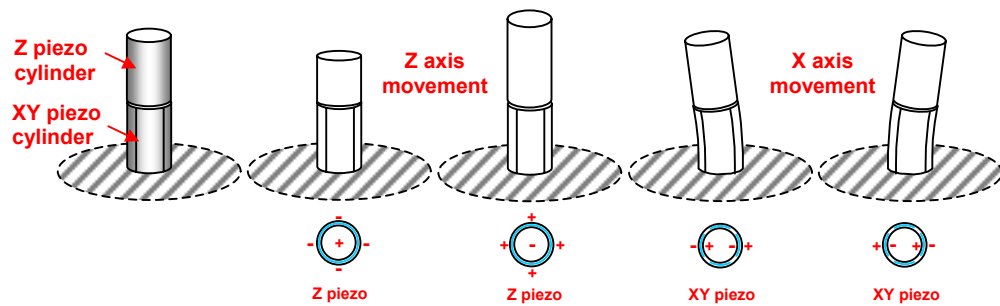
Figure 1-3 Voltages applied to the piezo cylinders to generate scanner movement of the probe.

1.2.3 The Probe and Sensor Electronics

Now let's look at the 'probe' part of scanning probe microscopy. There are several mechanisms which can be used to sense the probe's proximity to a surface. Two of the most common sensing mechanisms, STM and AFM, are described below as examples.

Scanning Tunneling Microscopy (STM)

Historically, STM is the first of the modern scanning probe microscope techniques. It was invented in the early 1980's, and its development ultimately led to the Nobel prize in physics for its inventors.

In the STM imaging technique, a small voltage is applied to the sample, typically 10-500 mV, and then a finely sharpened tip is brought close enough to the sample to produce a measurable tunneling current between the tip and the surface (Figure

1-4). Ideally the tip does not actually touch the surface when the tunneling current is established. When the tip-sample separation is of order a few Angstroms the tunneling current will be of order 1 nanoampere, and this current is amplified and converted into a sensor output signal of order 1 volt.
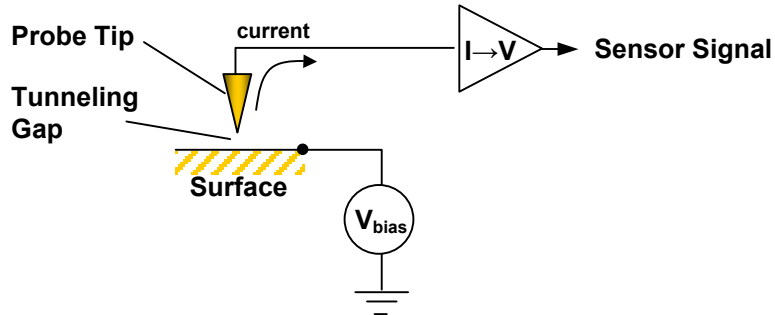
Figure 1-4 STM sensor signal generation.

The tunneling sensing mechanism is extremely sensitive. The sensor signal changes by about a factor of 10 for every Angstrom change in the vertical height of the probe, giving the STM imaging technique an extremely high position sensitivity. Atomic-scale resolution is readily obtained in this way.

STM is not an all-purpose imaging technique, however. It has the serious disadvantage of requiring the probe and the surface to be electrical conductors, and these surfaces must be very clean, free of oxides and other contaminants. These restrictions make STM unsuitable for general purpose in-air laboratory imaging requirements.

Atomic Force Microscopy (AFM)

The AFM imaging technique uses a microfabricated cantilever with a small sharp point protruding from its underside. The position of the probe point is measured via the deflection of a laser beam which is reflected off of the back side of the cantilever (Figure 1-5). As the cantilever moves up and down the position of the laser spot on a split-diode photodetector changes, producing top T and bottom B photocurrents in the top and bottom diodes. The difference in these currents, T-B, indicates how much the cantilever bends. The contact mode and intermittent-contact mode AFM imaging techniques use the T-B signal in two different ways:
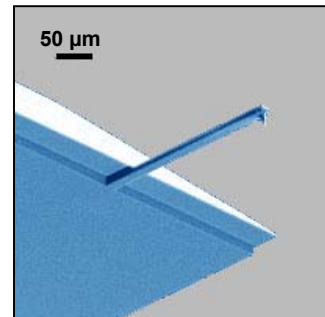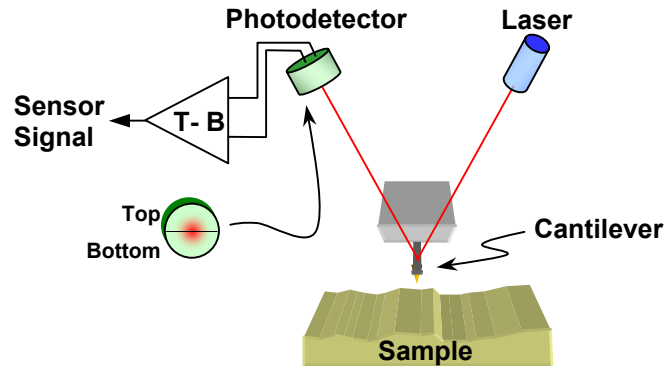
Figure 1-5 AFM sensor signal generation.

- **<u>Constant Contact</u>**

    The point of the probe touches the sample surface at all times. The *T-B* signal is used directly to sense the probe's position with respect to the surface via the cantilever's deflection up and down.

- **<u>Intermittent Contact</u>**

    The cantilever is vibrated with a small piezoelectric 'shaker'. (This is not shown in Figure 1-5, but it would be added just above the block to which the tiny cantilever is mounted.) The cantilever is vibrated at its resonance frequency, typically of order 100 kHz, so that it obtains a vibration amplitude at the probe point end of order 100 nm. As the cantilever vibrates the *T-B* signal tracks the motion, oscillating at the same frequency. Thus the amplitude of *T-B* gives a direct measure of the amplitude of vibration of the cantilever. When the vibrating cantilever is brought next to the surface it intermittently contacts the surface on the downward stroke of its motion. This dampens the amplitude of vibration, and it is this dampening effect on *T-B* which is used to sense the probe's position with respect to the surface.

SPM Image Resolution

The ultimate limiting factor which determines the image resolution achieved with an SPM probe is the sharpness of the point.

Ideally, the probe is in the form of a very narrow angled cone, terminating with just a small cluster of atoms at the apex of the cone. The small cluster of atoms at the apex will give the probe sufficient lateral resolution to image the atomic lattice

of crystal structures. The narrowness of the cone will allow the probe to reach down into crevisis of the surface, and scan very close to the vertical walls of step-shaped features on the surface.

In reality, the probe tip is normally not nearly so sharp, and the cone angle is not nearly so small, and these factors may compromise the quality of the image obtained. The condition of the probe point is of paramont importance in obtaining the best quality images from an SPM instrument.

Primary and Secondary Probe-Surface Interactions

SPM sensors often have two sorts of interations with the surface. There is always a 'primary' interaction, which provides information about how high the probe is with respect to the surface. This is used by the z feedback control electronics to track the surface topology.   In addition to this, some probes also provide a 'secondary' surface interaction which allows the probe to detect other physical characteristics of the surface other than the topology. Examples of quantities which may be measured via secondary interactions include the surface magnetic structure, the surface temperature, and the elastic properties of the surface material.

1.2.4 The SPM in Action

This is an overview of how an SPM works. We start with the probe far away from the sample surface (several millimeters), so there is ample room to slide the sample under the probe. Then with the *Coarse Z Movement* mechanism the probe is brought close enough to the surface to interact with it.

Once the *Coarse Z Movement* mechanism has done its job, the vertical position of the probe is controlled by the 'z feedback control loop', or 'z servo loop'. The loop consists of these parts: the z section of the piezo scanner, the probe and sensor electronics, the setpoint voltage, the error voltage calculator, and the PID control circuitry. In order to understand how the z feedback control works its best to just jump in and see what one component is doing, and then follow this component's output to the next component in the loop to see how it responds, and continue the analysis of the actions of each subsequent component in the loop until the effect returns back to the first component considered.

Let's begin with the probe. The probe and its associated sensor electronics produce a signal that changes in a very sensitive way to changes in the z position of the probe. This signal goes into the *Control Electronics* where it is compared to the *Setpoint Signal*. The *Setpoint Signal* is set by the operator of the microscope.

This control determines what physical quantity the z feedback control loop tries to hold at a constant value. For example, in STM mode it would be a certain tunneling current, in contact AFM mode it would be a certain amount of force between the cantilever point and the sample surface, in intermittent-contact AFM it would be the cantilever's vibration amplitude.

So, the difference between what we say we want the probe state to be (*Setpoint Signal*) and what the probe sensor reads as the state of the probe (*Sensor Signal*)is the error in the feedback control (*Error*).   The error signal goes into the 'intelligence' of the servo mechanism, called the *PID* controller.   The *PID* controller decides how to respond to the error signal, i.e., how fast and in what direction to change its output voltage (*Z Scan*). For example, if at some point in time the error voltage is high, indicating the probe is too far from the surface, then the *PID* will slew the *Z scan* voltage to a more positive value to cause the z piezo to gradually expand. As the z piezo expands the probe is lowered closer to the surface, and the error signal gradually decreases, eventually reaching a value of zero. At the instant in time that the error reaches zero the *PID* stops changing the *Z Scan* voltage. The z feedback loop has reached its goal: the probe is in the state we've defined via the *Setpoint* parameter.

The action of the z feedback loop happens very rapidly, so at any instant in time the *Z scan* voltage has been adjusted to keep the error voltage very close to zero. An image of the surface topology is produced by rastering the probe across the surface in a series of scan lines to gradually map the profile of a square region of the surface. As this rastering takes place the z feedback circuitry continually raises and lowers the probe to track the surface with a constant sensor signal.   Provided that the Z piezo expands and contracts linearly as the applied voltage changes, the *Z Scan* signal will be proportional to the actual vertical profile of the surface.   The surface image is formed by measuring the *Z Scan* signal, converting it into its equivalent height by multiplying by an appropriate conversion factor (so many μm height per so many *Z Scan* volts), and then plotting the result as a color bitmap on the computer screen. Each pixel in the bitmap corresponds to a point in the xy raster of the probe, and the vertical height of the surface at that point is represented by an entry in the color palette, usually set up so that 'higher' means 'brighter color'.

This is no more than an introduction to the operation principles behind scanning probe microscopy. Further information is found in the chapters of this manual and the manual supplements.

2   Setting up the System

2.1   LOCATION CONSIDERATIONS

The SPM is a delicate instrument. It is sensitive to vibrations, acoustical noise, air currents, and temperature changes. Successful results with your instrument will depend in part on the extent to which it can be isolated from these environmental effects.

Vibration and Noise

If possible, place the microscope on the ground floor or basement level to minimize building vibrations. The stage/scanner assembly is the sensitive portion of the microscope.

A simple low-cost arrangement to dampen vibration is to place several layers (e.g., 2 - 4 inches) of foam rubber under the stage. Other solutions include air tables and mechanical vibration isolation systems.

Air Currents and Temperature Fluctuation

At the minimum, a simple cover of some sort should be used to shield the microscope stage from room air currents. Air currents can have a dramatic effect on an image, producing line-to-line noise and artificial "roller coasting" of the surface. It is also best to place the system in a room where a relatively constant temperature is maintained to minimize long-term temperature-dependent effects in the scan tube and electronics.

The AVIC Option

Ambios supplies, as an option, a simple and inexpensive means of isolating your SPM from air currents, acoustic noise, and mechanical vibrations— the AVIC (Acoustic and Vibration Isolation Chamber). The AVIC is a fiberglass chamber lined with one-inch acoustic damping foam, having a transparent access door at the front for changing samples and making scanner adjustments. A passive mechanical spring system inside the chamber isolates the SPM from external mechanical vibrations. Placed on a sturdy bench or desk, this system is suitable for many applications requiring ~1 nm or better vertical resolution.

2.2   UNPACKING

Retain all packing material. Report any obvious damage caused by improper handling to the shipping company. Contact Ambios for assistance in filing a claim against the shipping company if any components of the microscope have been damaged in transit.

The microscope is shipped disassembled in two boxes. One box contains the stage and the scanner; the other box contains the Electronic Interface Unit (EIU) and the electronics cables. If the system includes an AVIC, it will be shipped in a separate crate.

Computers are shipped in the computer manufacturer's shipping containers. Unless special requests have been made, all software will be as supplied by the computer manufacturer, with the addition of the ScanAtomic software to control the microscope.

Q-Scopes   The Q-250 stage weighs about 35 lbs; the Q-400 stage weighs about 75 lbs. It is suggested that two people remove the stage from the packing box.

AVIC Option   The AVIC crate is fastened together with 2" drywall screws, and is banded across the top with a steel strap. Cut the strap with strong metal shears and remove the screws holding the top and front panels of the crate. (The front panel can be distinguished once the top panel is removed.) A power screwdriver makes this task much easier. Inside the crate there will be four padded 2"x4" studs holding the AVIC in place. Remove the sidewall screws to the studs and slide the studs out of the crate. Slide the AVIC out of the crate by its base. *Do not attempt to lift the AVIC by the latch handle on the lexan door. Do not attempt to lift the AVIC by the Stage Electronics box attached to the back of the unit. Neither of these points is designed to support the weight of the AVIC.*

Scanners   The scan head is packed in a separate box within the larger stage box. Open this box and inspect the scanner. The threads of the lens assembly protrude from the top of the scan head; this is protected by a red cap. The PZT and tip holder at the bottom of the head are protected by a metal sleeve called the "tip protector." The tip protector is fixed onto the head by a nylon screw. *Note that the tip protector must be attached to the scan head if the head is re-packaged and/or shipped, because even a slight lateral force can damage the PZT.*

2.3   ASSEMBLY

Arrange the components in the work area along the lines shown in Figure 2-1. Place the computer and the EIU on a regular office desk. Place the microscope stage on a separate sturdy table or workbench. This isolates the stage from the PC and EIU fan noise, as well as the table vibrations generated by the microscope operator with the computer mouse and keyboard controls.
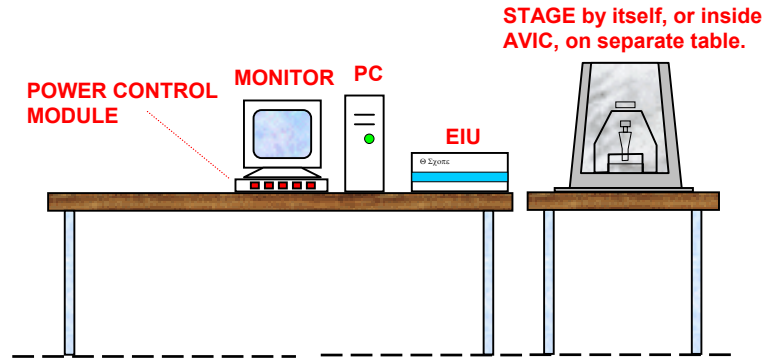
Figure 2-1 Suggested arrangement for the microscope system components.

❖Note: The *AC Power Control Module* is basically a fused power switch box with six AC outlets on the back panel controlled by six switches on the front panel. A power control module is provided by Ambios when the instrument is shipped to a country having 120VAC electrical power.   When the SPM is shipped to countries with 240VAC power it is up to the user to provide the power control module.

2.3.1 Installing the Scan Head

Care should be exercised to insure that the scan head probe holder (the gold colored piece at the end of the tube) does not bump into any surface.

Q-Scope Models 250/400

Refer to Figure 2-2. Remove the tip protector. The dovetail extension at the lower end of the scanner fits into the dovetail plate attached to the stage. The scanner should be positioned against the bottom stop of the dovetail plate.   Secure the scanner to the stage by tightening the thumbscrew on the right side of the dovetail plate.

Figure 2-2   Mounting the scanner into the Q-Scope granite stage.
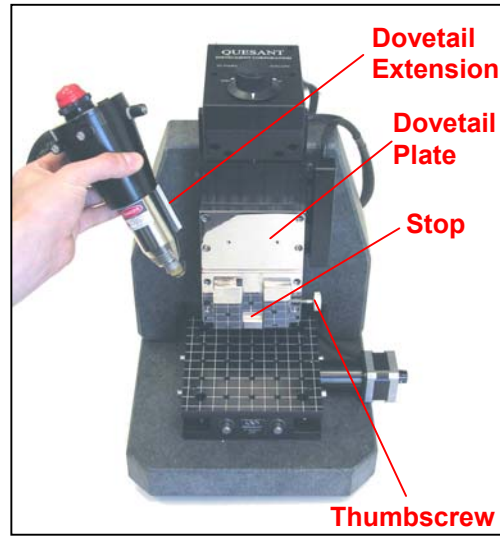
The Nomad

Rotate the large threaded ring counterclockwise so that its almost completely unscrewed from the stage. Place the stage on the surface to be imaged.   Remove the tip protector from the scanner and carefully insert it into the stage. Now rotate the threaded ring to bring the probe holder within about 1 mm of the surface. Tighten the thumb-screw.
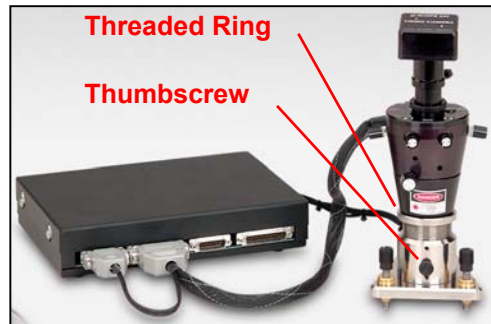
2.3.2 Installing the Video Camera

Refer to Figure 2-3. Remove the red plastic cap covering the threads of the lens assembly at the top of the scanner. The video camera and camera extension tube are located in the same shipping box as the scanner. Screw the extension tube onto the lens assembly threads until it is firmly seated. Then slide the camera body onto the top of the extension tube. The two electrical connections at the underside of the camera body should be oriented toward the back. Lock the camera in place with the black nylon screw.   Later, when the software is running and the camera is turned on, it will be necessary to adjust the position of the camera body on the extension tube to focus the camera image.
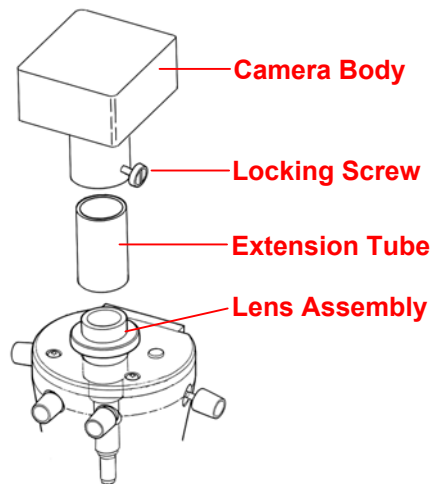
**Figure 2-3 Camera, extension tube,
and lens assembly.**

2.4   CABLE CONNECTIONS

A cable wiring diagram for the system is shown in Figure 2-4. Additional notes concerning the cabling are given below.

☐ **Power**   A 120 volt *AC Power Control Module* is supplied with all systems shipped to countries with 120V power lines.   For all other countries the user will need to obtain the power control module separately.

☐ **Computer Peripherals**   Connect the mouse, keyboard, and monitor to the computer following the instructions provided by the computer manufacturer.

☐ **Stage Electronics to Translation Stage**   The MiniStage motorized translation stage is an option for the Q-250. If you have this option, the stage electronics connections will be to the X and Y motors on the MiniStage. For Q-400 systems the stage electronics connections will be to the R and θ motors.

☐ **Camera to Stage Electronics and Computer**   Underneath the video camera housing are two connectors: a power input jack and a video output socket. Connect the camera's RCA-style video output receptacle to the video input of the video card in the computer. An adapter may be necessary between the RCA cable and the video card (this will be included with your system). Connect the camera's power jack to the Mini-DIN receptacle in the upper-left corner of the Stage Electronics box.

AC POWER CONTROL

Power   Aux1   Computer

To AC Power
Outlet

COMPUTER

120/240V AC

DSP
Video
Input

EIU

High Voltage Low Voltage

(15-Pin)   (25 Pin)

DSP

(37 Pin)

120/240
VAC

42 V

(3-Pin)

Z MOTOR

STAGE

4-Pin   Camera   EIU LV 25 Pin

9-Pin   Z Motor   EIU HV 15-Pin

Y / R

9-Pin   Y/R Motor

X / Θ   9-Pin   X/Θ Motor   Scanner 25 Pin

3-Pin   Motor 42V   15-Pin

**TRANSLATION
STAGE**

CAMERA

Camera   Video
Power
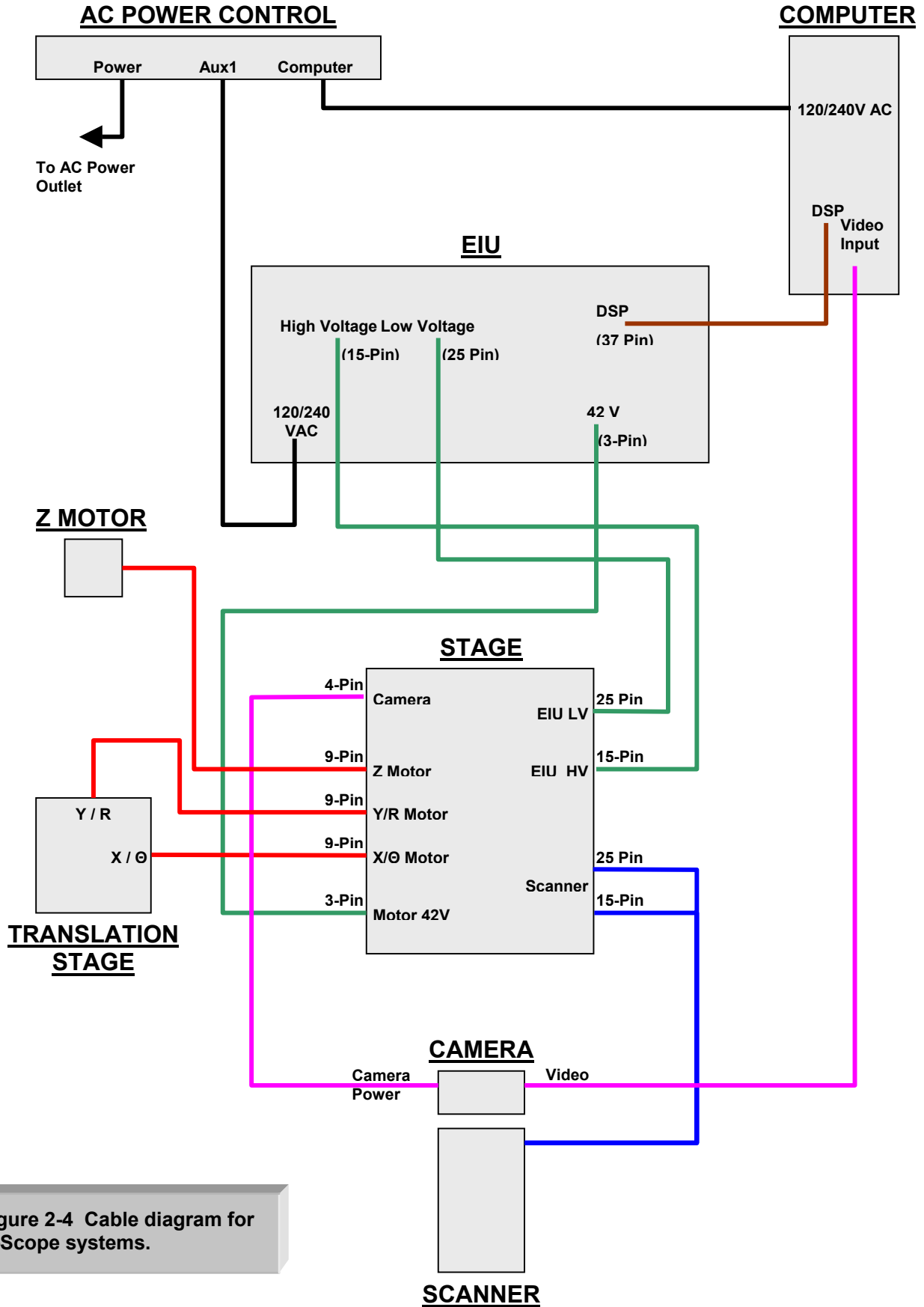
**Figure 2-4 Cable diagram for
Q-Scope systems.**

SCANNER

2.5   SOFTWARE INSTALLATION

2.5.1 Reinstalling/Upgrading the Software

All SPM systems are shipped from Ambios with the control software installed and fully tested with the instrument. A CD backup copy of the software package is included with each system. The contents of the CD (excluding optional RCP source code) are as follows:

- o A compressed file containing the ScanAtomic software to operate the microscope and the Qport software for data analysis. <ScanAtomic.cab>

- o A general library of SPM images. < Image_Library>

- o A utility folder containing software to manually install the Q-Scope's DSP interface software. <PciDsp>

- o An automated program for installing the ScanAtomic software onto a PC running the Microsoft Windows operating system. <autorun.exe>

- o A copy of the operator's manual in .pdf format.

Insert the CD into the drive and let the automated installation program guide you through the process. If the automated installation program does not start by itself it can be manually initiated by double clicking on the autorun.exe file icon.

It is strongly recommended that you install the software into a new folder, leaving the original SPM software installation intact as a backup in case something goes wrong in the new installation. This also helps you avoid the additional work required to perform a complete recalibration of your microscope from scratch. Simply copy the spm.ini file from your old installation folder into the new installation folder and the calibration will be recovered.

During the installation sequence it is normal to see several dialog boxes notifying you that an older file is about to be written in place of a newer file. This typically happens for one or more of the following files: comctl32.ocx, dao2535.tlb, wintvacc.dll, hcwwintv.ocx, wtvcap.ocx, and chsuite.ocx.   Unless you are instructed to do otherwise by Ambios, always select the option "keep the current version" at the dialog box notification.

❖Note: If you have purchased the RCP option refer to Section 2.5.3.

❖Note: If you are upgrading from ScanAtomic software versions 3.xx or 4.xx to version 5.xx then refer to Section 2.5.4.

❖Note: The Qport data analysis program must be registered with Ambios before it will be enabled. Instructions for registering Qport will be given when the program is started.

2.5.2 Installing the Software on a New Computer

If you wish to transfer the operation of your microscope to another computer you will have to install all the interface software for Ambios's DSP control card and the WinTV video camera card. The full process of installing the software is outlined below.   Refer to Sections 2.5.1 and 2.5.4 for related information.

❖Note: The order of theses steps should not be altered. In particular, do not install the DSP card before the WinTV card is succesfully installed.

1) Install the WinTV video camera card first. Instructions are provided in the manufacturer's booklet.

2) After the WinTV card has been installed shut down the computer. Insert Ambios's DSP card into an available PCI slot. Fasten the card in place. Connect the 37-pin ribbon cable from the EIU to the card.

3) Turn on the PC. The Windows operating system will generate a message box indicating that it has detected new hardware (the DSP card) and it will request the driver software for the new hardware.   This is located in the PciDsp folder of the installation disk.

   ❖Note: There are separate subfolder for the different versions of Windows: folder Win9xME is for Windows 95, 98, or ME; folder WinXP is for the XP operating system, etc. Follow the instructions given by the ReadMe.doc file within the subfolder that matches your operating system.

   ❖Note: Do not select the hardware installation option to have Windows automatically search for the best driver for the DSP card.   Windows invariably selects the wrong driver and fails to do the installation correctly.

4) Execute the ScanAtomic automatic installation program *autorun.exe*, as outlined in Section 2.5.1.

5) Restart the computer so that the DSP interface software will be registered into the Windows operating system.

6) Check the computer monitor display settings. The graphics must be set to a resolution of 1024x768, 16-bit color.

7) Turn on the EIU. Run the ScanAtomic SPM control software. Because this will be the first time the software is executed on this machine, message boxes will be displayed indicating that there is no calibration data

for the scanner.   Click 'yes' to these messages to save the default calibration data being created.

8)   Setup the hardware configuration parameter as explained in Section 2.5.5.

The software should now be fully capable of controlling the microscope hardware. A simple test to find if all is well is to press the *Withdraw* toolbar button and see if the scanner retracts a short distance.

❖Note: The Qport data analysis program must be registered with Ambios before it will be enabled. Instructions for registering Qport will be given when the program is started.

2.5.3 The RCP Option

The RCP software option is only available for version 4.05 of the ScanAtomic software. It will be necessary to have a separate 4.05 software installation on your computer to access the 4.05 RCP code. The latest release of ScanAtomic, version 5.00, does not support the RCP software option.

Refer to Chapter 2 of the 4.05 Operator's Manual for software installation instructions.

2.5.4 Upgrading to ScanAtomic 5.xx from Earlier Versions

The spm.ini file format for ScanAtomic software versions 3.xx and 4.xx is not compatible with the spm.in file format for software version 5.xx. If you are upgrading from one of these older versions of the software to 5.xx then you must take these steps after installing this version of the software onto the computer:

Before you start the new version of ScanAtomic:

- If you have a metrology system it will be necessary to manually transfer some of your EIU calibration settings from the older version of the software to the newer version.   In your old spm.ini file locate the text lines under the heading indicated below and transfer them into the new spm.ini file in the section having the same heading.

   [Head13] or **[Head14]** depending upon whether you have an 80 µm or 40 µm metrology scanner.
   CC(0)=xxxxxxxxxxx

       -- through --   Transfer

   CC(39)=xxxxxxxxxx

- If you have a USPM system with the STM option it will be necessary to manually transfer some of your EIU calibration settings from the older version to the newer version. In your old spm.ini file locate the text lines under the heading indicated below and transfer them into the new spm.ini file in the section having the same heading.

   [Advance Scan]
   nA_CurrentSensorRange=xxxxx
   nA_CurrentSensorOffset=xxxxx   } Transfer
   vBiasVoltageOffset=xxxxx

After you start the new version of ScanAtomic:

- Define the hardware profile for your system. (Ref. Section 2.5.4)

- Recalibrate each of your scanners. (Ref. Chapter 9 for Standard Mode, and Manual Supplement 6 for Metrology Mode.)

- Select a Graphics Editor program. (Ref. Section 7.8)

- Reset the AutoEngage cantilever profile data (Ref.   Section 5.6, *AutoEngage Cantilever Settings*).   The standard Wavemode cantilever has these settings:

$$\text{Type} = \text{NSC16}, \quad \text{kHz} = 170, \quad \text{Level} = 0.11$$

- If your system has a motorized translation stage, calibrate the camera view. (Ref. Section 6.2.2)

- If you have purchased the lithography option you will need to reinstall the lithography software using your original lithography installation disk, a 3.5" floppy. (Ref. Manual Supplement 1)

- If you have a metrology scanner or the STM option you will need to reset one of the factory calibration settings for the EIU. Open the **Advanced Configuration Parameter** window and double click on the *EIU Setpoint Offset* text box. The box will flash yellow momentarily and the value will automatically be set.

2.5.5 Setting the Hardware Configuration

Open the *Instrument Model Options* dialog box (**ScanAtomic** > *Utilities* > *Instrument Model Options...*) and check the option boxes as appropriate for your system hardware.

In the *Translation Stage* panel, the *Rotary* motorized stage is for the Q400 and the *MiniStage* motorized stage is for the Q250. *MiniStage* models purchased before c. 2000 were of the *OLS MiniStage* model type. All other models are *HS MiniStages*.

In the *WinTV Version* panel, all Q-Scope systems equipped for a camera view of the sample which were purchased after 1997 have the *WinCast* option.
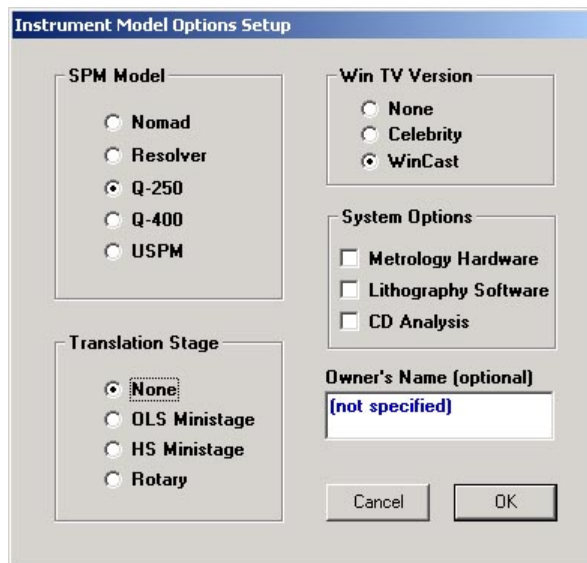
Figure 2-5 The Instrument Model Options Setup dialog box.

3   Basic Operation: Contact Imaging

This chapter serves two purposes: It provides a fairly detailed overview of the basic steps needed to image a surface an any scanning mode of the instrument, and more specifically, it explains how to image a surface in the scan modes where the probe tip remains in constant contact with the sample surface: *Z Height*, *Broadband*, and *Lateral*.

The basic steps required to image a sample are as follows:

- Power up the system.
- Select and install a probe.
- View the probe in the video camera.
- Align the laser optics.
- Set up the scan parameters for the selected imaging mode.
- Position the sample under the probe.
- Lower the probe onto the sample surface.
- Scan the surface.

These steps will be discussed sequentially .

3.1   POWERING UP THE SYSTEM

1. If your SPM system has an AC Power Control Module (Ref. Section 2.3) set the *Computer*, *Monitor*, and *Aux1* switch positions to ON. If your system does not have an AC Power Control Module then turn on the computer, the computer monitor, and the EIU electronics with the power switches on each device. The computer is usually started by pressing a power button on the front panel of the computer, but note that some computers have an additional AC switch on the back of the case.

2. The yellow ON light at the front panel of the EIU should be glowing, and the green READY light should be off. This indicates that the EIU is receiving AC power, but has not yet been initialized by the software. If the yellow light does not come on check the position of the power switch located on the back panel of the EIU.

3. The computer will boot-up automatically with the Windows desktop displayed. To start the SPM control software, double click the *ScanAtomic* icon on the desktop. (The SPM software folder can also be reached from the desktop. Use the *Start* button in the lower-left corner of the Windows desktop and navigate to *Start*

> *Programs* > *SPM*.)   When the software starts the ScanAtomic main window should appear on the screen, and the green READY light on the EIU front panel should glow. The green light indicates that the EIU has been initialized and is ready to control the microscope. If either the READY light does not come on or an error message is generated by the software refer to the Appendix for likely causes and solutions.

3.2   SELECTING A PROBE

Anatomy of a Probe

Commercially manufactured cantilevers are fabricated on wafers of silicon or silicon nitride using semiconductor industry technology, i.e., vacuum chambers, photolithography, sputtering, and ion beams. As manufactured, a single wafer will contain hundreds of 1.5 x 3.6 mm "dies", each having a tiny cantilever protruding from one end. The dies are very difficult to manipulate by hand because of their size. For ease of handling, Ambios mounts the dies onto magnetic stainless steel mounting preforms, referred to as "crosses." The crosses fit into a slot in the gold colored "probe holder" at the front of the scanner.   The left and right edges of a cross are called "tabs." It is easiest to manipulate a cross by grasping one of the tabs with tweezers.

Throughout this manual the whole cross-and-die unit is sometimes referred to generically as a "cantilever" or "probe."
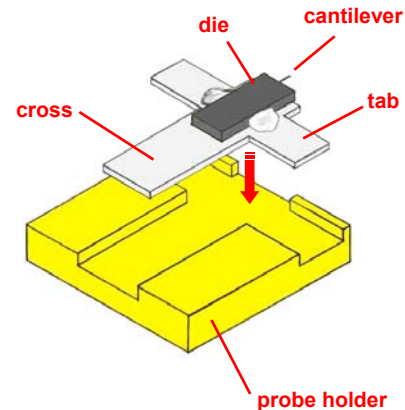
Figure 3-1 The probe and the probe holder.

Guidelines

SPM cantilevers fall into two classes: "Contact" type and "Intermittent Contact" type.   The characteristics of the surface you wish to scan, and the type of surface information you wish to obtain, dictate which type of cantilever you will choose.

Contact-type cantilevers work best in situations where the material to be imaged is reasonably hard (e.g. metals, ceramics, most polymers) and the surface topography does not have abrupt edges or tall, steep features. They are less expensive than intermittent type cantilevers. And because there are fewer instrument settings involved in using them, imaging a surface with contact cantilevers is easier than with intermittent cantilevers. Anyone new to the field of SPM microscopy should definitely learn to operate the microscope with a contact-type cantilever first. In

addition, contact cantilevers have the ability to detect lateral friction forces on the surface, when this type of measurement is desired.

Intermittent-contact cantilevers generally work well on all surfaces. They have the disadvantages of being more expensive and a bit more difficult to use, but they excel in imaging surfaces that are very soft (e.g. organics, polymer coatings) and surfaces with steep features.   Intermittent contact cantilevers also have the ability to detect the elastic and adhesive properties of surface materials, when this type of measurement is desired.

The above information provides a rough guideline for selecting a cantilever. Additional information is given in the sections of the manual covering specific modes of operation of the microscope. SPM systems are shipped from Ambios with one box of general purpose contact-type cantilevers and one box of general purpose intermittent-contact cantilevers.

3.3   INSTALLING A PROBE

The following steps pertains to the standard probe holder, which uses small magnets to hold the magnetic stainless steel cross in place.   Installation instructions for the optional nonmagnetic probe holder are given in Section 13.1.

1. The scanner incorporates a 5 mW class IIIa laser. To avoid eye injury the laser must be turned off whenever the head is removed from the stage. The laser on/off switch is located in the toolbar in the program's main window.

Laser ON/OFF

2. The scan head should be several millimeters away from the stage before removing it from the dovetail plate. If it is not, bring up the **Probe Position** window and hold down the *Z Fast Up* button until the probe is several millimeters away from the stage. (Ref. Chapter 6)

Figure 3-2 The front of the scanner: probe holder, cross, and tab.

Probe Position

3. Remove the scanner by loosening the thumbscrew on the dovetail mounting plate and carefully lifting the scanner off of the microscope stage.

When removing the scanner from the stage, take care not to bump or strike the probe holder, or the ceramic tube to which it is attached. Doing so may damage the PZT.

4. Place the scanner on a level surface, resting it on the flat end of the dovetail extension, with the probe holder facing you.

5. Refer to Figure 3-2. If a cantilever is already seated on the probe holder remove it by sliding the cross in the probe holder so that one of its tabs protrudes beyond the edge of the probe holder, and then lift it away with tweezers.

6. Open a cantilever box and select a replacement cantilever. The cantilevers are held in place within the box by a magnet pad. Using the points of the tweezers, slide the cantilever to the edge of the magnet pad so that a tab overhangs the edge. Then lift up the cantilever by the tab with the tweezers.   Do this carefully because if you drop it, it will most certainly be ruined. Lay the cross into the probe holder. With the points of the tweezers, center the cross laterally in the probe holder and then slide it fully forward.

7. Place the scanner back into the mounting plate on the stage.   The lower end of the dovetail should rest against a mechanical stop at the bottom of the mounting plate. Tighten the thumbscrew to lock the scanner in place.

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3.4   VIEWING THE PROBE IN THE CAMERA WINDOW

3.4.1 Opening the Camera Window

Probe
Position

The camera view of the cantilever is displayed in the **Probe Position** window. When the cantilever tilt is set correctly, and the view is properly illuminated and in focus, the camera view will appear similar to Figure 3-3. Refer to Section 3.4.3 if the camera view is out of focus.

Compare the cross, die, and cantilever positions in Figure 3-3 to Figure 3-2. Note that the cantilever is the only object in-focus. The front of the cross and the front of the probe holder are above the depth-of-field of the camera optics, and are blurred.   The sample surface beneath the cantilever is below the depth-of-field, and is also blurred. The cantilever will appear more distinctly in the camera view when the surface in the background is at least partially reflective. For example, the cantilever tends to disappear against the flat-black surface of the XY translation stage, but it can be viewed much more clearly if a glass slide is placed on the stage.

The illumination of the camera view is adjusted with the light intensity slider control in the **Probe Position** window.

Note that as the light intensity is increased a point may eventually be reached where the video camera's automatic brightness control feature will become active, and the camera view will not brighten even though the illuminator light intensity is increased. Avoid unnecessarily bright camera illumination settings.   Doing so will reduce extraneous heating effects inside the scan head.

Figure 3-3   The normal camera view of a "diving board" contact-type cantilever when it is several mm above the sample surface.   Other cantilever types may appear shorter, thinner, or V shapped.

The next three sections explain how to improve the cantilever view when the view is poor.

3.4.2 Adjusting the Cantilever Tilt

The tilt of the cantilever can be varied over a range of about $\pm 4°$ with the small tilt lever located at the back of the probe holder. The purpose of the tilt adjustment is to compensate for manufacturing variations in the tilt of the cantilever. Later, when the laser optics in the scanner are aligned (Section 3.5) the exact setting of the tilt lever will be made. Here, for the purposes of viewing the cantilever, it is only necessary to adjust the tilt lever to approximately the right position. If the tilt lever is set too low, as shown in Figure 3-4 (A), the cantilever will tilt steeply downward and reflect very little of the illumination light back toward the camera. The cantilever will appear to fade into the background. On the other hand, if the tilt lever is set too high as in (B), the cantilever will be close to horizontal and it will appear mirror-like in the camera window. The correct adjustment falls between these two extremes, as shown above in Figure 3-3. Adjust the tilt of your cantilever accordingly.
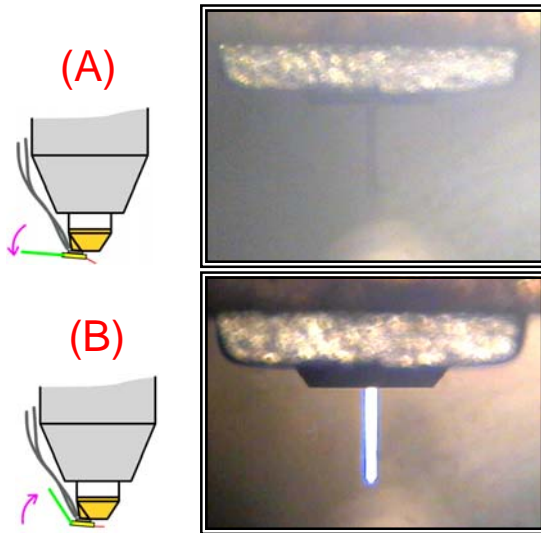
Figure 3-4 Cantilever appearance when the tilt lever is too low (A) and too high (B).

3.4.3 Focusing and Rotating the Camera View

Refer to Figure 3-5. Loosen the plastic locking screw on the camera body. By sliding the camera body along the extension tube the position of the focal plane of the camera can be varied. Rotating the camera body will rotate the camera image. Set the focal plane so that the cantilever appears sharply in focus in the camera image, and rotate the camera so that the cantilever falls along the y-axis of the video screen. Tighten the locking screw.
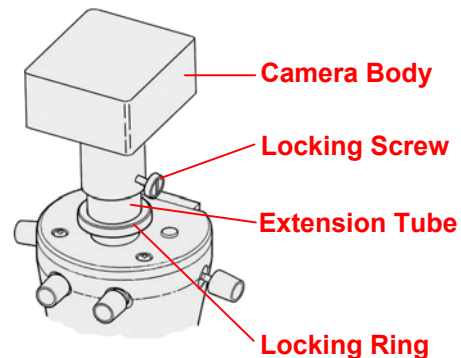
Figure 3-5 Camera mechanical adjustments.

Centering the Camera View

The camera view is centered at the factory; normally it will not be necessary to adjust it. If for some reason the cantilever position becomes shifted out of place in the camera view, however, do the following:

1. Loosen the locking screw and raise the camera body so that approximately 2 cm of the extension tube is exposed.

2. Unscrew the extension tube from the lens assembly by about a quarter of a turn. Tighten the locking screw to hold the camera in place.

3. Loosen the locking ring by unscrewing it by no more than a quarter turn.

4. The lens assembly will now be free to move laterally by about 1 mm in all directions. As the lens assembly is moved the center of the camera image will also move. Shift the lens assembly as necessary to center the cantilever near the top of the camera window. Then tighten the locking ring.

5. Screw the extension tube back down onto the locking ring surface. Refocus the camera image as described earlier.

Note that when the locking ring is loose it is also possible to rotate the whole lens assembly into or out of the scan head. Doing so will change the magnification of the camera optics. It is recommended that the magnification is not varied from the factory setting.

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3.5   ALIGNING THE LASER OPTICS

The position of the cantilever is measured by bouncing a laser beam off of its mirror-like back surface and detecting the angle of the reflected light. Due to manufacturing variations between different cantilevers, and variations in how the cross is inserted into the probe holder, it is necessary to adjust the laser optics every time the cantilever is changed.

There are three basic steps to aligning the laser optics of the scanner. The first step is to direct the laser beam onto the back of the cantilever. The second step is to adjust the tilt of the cantilever to direct the light reflecting off of the back of the cantilever toward the optical detector. And the third step is to adjust the position of the optical detector for the optimum laser signal. These steps will be covered in detail below. The alignment control locations, and the path of the laser beam inside the scan head, are shown in Figure 3-6.
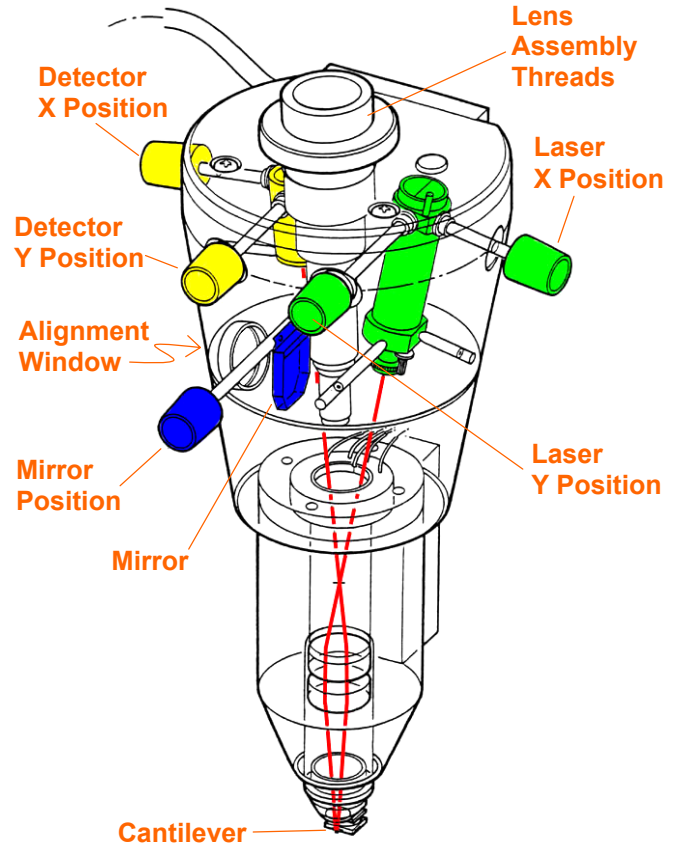
Figure 3-6 Laser alignment controls.

3.5.1 Directing the Laser Beam onto the Back of the Cantilever

First, locate the position of the laser beam in the camera window by rotating the *Laser Position* knobs to direct the laser onto the back of the cross, as shown in Figure 3-7(A). Once this is accomplished, shift the laser spot on the cross to a point just to the left of the cantilever, as it appears in (A). The spot is approximately 3 widths of the cantilever to the left of the cantilever. Now if the laser Y position knob is rotated counterclockwise by about a quarter of a turn the laser spot will slide off of the cross and down onto the end of the cantilever, as shown in (B). It will probably be necessary to also adjust the X position control slightly to center the laser spot on the width of the cantilever.

The camera images in Figure 3-7 show a diving board shaped, contact mode cantilever. The performance of the microscope is not sensitive to the exact laser spot position. For this type of cantilever, the laser spot may be positioned anywhere on the lower half of the cantilever's length.

Silicon nitride contact-mode cantilevers are V shaped for extra stiffness. They are usually manufactured in pairs at the end of the die. Either of the V's may be used, but the microscope may perform erratically if both probes contact the surface at the same time. When adjusting the laser beam position it is important to be sure that the laser is being reflected from the apex of the cantilever and not from one of the arms.
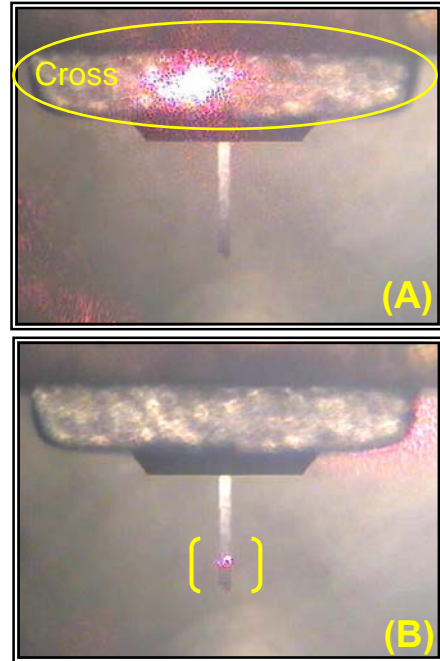
Figure 3-7

3.5.2 Adjusting the Cantilever Tilt

Rotate the *Mirror Position* knob fully counterclockwise. This will flip a small mirror inside the scan head into the path of the laser beam, redirecting the laser beam toward the alignment window on the left side of the scanner. The alignment window is made of frosted glass, and the laser spot will appear as a red dot on its surface.

When the cantilever is positioned properly the laser dot will fall near the middle of the alignment window. Exact centering is unnecessary: anywhere within the circle indicated in Figure 3-8 will be sufficient. If adjustments are necessary to bring the laser spot within the acceptance circle it is usually sufficient to just move the laser spot laterally. This is accomplished by adjusting the tilt of the cantilever. Refer to Figure 3-4. Move the tilt lever at the back of the probe holder up or down slightly as necessary to reposition the laser spot in the alignment window.
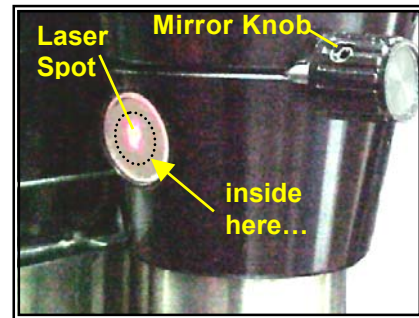
Figure 3-8 Alignment window.

It is usually unnecessary to center the laser spot vertically within the alignment window. When required, however, the laser spot can be shifted vertically by sliding the cross laterally within the probe holder. Note that when the cross is

moved the laser X and Y position controls will have to be readjusted to direct the laser beam onto the back of the cantilever.

Be sure to rotate the mirror position knob fully clockwise before continuing with the next alignment step— adjusting the optical detector position. A common mistake is to accidentally leave the mirror in the laser path, and then attempt to adjust the detector position for a laser signal that does not exist.

3.5.3 Adjusting the Optical Detector Position

Beam
Align

Open the **Beam Align** window (Figure 3-9). On the right side of the **Beam Align** window is a pointer placed against a logarithmic scale which represents the intensity of the laser light striking the optical detector. Within the central area of the window there is a red dot set against a green target pattern which graphically represents where the laser beam is striking the optical detector.

At this step in the alignment process the direction of the laser beam is fixed, and the red dot is moved in the target pattern by shifting the position of the optical detector with the detector's X and Y position controls. The correct position of the red dot is determined by the type of probe in the probe holder.   For contact mode topology imaging (that would be *Z Height* or *Broadband*, both to be discussed in the following sections) the correct position of the red dot is at the intersection of the vertical green line and the innermost target circle, as shown in Figure 3-9.

If after this final adjustment is completed the laser intensity pointer falls anywhere in the green zone, as indicated in Figure 3-9, then the laser optics alignment process is complete, and the **Beam Align** window can be closed. If the intensity falls in the yellow or red zones, however, then the laser signal is too weak for the microscope to work properly. This does not happen very often, but when it does happen further adjustments will be necessary.   The problem usually lies in the reflectivity of the cantilever.   There are two solutions.   The first is to use the laser position controls to redirect the laser to a more reflective spot on the back of the cantilever, and then readjust the detector position. The second solution is to replace the cantilever altogether and repeat the entire laser optics alignment sequence.

Figure 3-9   The Beam Align window, showing the normal laser beam position and laser intensity for contact mode imaging.

To better understand the operation of the microscope it helps to understand what is physically being adjusted by the position of the red dot.   Ultimately what this

adjusts is the contact force between the cantilever point and the surface when the probe is engaged with the surface. The contact force is determined by two factors: the spring constant of the cantilever and the distance the cantilever is deflected (bent). The distance of the red dot above the horizontal green line in the target pattern determines the distance the cantilever will be deflected when it is in contact with the surface.

For example, if the cantilever has a spring constant of 0.2 N/m, and the red dot is positioned in the normal way as in Figure 3-9 then the probe point will be pressed into the surface with a force of approximately 10^{-7} N during a scan. If the red dot is set higher than this, the cantilever deflection will be larger, and the contact force will be greater than 10^{-7} N. This tends to wear down a probe tip more quickly, and generally should be avoided.   On the other hand, if the red dot is set lower than the normal position the cantilever deflection will be smaller and the contact force will be lower than 10^{-7} N. This is better from the point of view of cantilever tip wear, but it also means that the vertical feedback circuitry will have a smaller force signal to work with during a scan. Scans may have to be performed more slowly, and the resulting image may be more noisy.

❖Note: Section 10.3.6 gives instructions on how to calibrate the cantilever optics to measure and adjust the contact mode scanning force.

❖Note: The **Beam Align** window access contols are disabled whenever the probe is engaged with the sample surface. Retracting the probe with the *Withdraw* command will re-enable the **Beam Align** access buttons.

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3.6   SETTING THE SCAN PARAMETERS

3.6.1 General Description

SPM
Configuration
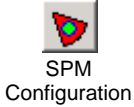
The scan parameters in the **SPM Configuration** window determine where and how an image is obtained. To achieve the best imaging results it is important to choose the most appropriate scan parameters for the sample being studied.

The dial controls work by the click and drag method: position the mouse cursor on the tip of the pointer of a dial, hold down the left mouse button, and rotate the pointer until the desired parameter value appears in the window. To increase the resolution of the rotary adjustment the cursor can be moved further from the center of the dial while the mouse button is held down.
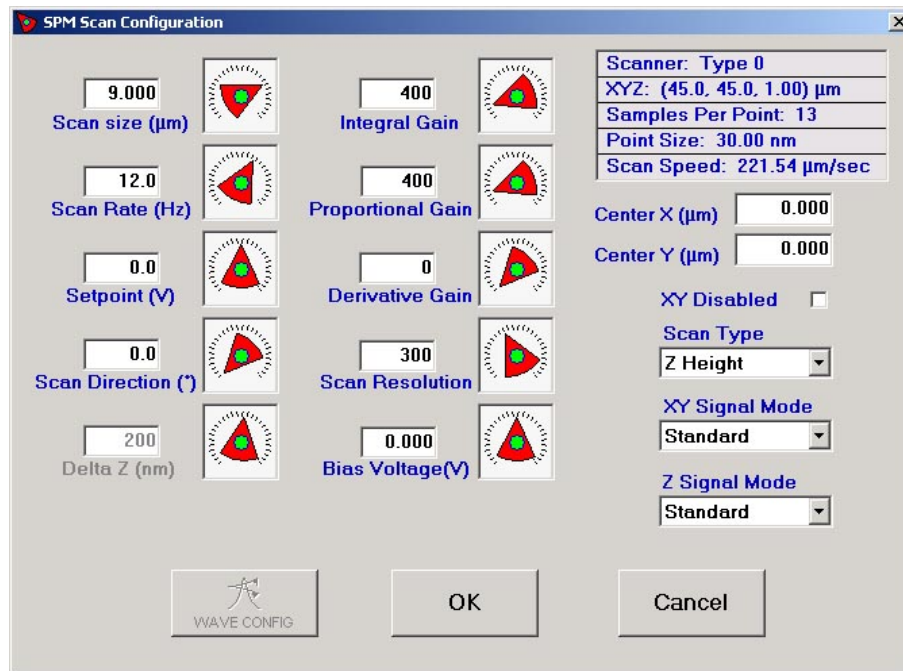
Figure 3-10 The SPM Configuration window.

The functions of the various controls in the **SPM Configuration** window are explained below. Note that some controls may be disabled at times, depending on the mode of operation of the microscope.

- **Scan Size** is the length of one side of the square area scanned. Thus, a value of 10 μm means a 10 μm x 10 μm area will be scanned. The smaller the value, the higher the magnification.

- **Scan Direction** sets the angle of the scan raster relative to the x-axis, which is defined as a vector running from left to right along the

microscope stage.   The usual setting is 0.0°; data will be recorded as the probe moves from left-to-right along the x-axis. Increasing the angle will rotate the scan counter-clockwise. The scan direction is normally changed only when it is necessary for the probe to move across certain features of the surface in a specific direction (e.g. perpendicular to a surface crack or step).

Figure 3-11 Coordinate relationships between the scan size, scan center, and scan direction

- **X Center, Y Center** specify the center coordinates of the scan relative to the center of the total scan area accessible to the scanner. For example, a 40 μm scan head can access a total scan area of 40 μm x 40 μm. The center of this area is defined as position (0 μm, 0 μm), thus *Center X* and *Center Y* may be varied over a range of -20 μm to +20 μm.

❖Note: If the probe is in contact with the surface when either of these coordinates is changed, pressing the *OK* button will cause the probe to move to the new coordinates at the currently defined scan speed (the speed is shown in the upper-right portion of the window). If the scan speed happens to be very slow, and the distance the probe must move is relatively large, then the time required to move the probe can be many seconds. If the required time is more than 3 seconds a message box will appear asking if it would be preferable to move at a faster rate, or if would be better to cancel the operation so that the *Center X,Y* coordinates may be redefined.

- **Scan Rate** sets the number of image lines scanned per second, e.g., a setting of 2 Hz means that two scan lines will appear on the screen per second.   Samples with sharp features should be scanned at a slow scan rate (≤ 0.5 Hz) to allow the feedback circuitry more time to react to sharp image contour changes. Slower scan rates imply more time to acquire an image, however.

- **Scan Resolution** is the number of image points in a horizontal line of the scan. This is also equivalent to the number of lines in the scan. Higher scan resolutions reveal greater surface detail, but require more time to acquire the image. Exploratory scans with a resolution of 300 are good. Final scans with a resolution of 400 to 600 are better.

- **Scan Type** selects between the different types of data which may be measured as the probe is rastered. The choices are listed below. First-time SPM users should select *Z-Height*, which is the simplest mode of operation.

  o *Z-Height* This is a contact-mode topology scan based on maintaining a constant force between the probe tip and the surface. The Z feedback loop makes the piezo tube contract and expand as necessary to keep the deflection of the cantilever constant. The image is formed from the Z control voltage of the PID circuitry. The Z control voltage is converted into a vertical distance with the Z calibration factor. (Ref. Section 9.2)

  o *Broadband* As in *Z Height* topology scanning, the system attempts to maintain a constant contact force between the tip and the surface during a *Broadband* scan.   The difference is that any deviations from the nominal constant force condition between the probe and the surface are corrected for during rastering. Deviations from the constant force state imply deviations in the deflection of the cantilever.   During a *Broadband* scan the deviation in the cantilever flexure is measured and this information is combined with the Z control voltage to produce a more accurate measurement of the surface profile. (Ref. Section 3.9)

  o *Lateral Force*   This is a recording of the twist of the end of the cantilever as it is rastered over the surface. During a contact-mode scan there will be a friction-induced shear force applied to the probe tip which will cause the entire cantilever structure to twist. The degree of twisting is, in part, a reflection of the strength of the frictional force between the probe tip and the surface. The frictional force may vary as the probe passes over different materials in the sample surface.   In favorable circumstances this can be used to extract information about where different materials are located in the surface topography.   (Ref. Chapter 11)

  o *BiLateral Force* The measurement performed here is the same as in *Lateral Force* mode, except that data are recorded for both the forward and reverse raster of each scan line.

  o *Wavemode* This produces a topological view of the sample surface. The cantilever is set into vibration with an amplitude of order 100 nm. Then the probe is lowered to the surface where it makes intermittent contact with the surface, damping the oscillation amplitude. Recall that in the contact imaging modes it is the *deflection* of the cantilever which is held constant by the Z feedback circuitry.   Wavemode differs from the contact modes in that the Z feedback circuitry expands and contracts the piezo tube as necessary to keep the *damping* of the probe's oscillation constant as it is rastered. *Wavemode* is discussed in Chapter 4.

o *BB Wavemode* This is another topological imaging mode. Similar to the *Broadband* mode, *BBWavemode* attempts to correct for any deviations from the ideal constant damping condition in a *Wavemode*-type scan. (Ref. Section 4.9)

o *Phase* During a *Wavemode* surface scan, not only is the amplitude of the cantilever's motion dampened as it bumps into the surface, but the phase of the motion is also shifted. Contact with different materials on a surface may cause this phase shift to differ. For example, a hard surface will advance the phase, while a soft or sticky surface will retard the phase. In favorable circumstances this can be used to extract information about where different materials are located in the surface topography. (Ref. Chapter 12)

o *BiPhase* The measurement performed here is the same as in *Phase* mode, except that now data are recorded for both the forward and reverse raster of each scan line.

o *ME Camp/Cphase/Tamp/Tphase* These four modes are used for both Magnetic Force Microscopy (MFM) and Electrostatic Force Microscopy (EFM). MFM maps the magnetic field gradients above a surface; EFM maps the electric field gradients above a surface. MFM is discussed in Chapter 13. EFM is discussed in Chapter 14.

o *C-AFM* This mode produces a map of the contact current between a conducting probe and the surface.   The required hardware is optional.

o *STM Log, STM Lin* Scanning tunelling microscopy. The hardware required for these modes is not available for Q-Scope and Nomad systems.

- **XY Signal Mode** selects between the different methods of rastering the probe across the surface. Systems fitted with the metrology option may be operated in *Standard* or *Metrology* modes of scanning. The *Metrology* mode is discussed in Manual Supplement 11. Microscope systems without the metrology option may only be operated in *Standard* mode.

- **Z Signal Mode** selects between the different methods of measuring the Z position of the probe tip. Systems fitted with the metrology option may be operated in *Standard* or *Metrology* mode.   The *Metrology* mode is discussed in Manual Supplement 11. Microscope systems without the metrology option may only be operated in *Standard* mode.

- **X/Y Disable** disables the X,Y raster during a scan. This is used in the system diagnostics discussed in Sections 9.3, 9.4, and 9.5. For normal operation this control box must be unchecked.

- **Setpoint** functions differently depending on the *Scan Type* selection:

  In all scanning modes based on rastering the probe with constant surface-tip contact (i.e. *Z Height*, *Broadband*, *Lateral Force*, and *BiLateral Force*) the *Setpoint* is normally left fixed at zero. Moving *Setpoint* to nonzero values has the same effect as moving the red dot in the **Beam Align** window closer or further from the horizontal green line: it changes the contact force during the scan.   A positive value decreases the value of the contact force; a negative value increases the contact force.

  In all scanning modes based on intermittent surface-tip contact (i.e. *Wavemode*, *BB Wavemode*, *Phase*, *BiPhase*, and all *ME* modes) the *Setpoint* is adjusted to set the damping of the probe oscillation during scanning. Typical values are in the range of -0.2 to -1.0 volts. This topic is covered in Section 4.7.

- **Integral, Proportional, and Derivative Gain** These three controls determine the response of the Z-axis feedback circuitry— the circuitry responsible for maintaining the probe deflection (contact mode), vibration damping (intermittent-contact mode), or tunneling current (STM mode) when the probe is engaged with the surface. These parameters determine how well the probe will follow the contours of the surface as it is rastered back and forth.

- **Scanner, XYZ, Samples Per Point, Point Size, Scan Speed** This is additional information about the state of the microscope. *Scanner* indicates the type of scan head attached to the microscope stage. *XYZ* gives approximate values for the range accessible to the scanner along the three axis of motion. *Samples per Point* specifies how many signal samples will be averaged to produce the final datum at each point in the image. The value of *Samples per Point* is determined by the settings for *Scan Rate* and *Resolution*. *Point Size* is the length and width of the square area represented by each image point. *Scan Speed* is the average speed of the probe's motion along the fast rastering direction. Its value depends on the *Scan Size* and *Scan Rate* settings.

- **Wave Config** is enabled whenever the *Scan Type* control is set to one of the modes requiring an oscillating cantilever. This includes *Wavemode*, *BB Wavemode*, *Phase* mode, and all *ME* modes. Pressing this button brings up the **Wave Configuration** window, which has controls for setting the frequency and amplitude of the oscillation. Information about how to use the **Wave Configuration** window is found in Sections 4.6 and 12.2.

- **Delta Z** is enabled when one of the *ME* modes of operation is selected. This determines how high the probe will be raised above the surface when the field gradient is measured. (Ref. Chapter 13 for MFM and Chapter 14 for EFM)

- **Bias Voltage**   This control sets the voltage of the probe holder. This is used in the STM, EFM, and C-AFM imaging modes.   For all other modes the bias voltage should be set to zero.

- **OK/Cancel**   Changes made to the settings in the **SPM Configuration** will not come into effect until the *OK* button is pressed. This action also closes the window.   *Cancel* reverts any control changes to their original settings.

3.6.2 Scan Parameters for Z Height Imaging

The scan parameters in the table below are a starting point for first-time work in *Z Height* imaging. Once reasonable images have been obtained with these settings move on to the next step of experimenting with the settings to get a feel for the instrument.

Scan Size	20 μm	Integral Gain	350	Image Mode	Z Height
Scan Rate	2 Hz	Proportional Gain	350	XY Disable	no
Setpoint	0	Derivative Gain	0	Center X	0.000 μm
Scan Direction	0 °	Scan Resolution	300	Center Y	0.000 μm
				XY Signal Mode	Standard
				Z Signal Mode	Standard

Table 3-1 Initial scan configuration settings for Z Height imaging.

The parameters with the most 'mystery' in the table above are the *Proportional*, *Integral*, and *Derivative* (PID) gains. Learning to adjust these parameters for the best performance of the microscope requires practice. It takes a while to develop intuition as to what settings work best in a given situation.

Here are some guidelines to get started: The derivative factor does not improve the image in most instances, so set the *Derivative* gain to 0.   Useful minimum and maximum settings for both the *Integral* and *Proportional* gain controls are typically 100 and 600, respectively.   Good performance is generally obtained when the *Proportional* gain is in the range of 1-3 times the *Integral* setting. When in doubt as to where to begin, start with the *Integral* and *Proportional* gains at 350 and modify the settings if the image quality is not as good as expected. Note that all three gain settings can be changed while the surface is being scanned, so the effects can be observed instantly. (Ref Section 3.8.1).

Low *Integral* and *Proportional* gains will be sufficient to image flatter surfaces, at slower scan rates, and over smaller areas. Conversely, rough surfaces with abrupt rising or falling edges, fast scanning, and the scanning of large surface areas require higher gains.

❖Note: If any of the gain factors is too high the scanner pzt tube will oscillate. When a gain control is only slightly too high the scanner oscillation will just produce fuzzy bands in the image near the rising or falling edges of the surface contours. The image quality is compromised in those areas, but otherwise the microscope functions normally. When a gain control is far too high, however, the image quality will be extremely poor, and a high-pitched audio frequency squeal will be heard coming from the scan head. This situation should be avoided. It will certainly damage the probe tip, and may damage the scan tube itself.

3.7   ENGAGING THE PROBE WITH THE SAMPLE SURFACE

In short, the first step is to manually lower the cantilever to within about 1.0 mm of the sample and position the area of interest under the probe point. The second step is to manually lower the probe to within about 0.2 mm of the sample surface and then initiate the automatic routine achieve surface contact.   Details are given below.

3.7.1 Positioning the Sample

Probe
Position

Making sure there is ample clearance between the cantilever and the sample stage, slide the sample under the scan head. Use the *Fast Down* button in the **Probe Position** window to bring the probe within 1.0 mm of the sample surface.

The probe should now be close enough to the surface for the surface features to be roughly in focus in the camera view. Adjust the camera illumination if necessary to get a clearer view.

Move the sample laterally to position the area of interest under the probe tip. This can be done by hand by sliding the sample on the sample stage. If the stage has manual X and Y vernier knobs, the sample may be accurately positioned by rotating the vernier knobs. Or if the stage is motorized, the sample may be positioned with the stage software controls.
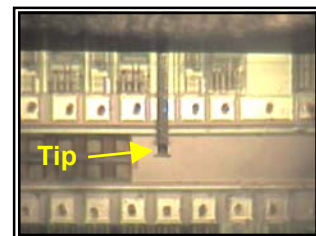
3.7.2 The Engage Window

The major elements of the **Engage** window are outlined below.
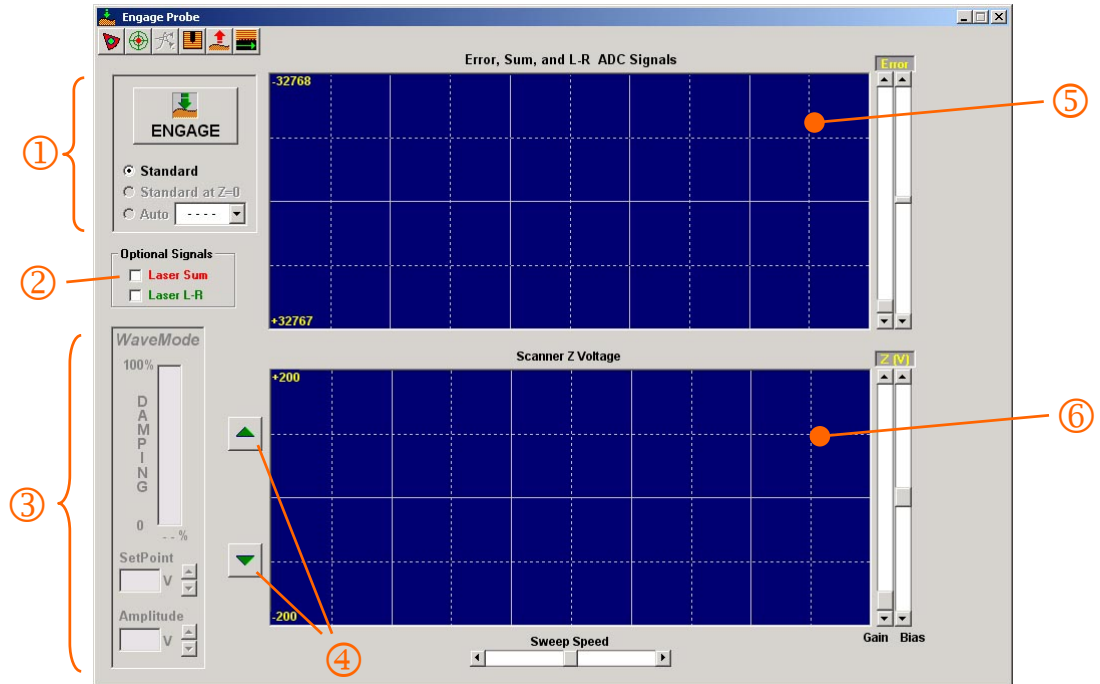
Engage

Figure 3-12   The engage window.

① The *Engage* button initiates the process of automatically lowering the probe to the sample surface. There are three engage methods: *Standard*, *Standard at Z=0*, and *Auto*. The *Standard* engage method is the simplest method, and is illustrated below. The *Standard at Z=0* and *Auto* engage methods are advanced features of the software which are described in Section 5.4.

② The two optional photodetector signals, *Sum* and *L-R*, may be plotted in the top graph by checking the appropriate box in this panel. These signals are rarely used. They are mostly applied in diagnostic testing of the instrument.

③ The *Wavemode* control panel is used to adjust the damping factor for intermittent contact AFM scanning. This topic is covered in Chapter 4.

④ The *up* and *down* arrows move the scan head up or down one step of the Z-axis motor at a time. This is useful for adjusting the expansion and contraction of the piezoelectric scan tube after the probe is in contact with

the surface. Each click of an arrow moves the probe approximately 0.25 μm.

⑤ This graph displays the *Error* signal in the Z feedback loop as a function of time.   Two other signals may also be plotted: the sum of the four photodetector outputs *Sum* and the difference between the left and right photodetector signals *L-R*. Normally only the *Error* signal is of interest.

⑥ This graph shows the voltage applied to the Z electrode of the scan tube as a function of time. The tube expands under positive voltages and contracts under negative voltages.

3.7.3 The Standard Engage Method

The *Standard* engage method is a two step process:

1. Use the *Fast Down* or *Slow Down* buttons in the **Probe Position** window to bring the probe tip to within about 0.2 mm of the sample surface. Because the cantilever is so small it is often difficult to judge the distance between the cantilever and the surface by eye.   As an alternative, try monitoring the gap between the gold probe holder and the surface as the scan head is lowered. When this gap is about 0.5 mm the cantilever will be within about 0.2 mm of the surface.
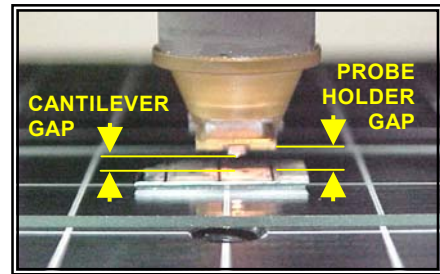
    ❖Note: If the cantilever becomes very bright in the camera window, or disappears all together, most likely the probe has crashed into the surface and is ruined. When this happens, raise the scanning head clear of the surface and replace the cantilever.

2. Open the **Engage** window, select the *Standard* engage method, and click the *Engage* button. The *Standard* engage method follows this sequence:

    a. The probe is completely retracted by applying the maximum negative voltage to the z piezo.

    b. The Z motor moves the scanner downward by a distance of approximately 1/2 of the Z Range of the scanner. For example, if the scanner has a total vertical range of 4 μm, the scanner will be lower by 2 μm.

> c. The voltage applied to the z piezo is increased linearly to extend the probe toward the sample surface.
>
> d. If the probe does not encounter the surface then the process cycles back to step (a) and repeats to search for the surface. If the probe does encounter the surface then two or three small steps are taken by the z motor to position the probe near the center of the voltage range and the engage sequence terminates.

The shape of the traces seen in the **Engage** window before the probe contacts the surface are indicated in time interval *A* of Figure 3-13. The relatively straight line in the top graph indicates that the z feedback loop has a constant positive error voltage, corresponding to the system state with the probe too far above the sample surface. The sawtooth pattern in the bottom graph indicates the expansion and contraction of the z piezo section of the scanner.

After the probe contacts the surface (Figure 3-11 B) the error trace should drop to zero (Figure 3-11 C) indicating that the Z feedback loop is actively keeping the loop error at zero, as it should. The message "Feedback On" will appear above the top window as a second indication that the Z feedback loop is active. The bottom trace should level off, and you should see the message "In Range" flashing above the lower graph. This indicates that not only is the feedback circuit active, but the expansion/contraction of the tube is within the total vertical range available to the scanner for imaging.
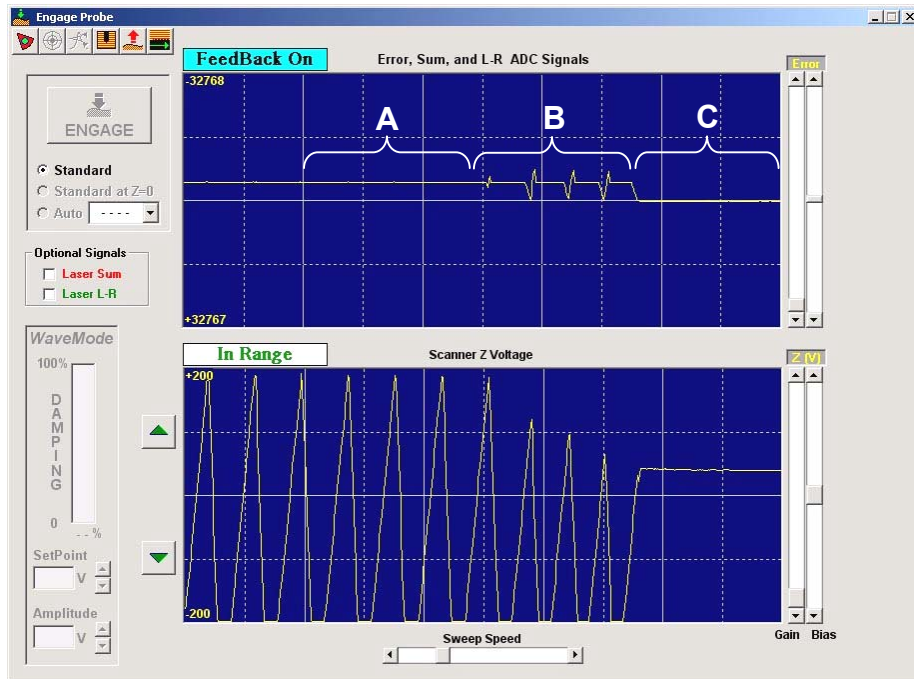
Figure 3-13 The signals seen in the Engage window during the Standard engage sequence, just as the probe reaches the sample surface.

3.7.4 Additional Information about Engaging the Probe

- The level of the *Error* signal in the top graph before the probe reaches the surface is a direct indication of how stable the feedback loop will be when the probe is in surface contact. If the level is almost zero this usually indicates that the laser optics are not set correctly and need realignment. Whenever this condition is noticed immediately abort the engage process, withdraw the probe from the surface, and realign the optics.

Withdraw

- After the engage process is successfully terminated as in Figure 3-13C the position of the trace in the bottom graph indicates the expansion/contraction state of the piezo tube within its total vertical range. For example, a 40 μm scanner has a total vertical range of about 4 μm. When the trace is near the middle of the graph the tube is near its rest state. When the trace is very high in the graph, the tube is expanded toward the bottom end of its range, -2 μm. This means the tube will not be able to expand down to track deep features in the surface. Conversely, when the trace is very low in the graph the tube is contracted toward the top end of its range, +2 μm. This means the tube will not be able to contract upward to track high features in the surface. There is the danger of crashing the probe into the surface when the tube is overly contracted, therefore this situation should be avoided.

    As an advanced feature for experienced SPM operators, the "z landing zone" for the automatic engage routine may be adjusted. See the Section 5.6, *Advanced Scan Parameters*.

- If while using the microscope the "In Range" message ever changes to "Lost Feedback" while the probe is nominally in surface contact it means that the tube is either over-expanded or over-contracted. This may happen after the system has been operated for a long time because of thermal drift, or because the probe happens to move over a very high or very low feature on the surface. When feedback is lost the options are to either *Withdraw* the probe and repeat the engage process, or use the *Z Up* and *Z Down* buttons to move the scanner back to within the Z scan range.

- If the SPM locks up at any point in time while the probe is in contact with the surface, withdraw the probe manually by turning the stepper-motor knob at the top of the microscope stage clockwise by at least a quarter of a turn. This will minimize the probe damage.

3.8   SCANNING THE SAMPLE

3.8.1 The Realtime Scanning Software

Realtime Scan

Once Z feedback has been achieved the sample can be scanned. All surface imaging is performed from the **Realtime** window. The major elements of this window are labeled below.
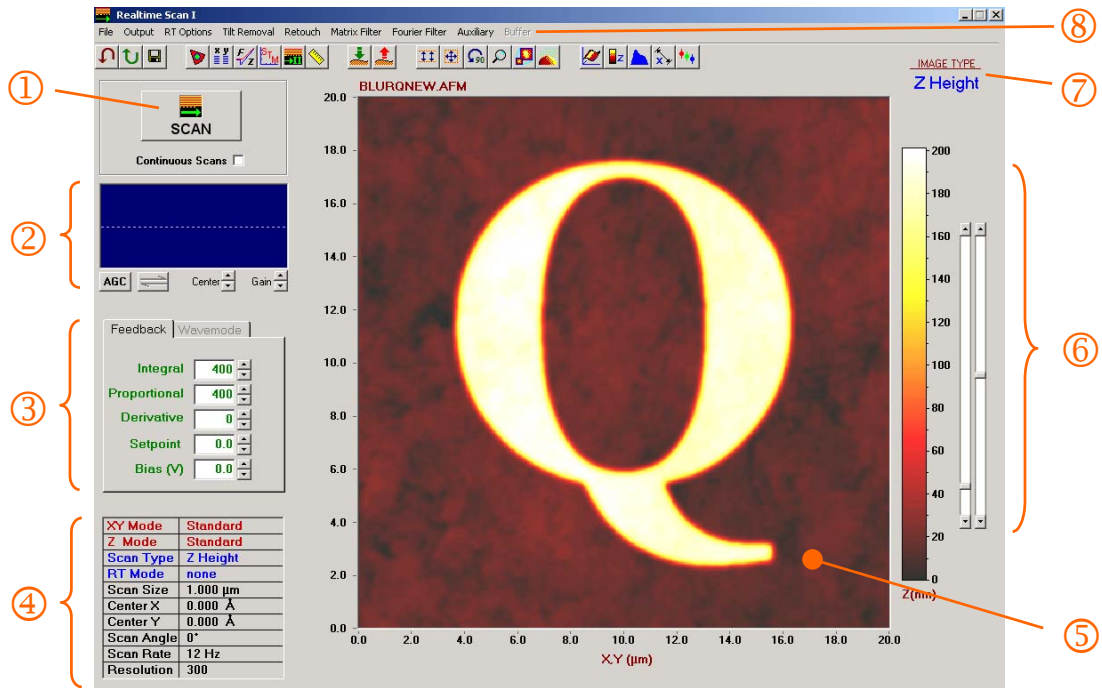
Figure 3-14 The Realtime scanning window.

①The *Scan* button initiates the scan process. Once a scan is underway this button switches to the *Stop* button, to allow the operator to stop the scan process at any time.   When the *Continuous Scans* check box is unchecked the scan process will stop when the end of the scan is reached. When the box is checked the scan process will be repeated over and over.

②This window graphically displays each line of the image data as it is acquired. In effect, it is showing a cross-section of the surface topology, or phase signal, etc., depending on the image type setting.

- When the *AGC* button is "up" the vertical scale of the graph corresponds to the maximum vertical scale of the data being measured. For example, this would be the full Z range of the scanner for a topology scan, or 65535

ADC units for a *Phase* mode scan. The *Center* and *Gain* controls can be used to manually shift and expand the section line view.

- When the *AGC* button is "down" the vertical scale is expanded and shifted so that the highest point in the data line reaches the top of the graph and the lowest point in a data line reaches the bottom of the graph.

In most scan modes the graph always corresponds to the image being created in the image panel, ⑤. The exceptions are the *BiLateral* and *BiPhase* modes. When scanning in either of these modes the user may display both the forward and reverse trace data with the ↔ button. When the ↔ button is "up" the graph corresponds to the image being created in the image panel, as usual, with the data appearing in green. When the ↔ button is "down", however, the complementary raster direction data are shown in yellow. The forward-reverse trace pairs are (Z, Z Reverse), (Lateral, Lateral Reverse), and (Phase, Phase Reverse). See ⑧ below for more details.

③ The PID gains, *Setpoint*, and the probe holder *Bias* voltage controls in this panel are identical to the controls in the **SPM Configuration** window. They may be adjusted at any time.   The PID gain controls allow the Z feedback loop to be optimized while scanning.

④ The parameters at the top of this panel, running from *XY Mode* down to *Resolution,* indicate where and how the scan will be performed when the *Scan* button is pressed. All of these parameters are identical to those found in the **SPM Configuration** window with the exception of *RT Tilt*, which is an advanced feature discussed in Section 5.3.

❖Note: These parameters are tied to the **SPM Configuration** window, not the image currently being displayed. Whenever an image is retrieved from the hard disk these parameters are not modified from their **SPM Configuration** window settings. To find information about the scan rate, resolution, scan angle, etc. for an image being viewed right-click on the image to bring up the **Scan Summary** window.

⑤ The scan data appear in the image panel, one line at a time as the surface is rastered, starting at the top of the panel. The scale units for the x and y axis are given at the bottom of the panel. The z-axis units are given at the bottom of the Z color scale. The type of image data being displayed is indicated by the *Image Type* parameter (See ⑦ below).

⑥ The numerical range of the z-axis of the image is shown in the Z color scale. This scale is updated 21 times during the course of an image scan: once when the very first scan line is acquired, then again as the image is 1/20, 2/20 … completed.   The *Contrast* and *Brightness* sliders to the right if the Z color

scale adjust how the palette colors are assigned to the height profile of the image.

⑦ The *Image Type* parameter specifies the type of image data being displayed in the image panel. For the various *Scan Type* settings there are as many as four sets of image information simultaneously measured by the microscope. Table 3-2 summarizes which *Image Type* information (i.e. Signals 1-4) is measured for each *Scan Type*.

⑧ While scanning the user can flip through the available buffer data using the **Realtime** window's *Buffer* pull-down menu list. The possible selections are given in the table below. The raw data may also be viewed after the scan is completed by flipping through the menu list, but note that changing the scan mode at the **SPM Configuration** window will disable access to the previous scan's raw data. Further information about the relationship between the software's raw data buffers and the z-buffer is given in Section 7.9.

Table 3-2   The image data measured for each Scan Type setting.

Scan Type	Signal 1	Signal 2	Signal 3	Signal 4
Z height	Z height	Error	ADC3	Lateral [†]
Broadband	Broadband	Error	ADC3	Lateral [†]
Lateral	Lateral	Error	ADC3	Z
BiLateral	Lateral	Lateral Reverse	Z	Z Reverse
Wavemode	Wavemode	Error	ADC3	Phase [†]
BB Wavemode	BB Wavemode	Error	ADC3	Phase [†]
Phase	Phase	Error	ADC3	Z
BiPhase	Phase	Phase Reverse	Z	Z Reverse
ME Camp	ME Camp	- - -	ADC3	- - -
ME Cphase	ME Cphase	- - -	ADC3	- - -
ME Tamp	ME Tamp	Z [††]	ADC3 [††]	- - -
METphase	Me Tphase	Z [††]	ADC3 [††]	- - -
Contact (I)	Current	Error	ADC3	Z
STM Log[†††]	Z	Error	ADC3	Current
STM Lin[†††]	Z	Error	ADC3	Current

[†] Available in Standard Z mode operation; not available in Metrology Z mode.
[††] For ME "T" modes Z is the height data recorded during the probe's first pass over each scan line, and ADC3 is the ADC2 channel data recorded during the probe's second pass over each scan line.
[†††] Hardware available on USPM systems only.

Error: The difference between the setpoint voltage and the voltage representing the cantilever flexure (contact mode) or vibration amplitude (intermittent contact).

ADC3: Normally just the sum of the four photodiode signals from the laser detector. In the software's *Advanced Scan* window this signal may be redefined to be the input from an external signal source (RCP systems only).

Z: The calibrated output voltage from the Z feedback circuitry, equivalent to *Z Height* or *Wavemode* when the Z signal mode is set to Standard.

Z Reverse: Equivalent to *Z Height* or *Wavemode*, but for the probe's return pass over each scan line. Z contains the data for the forward pass.

Lateral Reverse: Equivalent to *Lateral*, but the data are for the probe's return pass over each scan line. *Lateral* contains the data for the forward pass.

3.8.2   Scanning

At this stage of the process the probe should be in contact with the surface, and the system set and ready to scan. Whenever the *Scan Type* is changed at the **SPM Configuration** window the *Image Type* variable will always reset to Signal 1. So, for a *Z Height* scan type setting, the system will initially display *Z Height* image data when the *Scan* button is pressed.

Until you become familiar with the basic operation of the microscope it is best to turn off any pre-processing of the image data by going into the *RT Options* menu and making sure all the options are unchecked. This will make the *RT Tilt* parameter in the panel at the lower-left part of the **Realtime** window read "*none*."

To initiate a scan simply press the *Scan* button. When the scan size is about 5 μm or greater the movement of the cantilever can easily be observed in the video camera window. With a scan direction of 0.0º the probe will move to the upper left corner of the scan area and begin rastering from left-to-right, stepping through each scan line from top-to-bottom. Note that due to an optical illusion produced by the isotopic focal system, the sample rather than the cantilever will appear to be moving.

To permanently save a completed image select *File > Save As...* (Ref. Section 7.1.1). More information about the various menu controls in the **Realtime** window is presented in Chapters 4, 5, 7, and 8.

❖Note: Partial scan data may be recovered. When a scan is terminated before completion the previous completed scan is always returned to the z-buffer, but the partially scanned image can be recovered by clicking *Next*.

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3.9   BROADBAND IMAGING

3.9.1 The Broadband Concept

Z Height images are generated by laterally rastering the cantilever probe tip across the surface while the Z feedback circuit attempts to maintain a constant cantilever deflection. The surface height information recorded is a scaled version of the Z control voltage– the voltage which expands and contracts the piezo tube. Thus in Figure 3-15(i) the piezo contracts and expands as necessary to keep the cantilever deflection constant as it moves over the bump in the surface, and the height of this surface feature is proportional to the piezo voltage change.

But note that the resulting *Z Height* data are accurate only to the extent that the feedback control is able to maintain a constant flexure in the cantilever. Both the feedback gain factors (*Integral*, *Proportional*, *Derivative*) and the rastering speed of the probe affect the feedback circuit's ability to follow the surface contours. If the rastering speed is too fast the feedback circuit may not be able to respond quickly enough to maintain the flexure, as illustrated in (ii).   Hills in the resulting image become flattened, and valleys are filled in, as indicated with the green curve in (iii).

One way to scan surfaces at higher speeds is to increase the feedback gain. This must be done carefully, however, because increasing the servo gain may add electronic noise and transient oscillations to the image.
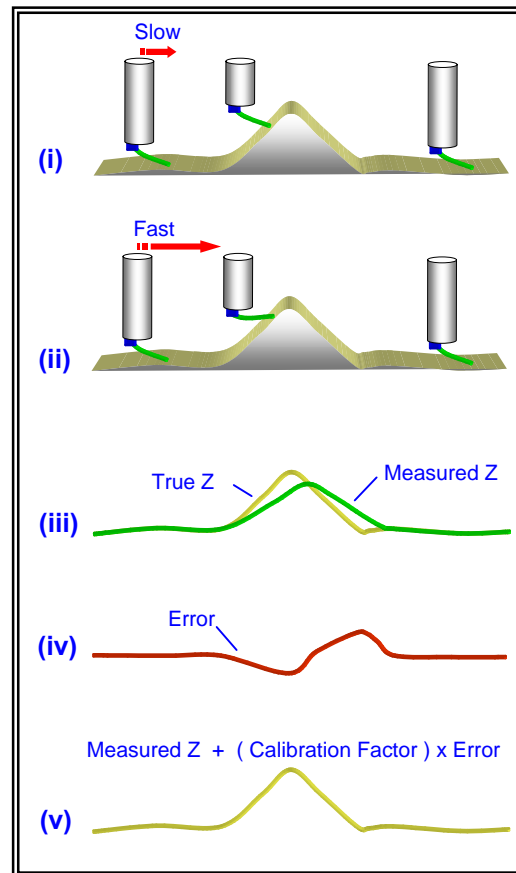
Figure 3-15   Broadband imaging.

A second way to scan at higher speeds is to switch to the *Broadband* imaging mode. In this mode the error signal generated by shifts in the cantilever flexure (iv) is used to correct the scan data. The error signal is calibrated so that shifts in the cantilever flexure are converted into a vertical distance error. This error distance is added to the measured Z-Height data to recover the correct surface topology profile (v).

The effect is illustrated in the series of scans of the standard calibration grating shown in Figure 3-16. The fine details observed in the 1 Hz scan are recovered at 20 Hz when the *Braodband* mode is used.

Z Height scan at 1 Hz.   Z Height scan at 20 Hz   Broadband scan at 20 Hz.
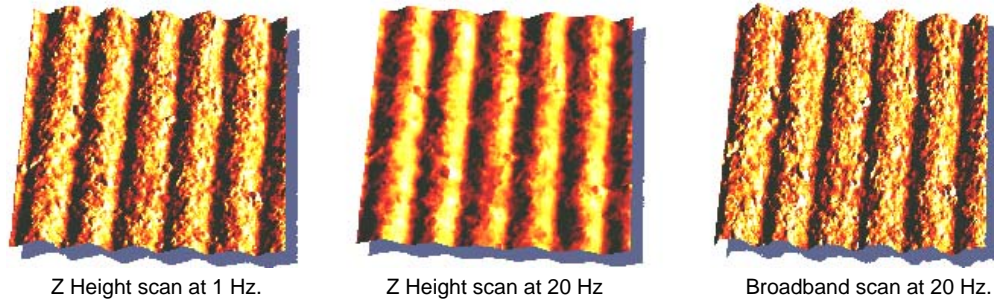
Figure 3-16   Left: slow scan of calibration grating in Z Height mode. Center: fast scan of the same surface in Z Height mode. Right: fast scan of the surface in the Broadband mode.

3.9.2 Setting the Broadband Calibration Factor

In order for *Broadband* imaging to work correctly the broadband calibration factor must be adjusted to match the mechanical properties of the installed cantilever. This is done at the **System Calibration** window.

Here are the steps for setting the *Broadband* calibration factor.

1. Engage the probe with a flat, clean, surface. N.B. To get an accurate calibration it is important that the cantilever point is not resting on the edge of a steep feature on the surface.

2. Open the **System Calibration** window and select the *Broadband* tab panel.

3. Click *Measure* to start the measurement. The program will change the *Setpoint* voltage by a small amount to make the deflection of the cantilever increase and decrease by a small amount. The measurement takes approximately 2 seconds.
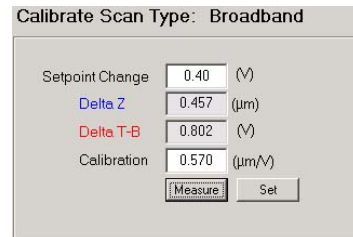
    The *Setpoint* change is adjustable. A typical value would be 0.4 volts for a contact mode cantilever (0.1 volts for an intermittent-contact cantilever).

At the end of the measurement two curves will be graphed as shown in Figure 3-17.   By measuring the distance moved by the piezo tube as the setpoint changes, *Delta Z*, and correlating this with the changes in the photodetector signal, *Delta T-B*, the program derives the necessary conversion factor to convert the movement of the cantilever into a vertical distance. The result is shown in the *Calibration* textbox.
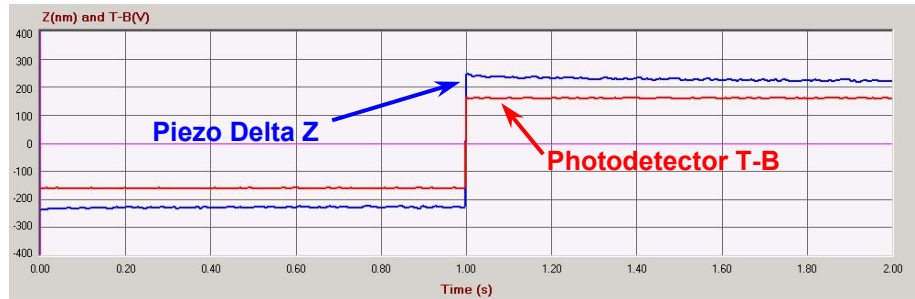
Figure 3-17 The vertical shift in the piezo position (blue line) and the corresponding change in the photodetector signal (red line) produced by changing the setpoint voltage by a small amount.

4. Examine the two graph lines. They should appear reasonably close to step functions. If the graph lines look odd, or noisy, try moving the probe to a different area on the surface or readjusting the laser to a different position on the cantilever.   If the photodetector signal is off-scale then repeat the measurement with a smaller setpoint voltage change setting in the tab panel.

5. The *Broadband* calibration factor varies between cantilever types. It depends primarily upon the length and stiffness of the cantilever. A typical value for the long diving board shaped contact-mode cantilevers is 0.8 µm/V. A typical value for an intermittent contact cantilever is 0.4 µm/V.   Press *Set* if the calibration factor you have measured seems reasonable.

❖Note:The calibration factor may also be adjusted manually by entering the value directly into the text box and pressing *Set*.

❖Note: For the most accurate results, whenever the cantilever in the scan head is changed, or the optics are adjusted, the broadband calibration factor should be re-measured before making *Broadband* scans of a surface.

❖Note: Systems equipped with the metrology scanner option have two vertical modes of operation: *Metrology* and *Standard*. The broadband correction is switched off in the *Metrology* mode of operation.

4   Intermittent Contact Imaging

4.1   OVERVIEW

4.1.1 The Intermittent Contact Imaging Technique

All intermittent-contact modes of operation of the microscope— this includes *Wavemode*, *BB Wavemode*, *Phase*, and *ME*— use stiff cantilevers which resonate at a frequency in the range of 70-200 kHz. A small piezoelectric vibrator mounted above the probe holder sets the probe into oscillation, and the operator adjusts the vibrator frequency to a point at or near the cantilever's natural resonance. The cantilever's oscillation is monitored by the laser photodetector, and it is this signal which is used in the Z feedback control circuitry. When the probe is lowered down to a surface, the motion of the probe is dampened on the extreme of its swing as it begins to contact the surface. The *Setpoint* control is adjusted to determine how much damping the Z feedback circuit seeks to maintain. A typical damping factor would be 50%.
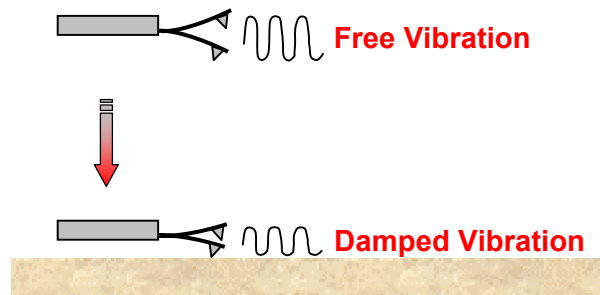
Due to the high "Q" (resonance quality factor) of intermittent-contact cantilevers, the response of the Z feedback loop to the vibration signal is about ten times slower than to the flexure signal in the contact modes of operation. Consequently, scan speeds for *Wavemode*, *BB Wavemode*, *Phase*, and *ME* imaging need to be slower. The maximum scan rate is about 4 Hz at large scan sizes.

There are several advantages to imaging in intermittent contact mode. Because the tip makes contact with the sample only at the very extreme of its oscillation, and because the contact time is very brief, shear forces and compressive forces can be very small, and surface-tip adhesive forces can be overcome. *Wavemode* excels when soft materials or materials with steep vertical features are to be imaged.

Note, however, that because of the more expensive probes, the greater tendency to break probes, and the more complicated adjustments required, the user is strongly

advised to become familiar with operating the microscope in contact mode before attempting intermittent contact operation.

4.1.2 Instrument Configuration

The steps required to setup the system for intermittent contact imaging are nearly identical to those for contact imaging. There are three differences:

- When the laser optics are aligned, the optimum laser position is at the center of the target pattern in the **Beam Align** screen.

- There is the additional step of adjusting the amplitude and frequency of the cantilever vibration.

- There is the additional step of setting the vibration damping factor before lowering the probe onto the surface.

The overall process of setting up the microscope for intermittent contact operation is outlined step-by-step in the following sections.   It is assumed that the operator is already familiar with the contact mode operation of the microscope, so that the procedure give here will not need to be described in as much detail as in Chapter 3.

4.2   INSTALLING A PROBE

Turn off the laser. Raise the scan head several millimeters away from the stage. Remove the scanner by loosening the thumbscrew on the dovetail mounting plate and carefully lift the scanner off of the stage. Place the scanner on a level surface, resting it on the flat end of the dovetail extension, with the probe holder facing you.

Open a cantilever box and select a replacement cantilever. Using the points of the tweezers, slide the cantilever to the edge of the magnet pad so that a tab overhangs the edge. Then lift up the cantilever by the tab with the tweezers. Lay the cross into the probe holder. With the points of the tweezers, center the cross laterally in the probe holder and then slide it fully forward.

Place the scanner back into the mounting plate on the stage.   The lower end of the dovetail should rest against a mechanical stop at the bottom of the mounting plate.   Tighten the thumbscrew to lock the scanner in place.
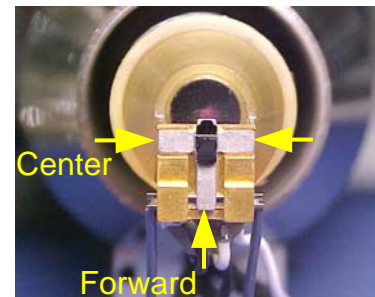
4.3   VIEWING THE PROBE IN THE CAMERA WINDOW

Probe
Position

Open the camera window with the **Probe Position** toolbar control and adjust the camera illumination and cantilever tilt to get a good view of the cantilever. If it is necessary to refocus, rotate, or center the camera view, refer to the instructions given in Chapter 3.
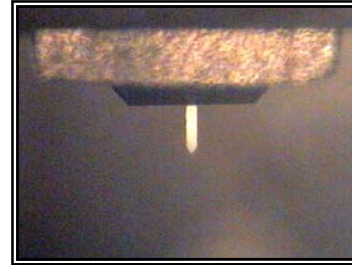
4.4   ALIGNING THE LASER OPTICS

1.   Direct the Laser Beam onto the Back of the Cantilever

Diving board style intermittent mode cantilevers are shorter than the same style of contact mode cantilever. The laser spot should be positioned somewhere on the lower third of the cantilever's length.
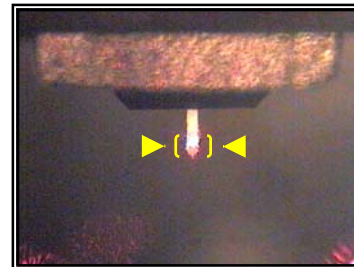
2.   Adjust the Cantilever Tilt

Rotate the mirror position knob fully counterclockwise to direct the laser beam toward the alignment window.   Move the tilt lever at the back of the probe holder up or down slightly as necessary to reposition the laser spot anywhere within the circle indicated at right. It is usually unnecessary to move the laser spot vertically within the alignment window. When required, however, the laser spot can be shifted vertically by sliding the cross laterally within the probe holder. Be sure to rotate the mirror position knob fully clockwise before continuing with the next alignment step.
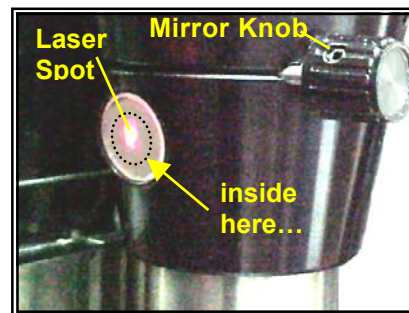
3. **Adjust the Optical Detector Position**

Beam
Align

Open the **Beam Align** window. For intermittent contact imaging the correct position of the red dot is at the center of the green target pattern, as shown in Figure 4-1.

If after this final adjustment is completed the laser intensity pointer falls anywhere in the green zone, as indicated Figure 4-1, then the laser alignment process is complete, and the **Beam Align** window can be closed. If the intensity falls in the yellow or red zones, however, then the laser signal is too weak for the microscope to work properly. This does not happen very often, but when it does happen further adjustments will be necessary.   The problem usually lies in the reflectivity of the cantilever.   There are two solutions. The first is to use the laser position controls to redirect the laser to a more reflective spot on the back of the cantilever, and then readjust the detector position. The second solution is to replace the cantilever altogether and repeat the entire laser optics alignment sequence.
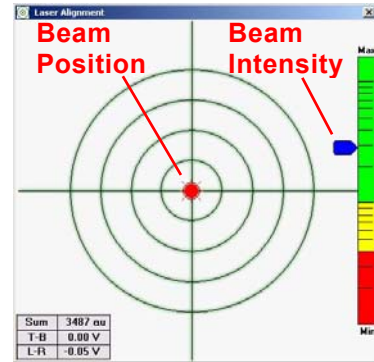
Figure 4-1 The normal laser spot position and laser intensity for intermittent-contact imaging.

❖Note: The position of the red dot adjusts the DC level of the oscillating photodetector signal. Ideally the DC level should be zero (red dot centered) so that the AC signal will have the widest possible range of operation.

4.5   SETTING THE SCAN PARAMETERS FOR WAVEMODE IMAGING

A detailed description of each control function in the **SPM Configuration** window is given in Chapter 3. The scan parameters in the table below are a starting point for first-time work in *Wavemode* imaging. Once reasonable images have been obtained with these settings move on to the next step of experimenting with the settings to get a feel for the instrument.

Scan Size	20 μm	Integral Gain	350	Image Mode	Wavemode
Scan Rate	1 Hz	Proportional Gain	350	XY Disable	no
Setpoint (see note)	- 0.7 V	Derivative Gain	0	Center X	0.000 μm
Scan Direction	0 °	Scan Resolution	300	Center Y	0.000 μm
				XY Signal Mode	Standard
				Z Signal Mode	Standard

❖Note: When the *Image Mode* is switched to *Wavemode* from one of the contact modes of operation, *Setpoint* will automatically be changed to -0.7 V. This value

is only roughly correct. The correct setting will be made at the **Engage** window when the *Damping Factor* is adjusted. This is explained in Section 4.7.

❖Note: The maximum useful PID gain settings will be lower in *WaveMode* compared to those in *Z Height* mode.

4.6   SETTING THE AMPLITUDE AND FREQUENCY OF VIBRATION

4.6.1 The Wave Configuration Window
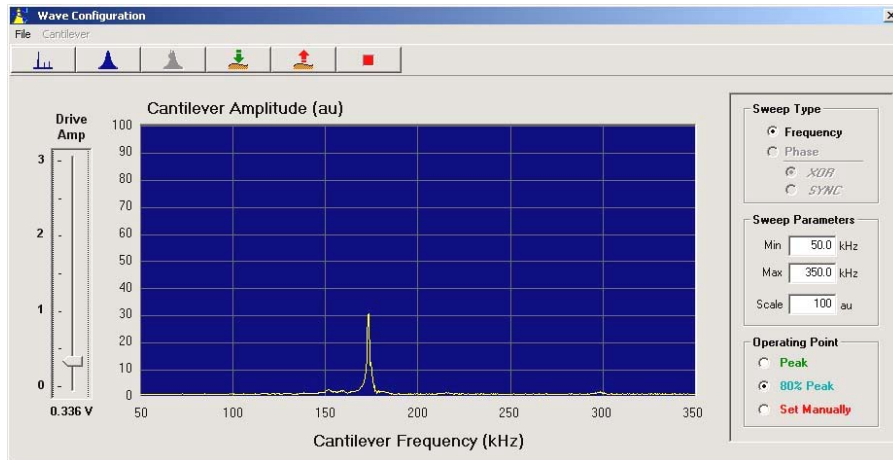
Figure 4-2   The Wave Configuration screen when a wide frequency sweep is under way.

Menu Controls

<u>File</u>

❖Note: When the *File* menu is clicked while the software is actively sweeping the frequency or phase the sweep will automatically stop, freezing the graph display. To initiate the sweep again use the wide or narrow sweep toolbar buttons.

- *Save Oscillation Data*   Saves the vibration amplitude or phase data as a text file.

- *Load Oscillation Data*   Retrieves saved vibration amplitude or phase data and plots it.

<u>Cantilever</u>

- *Calculate Force Constant*   This control is enabled when the **Wave Configuration** window is set to perform narrow frequency sweeps. When this software option is selected the system will perform a slow-sweep through the vibration resonance, lock the resulting graph data, and determine the resonance frequency and the Q of the resonance from this data. The resonance frequency and Q results, along with several other physical constants used to estimate the force constant of the cantilever, are posted in a panel appearing on the righthand side of the **Wave Configuration** window. Refer to the *Force Constant Panel* description below for further information.

Toolbar Controls
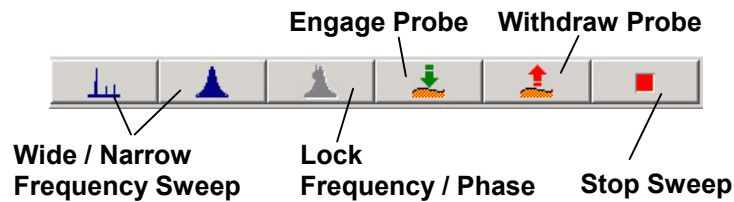
<u>Wide Frequency Sweep</u>

Sweeps the cantilever vibration frequency across a 50 - 350 kHz range. To automatically switch to a *Narrow Frequency Sweep* centered on the resonance, click the resonance peak on the graph.

<u>Narrow Frequency Sweep</u>

- When *Sweep Type* is set to *Frequency*, this narrows the frequency sweep to a range of 10 kHz centered on the most recently selected center frequency. The center frequency may be set an any time by clicking on the graph.

- When *Sweep Type* is set to *Phase,* the frequency is set to the most recent *Lock Frequency* value, and the phase detector is swept through 360 degrees. The phase detector amplitude as a function of detection phase is plotted.

<u>Lock Frequency/Phase</u>

- When *Sweep Type* is set to *Frequency*, the system will perform a slow-sweep through the vibration resonance and then fix the vibration frequency at the value determined by the *Operating Point* control panel selection.

- When *Sweep Type* is set to *Phase,* the detector phase is fixed at the angle manually selected by the operator. Refer to Section 12.2 for mor information.

Engage Probe opens the **Engage** window.

Withdraw Probe withdraws the probe from the sample surface.

Stop Sweep   The frequency or phase sweeping cycle will automatically stop, freezing the graph display. To initiate the sweep again use the wide or narrow sweep toolbar buttons.

Display Panels

Drive Amp Control

The slider adjusts the amplitude of the sine wave signal which drives the cantilever into vibration. The sine wave amplitude can be varied from 0 to 3.0 volts peak.

Graph Display: Vibration Amplitude vs. Frequency

This display shows a plot of the amplitude of the cantilever's oscillatory motion as the frequency of the sine wave driving the vibrator in the probe holder is swept.

The sweep range is 50 to 350 kHz when the *Wide-Sweep* button is pressed, or 10 kHz when the *Narrow-Sweep* mode is active.

The *Narrow-Sweep* mode may be manually activated by clicking within the *Signal Display* window at the desired center sweep frequency (e.g. click at 100 kHz to sweep from 95-105 kHz). It may also be manually activated by pressing the *Narrow Sweep* button, which will produce a 10 kHz sweep centered about the frequency where the oscillator was last locked. The narrow-sweep mode is automatically activated when the **Wave Configuration** window is reopened after the frequency has been locked.

The amplitude scale for the *Signal Display* is set to 0 - 100. The scale is arbitrary because the cantilever vibration signal depends upon the length of the cantilever and where the laser spot is positioned along its length. There is no fixed relationship between the vibration amplitude signal and the actual movement of the cantilever tip. Refer to Section 10.3.7 for instruction on on how to measure the cantilever vibration amplitude.

Sweep Type Panel

- **Frequency Sweep** Sweeps the cantilever vibration frequency between the minimum and maximum frequencies set at the *Sweep Parameters Panel*, and plot the cantilever's amplitude of vibration as a function of drive frequency.

- **Phase Sweep** The cantilever vibration frequency is locked to the most recent Lock Frequency value and the phase of the reference oscillator is swept through 360 degrees. The phase detector amplitude as a function of detection phase is plotted. (Ref. Section 12.2)

- **XOR**   select the Exclusive-OR gate phase detector. This generally has the better signal-to-noise ratio (SNR). The SNR ratio of the XOR detector is fairly independent of the cantilever drive amplitude over a wide amplitude range. (Ref. Section 12.2)

- **SYNCH**   select the synchronous detector output. This is essentially the output of a balanced mixer, so the amplitude of the output depends linearly on the cantilever drive amplitude, and sinusoidally on the phase difference between then the cantilever oscillator and the reference oscillator. The SNR of this detector depends on the cantilever drive amplitude. (Ref. Section 12.2)

Sweep Parameters Panel

- **Min**   The lefthand sweep limit for the graph display.

- **Max**   The righthand sweep limit for the graph display.

- **Scale**   The vertical range of the graph display. The scale units are arbitrary units (au).

Operating Point Panel

- **Peak**   The frequency where the cantilever vibrates with the largest amplitude.

- **80%**   The frequency point along the leading edge of the resonance curve where the amplitude is 80% of the peak value.

- **Set Manually**   A manually selected frequency or phase of the user's choice. The marker is moved with the mouse by clicking at the desired point in the graph display.

Force Constant Panel

❖Note: The force constant calculated here is only valid for "diving board" style cantilevers; it is not valid for "V" shaped cantilevers. The method is attributed to Dr. J. E. Sader. Reference: Rev Sci Instr, **70**, 1999.

- **Fluid Viscosity / Density**   The viscosity and density of the fluid the cantilever is vibrating in, typically air or water.

- **Cantilever Length / Width**   The length and width of a diving-board shaped cantilever. This information is provided on the manufacturer's data sheet.

- **Peak Frequency**   The resonance frequency of the cantilever's vibration.

- **Quality Factor**   Calculated as ratio of the full-width-at-half-maximum (FWHM) frequency range divided by the resonance frequency.

- **Force Constant**   The result of applying the parameters listed above to Sader's method of estimating a cantilever's effective force constant.

- **Recalc**   Any of the six parameters in this panel may be manually changed. By pressing the *Recalc* button the *Force Constant* will be recalculated with the new values.

4.6.2 Procedure for Setting the Oscillator Frequency and Amplitude

❖Note: If problems are encountered in locating the resonance or obtaining sufficient vibration amplitude refer to the end of 4.6.2.

1. Press the *Wide-Sweep* toolbar button. The frequency will scan from 50 kHz to 350 kHz, with a refresh rate of about twice per second. Raise the oscillator amplitude with the slide bar until a pattern of resonances appear in the frequency sweep.   The highest peak is generally the natural resonance frequency of the cantilever. This frequency is listed in the manufacturer's data specifications sheet. The frequency sweep may also show smaller secondary resonances at higher or lower frequencies. They are not important.

   Full Sweep

2. Narrow the frequency sweep to a 10 kHz interval about the main resonance by clicking the sweep display at the location of the peak. An expanded resonance curve will appear, similar to the one shown below in Figure 4-3.
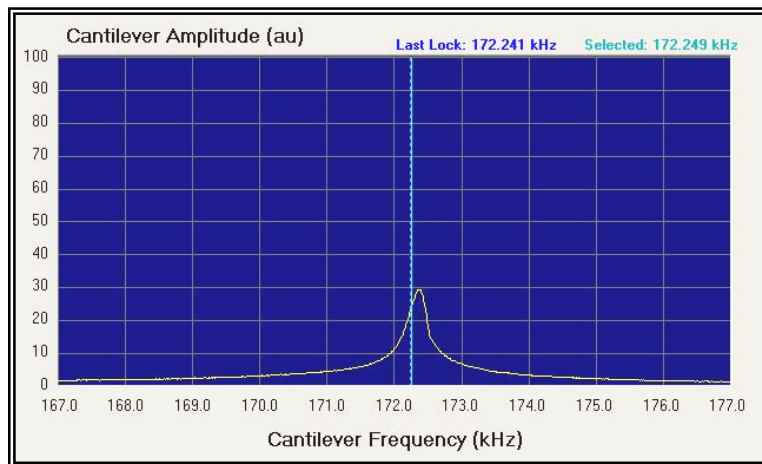
Figure 4-3 A 10kHz sweep through the cantiver resonance.

3. For many imaging situations the best amplitude is about 30%, as shown in Figure 4-3. Adjust the amplitude slider accordingly.

Lock Frequency

4. The final step is to select the operating frequency for surface scanning. For normal topology imaging the usual choice is the frequency at which the amplitude is 80% of the peak of curve. In the *Operating Point* panel select *80% Peak*, and then click the *Lock* button in the toolbar to lock the oscillator to the selected frequency. Pressing *Lock* generates one last slow frequency sweep to get the best frequency measurement.   Then a horizontal yellow line will be traced across the screen, indicating the amplitude of cantilever vibration at the selected frequency. Moving the *Drive Amp* slider will change the cantilever's amplitude at this frequency.

The system is now ready to engage the probe with the surface. Pressing the *Engage* toolbar button will close this window and open the **Engage** window.

❖Note: After the first pass through the above **Wave Configuration** frequency-lock steps, upon re-opening this window the software will immediately jump to step #2. If the cantilever has been changed then it may be necessary to press the wide-sweep toolbar button to locate the resonance point of the new cantilever.

More information about setting the oscillator amplitude

Raising the amplitude above the 30% level will give a larger signal for the Z feedback circuitry, making it more stable, but this comes at the cost of increasing the rate of wear of the probe tip. For this reason it is advisable not to raise the amplitude above 50%. Higher amplitudes also imply the surface will experience greater compressive stress when the probe touches the surface. Very soft materials may become mechanically distorted by the act of rastering the probe over the surface.   Higher amplitudes are essential only when scanning surfaces with high, steep surfaces (e.g., a 1.0 μm step height grating).

Conversely, lowering the amplitude below the 25% level will lower the kinetic energy of the probe, decrease the rate of probe wear, and lower the compressive stress applied to the surface.   This comes at the cost of decreasing the stability of the Z feedback circuitry, making it necessary to scan the surface at slower speeds. It is advisable to gradually gain experience with lower amplitudes to develop intuition as to how the system will perform.

Improving the Cantilever Resonance

There are two reasons why a cantilever may not resonate well. First, due to manufacturing variations, a given cantilever may have a low mechanical Q. Second, the acoustic coupling between the probe holder and the cross may be poor due to interface misalignment, dust, or other forms of contamination where the two pieces of metal touch. In almost all instances tackling the problem by improving the acoustic coupling will improve the resonance sufficiently for good microscope performance. Here are the remedies to try:

1. Make sure the slot in the probe holder is clean. If necessary, clean the slot with alcohol and a cotton swab. Do not use acetone or other strong solvents.

2. While observing the resonance in the **Wave Configuration** screen slowly move the tilt lever up or down. When the coupling between the probe holder and the cross improves the resonance peak will jump up.

3. Slide the cantilever in the probe holder slot either to the right or the left and then realign the laser optics. Sometimes the cantilever will resonate much better when the cross is not at the center of the probe holder.

(Blank Space)

4.7 LOWERING THE PROBE TO THE SAMPLE SURFACE

Engage

4.7.1 The Engage Procedure

1. Open the **Engage** window.   When *Wavemode* operation is selected at the **SPM Configuration** window the *Wavemode Damping* panel in the lower-left corner of the window will be enabled, as shown in Figure 4-4.
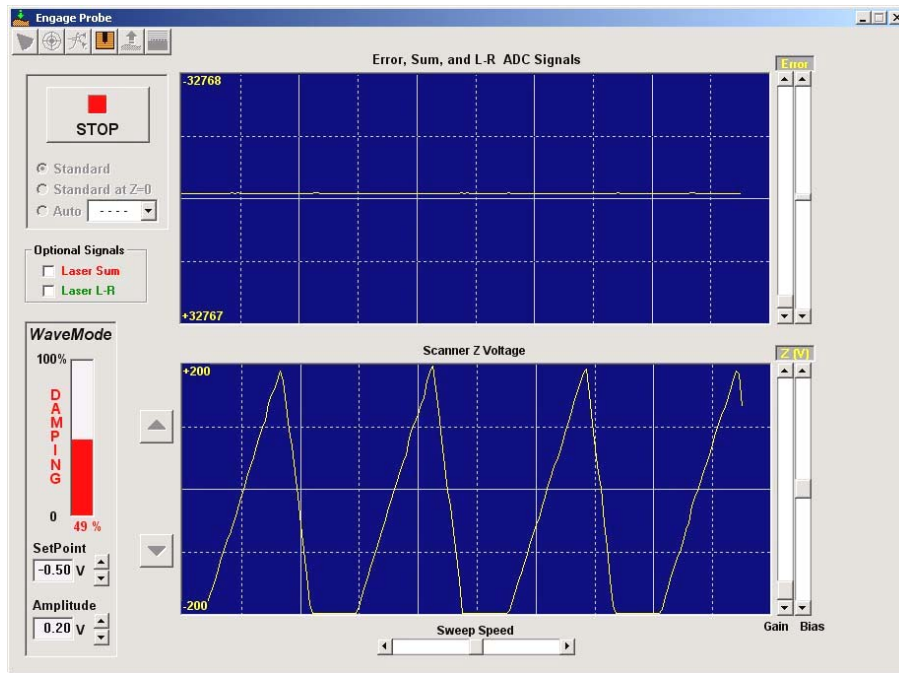
Figure 4-4 Appearance of the Engage screen as a Wavemode probe is being lowered to the surface. The Damping Factor has been set to 49%.

2. In the *Wavemode Damping* panel adjust *Setpoint* to make the damping indicator read close to 50%.   Information concerning the effect of using higher or lower damping factors is given in Section 4.7.2.

3. Initiate the *Standard* engage process by pressing the *Engage* button.   The Z motor will slowly lower the probe to the surface in steps of approximately 1/4 of the Z Range of the scanner.

   ❖Note: The *Error* signal level seen in the top graph is always lower in the intermittent-contact modes of operation than in the contact modes.

After the probe contacts the surface the error signal trace in the top graph should drop to zero, indicating that the Z feedback loop is actively keeping the loop error at zero, as it should. The message "Feedback On" will appear above the top graph as a second indication that the Z feedback loop is active. The trace in the *Scanner Z Voltage* graph should level off, and you should see the flashing message "In Range". This indicates that not only is the feedback circuit active, but the expansion/contraction of the tube is within the total vertical range available to the scanner for imaging.

❖Note: The damping factor indicator is switched off when the probe is in contact with the surface.

4.7.2   More Information about the Damping Factor Adjustment

The simplest interpretation of the 50% damping factor is as follow: With the probe off the surface the cantilever vibrates freely. This is the reference amplitude. When the probe is lowered to the surface the z feedback circuit's goal is to expand or contract the scan tube as necessary to reduce the vibration signal to 50% of the off-surface value. Thus a 100 nm free vibration amplitude of the cantilever will be reduced to a 50 nm intermittent contact amplitude when the damping factor is 50%. Similarly, a 40% damping factor will lead to a 60 nm intermittent contact amplitude.

The simple view is slightly complicated by the fact that when the probe is very close to the sample surface the amplitude is attenuated by air-damping effects as well as actual contact with the surface. This is illustrated in Figure 4-5. Between the 30 μm and 1 μm positions in the graph the amplitude of vibration gradually decreased from 400 nm to 200 nm. This is due to the increasing friction produced by the air in the narrowing gap between the cantilever in the surface. Consider how this affects the engage process: If the amplitude of vibration is set when the probe is at the 12 μm 'Withdraw Height', and the damping factor is set to 50%, then this means that the z feedback loop has been configured to seek and maintain an amplitude of vibration of about 0.5 x 350 nm = 175 nm. It can be seen that 3/5 of the required damping is introduced by the air damping effect before the probe reaches surface contact. It follows that the real damping factor being programmed is actually less than 50%. In this example it would be about

$$100\% \; x \; [\; (200\text{-}175) \; nm \, / \, 375 \; nm \;] = 7\%$$

Section 10.3.8 describes a technique for setting the damping factor to a known, measured value.

Generally speaking, the impulsive force the probe tip applies to the sample surface depends partly upon the damping factor setting and partly upon the cantilever

vibration amplitude setting. Off-surface settings of Amplitude = 25%, Damping = 50% work well in many situations. For a lighter surface touch on very soft surface materials the damping factor may be lowered and/or the amplitude setting may be lowered. Note, however, that this means the z feedback circuit will have a much smaller control signal to work with, and consequently the scan speed must be slower.
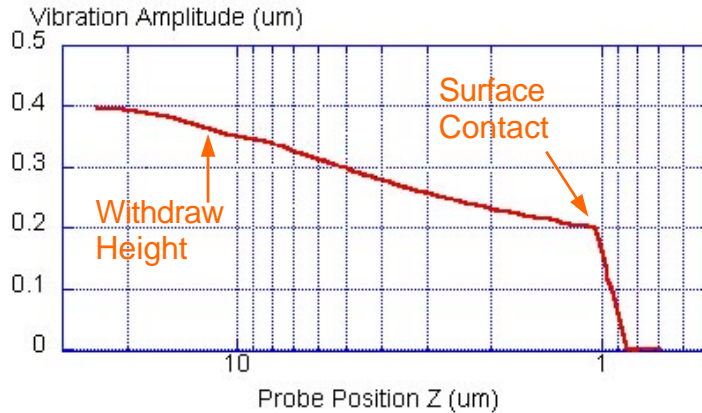
Figure 4-5 Amplitude of the cantilever's vibration as the probe is brought into surface contact, starting from a 30 µm separation.

4.8   SCANNING THE SAMPLE IN WAVEMODE

After the probe has been lowered to the sample surface the next step is to open the **Realtime** window and press *Scan* to start the scan sequence. Detailed information about the **Realtime** window controls is given in Chapter 3.

When the instrument is configured for any mode of operation requiring a vibrating cantilever, such as *Wavemode,* the *Wavemode Tab Panel* is enabled in the **Realtime** window (Figure 4-6). This tab panel has controls for adjusting the amplitude and frequency of the cantilever vibration, and the reference phase of the phase detector. Any changes to the amplitude and frequency made at the **Realtime** window should be made with care. Think of these controls as providing a means of tweaking the scan performance, to be used only in special imaging circumstances. For example, if a very flat ($\Delta z \cong$ nanometers), soft surface is being imaged there may be underlying structure which is elastically distorted by the intermittent contact force at the probe tip. To test for this, lower the amplitude by a small amount while scanning to see if image contrast improves and
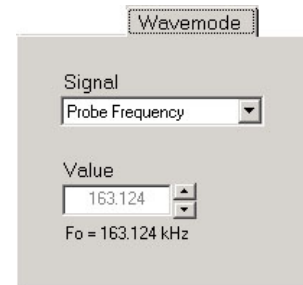
Figure 4-6   Wavemode tab panel in the Realtime window.

new image contours become visible.   Keep in mind that when the amplitude setting is lowered in this way it has the side-effect of increasing the damping factor. To decrease the amplitude and keep the damping factor the same it is necessary to retract the probe from the surface and go through the normal *Wavemode* adjustment sequence starting at the **Wave Configuration** screen.

Additional information about *Wavemode* scanning is found in Manual Supplement 13, *An Intuitive Model of the Probe-Surface Interaction in SPM Imaging*.

4.9   BB WAVEMODE IMAGING

The concept behind *BB Wavemode* is the same as *Broadband* (Ref. Section 3.9.1), but now applied to a vibrating cantilever. Once again, the error signal from the PID circuitry is scaled and added to the Z-axis position signal to improve the fidelity of the image. However, there is only about a factor of two improvement in the image quality with *BB Wavemode*— much less than in the case of the *Broadband*. This is because with a vibrating cantilever it takes time for the vibration amplitude to increase or decrease in response to changes in topology, and the resulting signal delay produces a slower Z response overall.

The instructions for calibrating *BB Wavemode* operation are identical to those presented in Section 3.9.2. A typical value for the tab panel control for the setpoint voltage change would be 0.1 volts for an intermittent-contact cantilever (0.4 volts for a contact mode cantilever).

As a reminder, be sure to recalibrate *BB Wavemode* whenever the cantilever is changed. The calibration factor will be lower with *Wavemode* cantilevers than with *Contact* mode cantilevers, because they are usually shorter. For example, a typical value for a 230 nm long *Wavemode* cantilever resonating at 180 kHz is 0.4 µm/volt.

❖Note: The *BB Wavemode* correction is turned off in metrology systems when the Z signal mode set to *Metrology*.

5   More About Scanning

5.1   MAGNIFYING THE VIEW: HARD ZOOM

Hard
Zoom

The size of a scan and the location of its center point can be set manually at any time at the **Configuration** window with the *Scan Size*, *Center X* and *Center Y* controls. The *Hard Zoom* control, found in the **Realtime** window, provides a graphical means of achieving the same result.

Hard Zoom is of great help when searching a large surface area for small objects of interest. Large exploratory scans can be made to search for the desired object, and then the *Hard Zoom* control can be used to perform a magnified scan of the object.

The steps are straightforward. Start with a completed scan in the **Realtime** window and then:

1. Click on *Hard Zoom* tool in the **Realtime** toolbar. The mouse cursor will change to a cross-hair when it is moved over the image area.

2. Move the cursor over the center of the feature of interest in the image.

3. Click and drag the mouse pointer away from the center. A square will form with its center at the selected point. The location and size of the square is indicated in a data box at the left side of the **Realtime** window.

4. Release the mouse button when the desired image size is reached.

5. If the selected area does not seem right in some way, click *Hard Zoom* again and redo the selection, starting at step #2.

6. Press *Scan* to perform a new scan of the selected region.

If it is only necessary to shift the center of the scan, but not change its size, this can be achieved more simply at step #3 by just double-clicking the image area at the desired center point and not dragging the mouse.

Additional Information about Hard Zoom

- Because of the inherent creep effects in piezoelectric scan tubes, a surface scan performed via *Hard Zoom* will initially tend to be distorted, particularly if there is a large shift in the center of the scan. (Exception: Metrology scanners

have no creep when operated in *Metrology XY* mode, and this distortion will not be present.) Each successive scan at the same location will improve in quality as the creep effect gradually subsides. Because of the creep effect, it is best to gradually zoom in on really small features instead of trying to magnify them by a large factor all in one step. As a rule of thumb, at each *Hard Zoom* step decrease the scan size by no more than about a factor of 3.

- It is possible with the *Hard Zoom* control to select a scan area falling outsize the scan range available to a particular scanner. Consider how this might happen with a 40 μm scan head: if the *Hard Zoom* request is for a 30 μm scan centered at x = 20 μm, y = 0 μm, the right edge of the requested scan area will exceed the 40 μm x 40 μm range of the scanner. Pressing *Scan* in this scenario would generate a message from the system indicating that the requested scan cannot be performed, and the scan size or scan center must be modified.

- If the probe is in contact with the surface when *Hard Zoom* is applied, the probe will be moved to the center coordinates of the new scan area at the currently defined scan speed (refer to the box at the upper-right portion of the **SPM Configuration** window). If the scan speed happens to be very slow, and the distance the probe must move is relatively large, then the time required to move the probe can be many seconds. When the required time is more than 3 seconds a message box will appear asking if it would be preferable to move at a faster rate, or if would be better to cancel the operation so that the *Center X,Y* coordinates may be redefined.

5.2   AUTOMATICALLY SAVING SCAN IMAGES

When the *AutoSave* feature is enabled scan images will be stored automatically at the end of every completed scan.

The **AutoSave** setup window is accessed via **Realtime** > *File* > *Setup AutoSave...*

To activate *AutoSave*, enter an alphanumeric string into the *Base File Name* text box, select which image data you wish to save from the *Save...* panel, and then check the *Enable Auto* Save checkbox.

How *AutoSave* works is best explained by example:
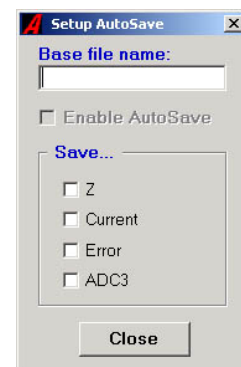
Suppose *Base File Name* is set to "MyScan", and the selected images to save are the *Wavemode* and *Phase* data.   The surface is scanned, and at the end of the scan two images are automatically save under the names "MyScan (1).afm" and "MyScan (2).afm". The first contains the *Wavemode* image and the second contains the *Phase* image. Scanning the surface again will create two more image files,   MyScan (3).afm and MyScan (4).afm, containing the next *Wavemode* and *Phase* images. And so on.

Continuing with this example, suppose "MyScan" was used in the morning to obtain images MyScan (1) through MyScan (8) and the ScanAtomic software is shut down.   Then in the afternoon the software is restarted and 'MyScan' is entered again for the base file name. At the completion of the first scan the software will display a message indicating that MyScan (1) already exists. It will ask if you wish to use the next available file name to store the data. If you reply 'yes' to this question the data will be saved under file names MyScan (9), MyScan(10). And so on. If you reply 'no' then the you will be prompted every time the software attempts to overwrite one of the pre-existing files.

The *Comments* field of the **Image Data Summary** will be filled with the image-type description before the image is saved. In the example above, the *Comments* field for MyScan (1) would read "Wavemode" and the comments field for MyScan (2) would read "Phase". Some other points to note about the *AutoSave* feature are:

- ❖Note: *AutoSave* works in the background using the Undo/Redo image buffers (Ref. Section 7.9). This means that after the selected images have been saved the text label above the image being viewed in the **Realtime** window will still indicate that the image has not been saved. If you press the *Previous* button, however, you will see the saved images which were autosaved.

- *AutoSave* can be turned on/off at any time with the *Enable Auto Save* checkbox.

- The following characters are not allowed in the base file name string: */.:<>?()

- The *AutoSave* feature is used by the software facility for scanning a surface at a preset sequence of coordinates. Refer to the **Scan Sequence** software description in Section 6.3.

- The maximum number of images which may be saved under one base file name is 32767.

5.3   AUTOMATIC TILT REMOVAL WHILE SCANNING

To maintain the maximum image information you would scan and save the raw data before modifying it in any way. But sometimes it is significantly more convenient to apply correction factors to the scan data as the image is acquired, so that the improved image can be seen in "real time." There are four real-time tilt removal methods built into the SPM software: *RT Parabolic, RT Edge, RT L/L Parabolic*, and *RT Topology Map.* They can be selected or deselected with the **Realtime** > *RT Options* menu.   The tilt correction operations can be applied to any of the available raw image data buffers generated by a particular *Scan Type*. (Exception: *RT Topology Map* may only be applied to surface topology data.) The selection is made from the list at the bottom of the *RT Options* menu. A description of each *RT* method follows.

- **RT L/L Parabolic**   As each scan line of image is measured the software calculates the coefficients of a parabolic fit to the data, and then subtracts the parabolic curve from the data.

  RT L/L Parabolic works well to flatten the profile of a known flat surface, e.g. a silicon wafer. It also can be used to automatically remove the effects of thermal drift, which would otherwise cause the image to tilt along the y-axis.

- **RT Edge**   When this tilt removal method is selected the software will perform the preliminary task of moving the probe around the perimeter of the scan area prior to starting the imaging raster. As the probe moves around the edges of the scan area the average height of each of the edges is computed, and from this information the tilt of a plane which represents the general tilt of the scan area is determined. This tilt is subtracted from the scan data as the probe is rastered, flattening the image.

  If *Continuous Scans* is checked and the scan process isn't interrupted, in the second and subsequent scans of the surface the average tilt of the surface is recalculated at the end of each scan using the new image data, and the updated tilt correction is then applied to the next scan.

In favorable circumstances *RT Edge* will remove most of the tilt in a surface, slightly modify the appearance of the over-all curvature, and generally emphasize any small features present. *RT Edge* does not work well if the edges of the image are not on the same plane. For example, the image will be tilted upward along the x-axis when a diffraction grating is scanned if the left edge of the image falls in a trough and the right edge falls on a crest.

❖Note: Any drift in the z position of the probe will reduce the effectiveness of the tilt correction along the y-axis of the image.

- **RT Parabolic**   When this tilt removal method is selected the software will perform the preliminary task of moving the probe across the center of the scan area along both the vertical and horizontal directions prior to starting the imaging raster. Height information obtained during these preliminary passes is fit with a paraboloid contour, which is subtracted from the scan data as the probe is rastered, flattening the image.

  If *Continuous Scans* is checked and the scan process isn't interrupted, in the second and subsequent scans of the surface the paraboloid contour is recalculated at the end of each scan using the new image data, and the updated contour correction is applied to the next scan.

  ❖Note: Any drift in the z position of the probe will reduce the effectiveness of the tilt correction along the y-axis of the image.

- **RT Topology Map**   *RT Topology Map* helps to correct a problem observed with all scanners: When a perfectly flat surface is scanned without any pre-processing of the data, the image obtained will always appear tilted and curved. These imperfections are due to the inherent non-ideal characteristics of the piezoelectric scan tube and mechanical misalignment of the sample stage or scanner.

  The central idea behind the *RT Topology Map* correction method is that if a scanner is asked to scan the same area of a flat surface in the same way (scan speed, resolution, etc.) the distortion will more-or-less remain the same. This being the case, its reasonable to record this distortion and then apply it as a background image correction for any scan performed with the same settings.

❖Note: This feature is intended to be used with *Z Signal Mode* set to *Standard Z*. In *Metrology Z* mode the scanner performance is already very flat by design and this feature is not needed.

The steps required to use *RT Topology Map* are:

A. **Calibrate the RT Map**

　　1)　Place your fatness standard— a known microscopically flat, clean sample— under the scanner and image the surface. If the area selected shows any large dust particles or other prominent defects then move to a different area on the surface and scan again.

　　2)　Turn off all *RT Tilt* correction options. Set the scan rate, size, resolution, etc to the scan values you wish to create an image map for. Rescan this area repeatedly until it is clear that any thermal and mechanical drift in the microscope has attenuated to a low level, and the images appears the same from scan-to-scan.

　　3)　Select *RT Topology Map > Options > Define Map Surface*. The surface will be filtered using the *Segment Low-Pass Filter* along both the x and y axis of the image to retain just the overall undulation of the surface profile. From this filtered image a reference topology map will be calculated and stored.

　　　　❖Note: You may wish to save several scan images of your reference flatness standard under different conditions (scan size, resolution, etc.). These images may be reload later at any time to generate alternative topology calibration maps by going directly to step 3 above.

B. **Apply the RT Map Option**

The ScanAtomic software automatically recalls the stored *RT Map* calibration data when the **Realtime** window is opened. To view the scan settings used to generate the calibration, select *RT Topology Map > Options > Review RT Map scan settings*. The values will be posted in a message box.

The *RT Map* option is enabled only when the **SPM Scan Configuration** settings match the calibration settings.   To

automatically make the current settings match the calibration settings select *RT Topology Map > Options > Apply RT Map scan settings*.

Once it is enabled, select the *RT Topology Map* option from the *RT Option* list. Surface scans should be noticeably flatter with this correction activated.

❖Note: *RT Topology Map* will be disabled automatically if the **SPM Scan Configuration** settings are changed from the calibration settings.

❖Note: Any drift in the z position of the probe will adversely affect the tilt correction along the y-axis of the image.

5.4   ENAGAGE OPTIONS

There are three methods for engaging the probe with the sample surface: *Standard* engage, *Standard at Z=0* engage, and *Auto* engage. The *Standard* engage method is the safest, most basic way to engage the probe with the surface. It is described in Chapers 3 and 4. The main disadvantage of *Standard* engage is that it slow. It requires the operator to bring the probe very close to the sample surface to minimize the engage time, and this can be a bit tedious.

The *Auto* and *Standard at Z=0* engage options are much faster, but there are caveats associated with these methods which should be understood before applying them. In particular, *AutoEngage* only works with wavemode cantilevers, and it is not guaranteed to work with every cantilever inserted into the probe holder. *Standard at Z=0* works with all probe types— AFM cantilevers, STM probe wires, and the Hystron Triboscope module— but it is absolutely essential that the operator set the Z=0 level correctly or the probe will crash into the sample surface.

Detailed information for *Auto* and *Standard at Z=0* engage methods is given below.

5.4.1 AutoEngage

Auto Engage follows a two step process. In the first step the system sets the cantilever into vibration, and while it monitors the cantilever vibration amplitude it rapidly lowers the scan head toward the surface. Signature changes in the cantilever amplitude indicate when the probe is within about 10 μm of the surface.

When these changes are detected the system immediately switches to the second step, which is the standard step-and-seek engage process, to gently lower the probe onto the surface.

Every cantilever type has a unique vibration resonance frequency and signature amplitude change. For this reason the user must specify the type of cantilever installed in the probe holder before initiating the *Auto Engage* process. The drop-down list next to the *Auto* check box lists the standard cantilever types available from Ambios. Make the appropriate selection before pressing the *AutoEngage* button. The contents of the drop down list may be edited in the **Advanced Scan Parameters** window, as discussed in Section 5.7.

If problems are encountered in using *AutoEngage* refer to Appendix A for possible causes and solutions.

5.4.2 Standard at Z=0 Engage

Like *AutoEngage*, this method quickly lowers the probe into surface contact when the probe is initially far above the surface. Unlike *AutoEngage*, this method requires a position calibration step before it may be applied.

Standard at Z=0 follows a two step process. In the first step the z-axis motor rapidly moves the scanner to the z=0 coordinate position . In the second step, the system switches to the slow step-and-seek process to gently lower the probe onto the surface.

The *Standard at Z=0* method is disabled until the origin of the z-axis motor movement is set. It is absolutely essential that this position is set sufficiently high above the sample surface to avoid a collision between the probe and the sample. Include in this determination any height changes that may occur when the sample is moved laterally by the sample translation stage.

Refer to Section 6.2.1 for instruction on how to set the Z=0 level with the controls in the **Probe Position** window.

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5.5   ADVANCED SCAN PARAMETERS

The **Advanced Scan Configuration Parameters** dialog box is accessed via the *Utility* menu in the ScanAtomic main window. These features should only be altered by experienced and knowledgeable users of the instrument.

Scan Parameters

Initial Warmup Cycles / Interscan Cycles

When a scan is initiated, the probe is repeatedly rastered over the first scan line "*Initial Warm-up Cycles*" times before data capture begins. When the scan is repeated continuously, (i.e. *Continuous Scans* is checked) on all subsequent scans the first raster line will be repeated "*Interscan Cycles*" times before data capture begins. Exception: when the selected *Scan Rate* is very slow these numbers are automatically reduced by the software to reduce the scan time. Both of these parameters are normally set to 5.

Disable Feedback Checking

When *Disable Feedback Checking* is checked the software will not require the probe to be engaged with the surface before beginning a scan. This makes it possible to raster the probe in the normal fashion without the probe actually touching the surface. Examples of situations where this may be useful include scans in electrochemical cells, and instrument diagnostic scans.

External Signal → ADC3

Systems with the RCP hardware option can take advantage of this control. Normally the ADC3 signal is the sum of the four laser photodetector signals. This signal is of little use except as a safety check during the probe engage process (see *Laser Sum Tolerance*). When the *External Signal→ADC3* control is checked the input to the 16-bit ADC3 analog-to-digital converter is temporarily rerouted to a BNC connector in the back panel of the EIU during a surface scan. In this way any external user-defined signal in the voltage range of +/-10V may be imaged as the probe is rastered. See the RCP manual for more information.

Enable Diagnostic Software

Several software windows and controls are only made visible or enabled when the instrument is placed in diagnostic mode. For the most part, these software components are only needed for evaluation, troubleshooting, or factory calibration purposes, and are rarely accessed by the microscope user. The diagnostic components are listed below.

General Utilities window
Ramp Utility window
Stage Test window
Std Utility tab in the Calibration window
Met Utility tab in the Calibration window
Lithography window macro command monitor
Metrology calibration image markers

STM/Conductance

Current Sensor Range

This is the range of the current preamp in either the STM probe module or the conductance probe module. The range for the STM/Standard module is either 100 nA or 10 nA, depending on the jumper position on the module. The range for the standard conductance module is 100 nA.

Current Sensor Offset

This is a correction used in the **STM Spectroscopy** software component to compensate for small shifts in the current signal level measured by the EIU electronics. It adjusts the zero-current reading in the current measurements. The *Current Sensor Offset* adjustment is made at the factory and normally does not need further adjustment.

Bias Voltage Offset

Small shifts in the bias voltage produced by the Stage electronics offset the zero position by a few millivolts. This software correction compensates for the hardware offset to ensure that a *Bias Voltage* setting of zero volts is truly zero within ±1 mV. The *Bias Voltage Offset* adjustment is made at the factory and normally does not need further adjustment.

EIU Setpoint Offset

Small errors in the setpoint voltage generated by the EIU electronics offset the zero position of the *Setpoint* control. For the AFM operation of the microscope the error is insignificant, but for the STM operation of the microscope the offset will lead to an error in the tunneling current of up to ~100 pA if uncorrected. The *EIU Setpoint Offset* adjustment is made at the factory and normally does not need further adjustment.

Approach Parameters

Engage Limits

When the probe is lowered to the surface from the **Engage** window the process terminates when the expansion/contraction of the probe falls between the *Upper Engage Limit* and the *Lower Engage Limit*. The numerical range of these variables is +32768 to -32767, corresponding to the range of the Z analog-to-digital converter. This numerical range may be converted into a distance range with the head parameter *Z Range*. For example, for an 80 μm scan head with a 12 μm *Z Range*, +32768 corresponds to +6 μm and -32767 corresponds to -6 μm. Normally the *Upper/Lower Engage Limits* are set to +11000 and -11000, respectively. This places the piezo tube in the middle third of its total vertical range at the end of the engage process. An experienced user may wish to raise these values to something like +32000 and +20000 when making an exploratory scan of a very rough surface, or a surface with deep holes.

Laser Sum Tolerance

During the engage process, as the probe is lowered to the surface the system continually checks the intensity of the laser signal reaching the photodetector to make sure there is a properly positioned cantilever in the probe holder. This is a failsafe mechanism to avoid serious head damage. *Laser Sum Tolerance* is the laser signal tolerance the system will accept when verifying that there is a working cantilever in the probe holder. Making *Laser Sum Tolerance* a larger positive number increases the signal range over which the system will say the cantilever is okay. Making it very large will in effect deactivate the failsafe mechanism.

AutoEngage Cantilever Settings

This is a list of the types of cantilevers available for use with AutoEngage, and their associated parameters. The *Type* parameter is the name of the cantilever. It is a text string of up to six characters. The *kHz* parameter is the center of the frequency range over which the system will sweep the vibration of the cantilever when searching for its resonance. The sweep will extend 30 kHz above and below the center frequency. The lowest allowed setting for *kHz* is 40 kHz. *Amp* is the fractional change in the cantilever's vibration amplitude at which the system will stop the fast engage process and switch to the slower step-and-search method. If *Amp* is too low the system will tend to trip on vibration noise spikes before the probe is near the surface, prematurely ending the fast part of the approach. If *Amp* is too high there is an increased risk that the probe will touch the surface before ending the fast part of the approach. This may damage the point of the probe. Any modifications to the *Amp* parameters should be very small, of order 0.01.

Several of the cantilever types in the list are left undefined (undef0, undef1, etc). Use these positions to specify new cantilever types for *AutoEngage*.

5.6   WITHDRAW CONTROL

Withdraw separates the probe from the surface by a distance that scales with the Z range of the scanner. For example, if the scanner has a 4 μm vertical range, at the end of the "Withdraw" event the probe will be separated from the surface by approximately 16 μm. If the scanner has a 10 μm vertical range the separation will be approximately 40 μm.

Withdraw

- If the *Withdraw* button is pressed while the probe is engaged with the surface the piezo scanner will first retract fully before the Z stepper motor is rotated. In the fully retracted state the probe is usually out of contact with the surface.

- If the *Withdraw* button is pressed when the probe is not engaged with the surface the Z motor will turn immediately.

- At the end of the Withdraw event the piezo scanner is placed in its neutral (zero applied voltage) state.

- Pressing the *Withdraw* button with the keyboard *Ctrl* key held down will invoke the *Retract Probe* movement option (**Realtime**>*Auxiliary>Retract Probe*).   The probe will first be withdrawn from the surface in the usual way, and then the scanner will be raised rapidly to a height of approximately 2 mm. This is usually sufficient clearance to make it easy to change samples.

5.7   REALTIME I VS. REALTIME II

The **Realtime I** and **Realtime II** software windows are functionally nearly identical. The obvious difference is that while scanning **Realtime I** presents one large view of a single image channel, while the **Realtime II** presents two smaller views of two image channels. You can flip between using the **Realtime I** and **Realtime II** windows with the toolbar buttons provided at the top of each window.

Realtime I

Realtime II

The two image panels in the **Realtime II** window are independent of each other. They can be assigned separate palettes, they can render images with slope shading switched on/off independently, etc. A central concept in the use of the **Realtime II** window is that only one of the two image panels is the "active" panel at any point in time. The active panel is indicated by the yellow highlighting of the file name above the image; you can switch between having the left or right panel be the active panel by simply clicking on the image. Here are some facts to keep in mind about the behavior of the active panel:

- Image operations such as tilt removal, spot removal, soft zoom, etc. are always applied to the active window. The previous contents of the panel are pushed into the Undo/Redo buffer in the usual way, and can be recalled via the *Next*/*Previous* toolbar controls. Note that there are not separate Undo/Redo buffers for the left and right panels. For example, an image which was in the left panel prior to performing a soft zoom operation can be made to appear in the right panel by clicking on the right panel to make it active and then pressing the *Previous* tool button.

- When an image is saved to the hard drive from the **Realtime II** window it is always the active panel image which is being saved.

- When the **Realtime II** window is minimized or closed the active panel image is placed into the image buffer for the other software windows (**Histogram Analysis**, **Section Detail**, etc.) to process.

- The contents of the left and right image panels are not stored when the **Realtime II** window is closed. When the **Realtime II** window is reopened, duplicate copies of the current image buffer image will be placed in both the left and right image panels.

- If a partial scan is performed by pressing *Stop* button before the end of the scan, the partial image data for both the left and right image panels are stored in the Undo/Redo buffer before restoring the original images in each panel. Pressing *Next* once or twice will allow you to view either of the partial data sets.

The following toolbar controls which are found in the **Realtime I** window are not found in the **Realtime II** window: *Surface Force, Scan Sequence, System Calibration*.

5.8   WHEN SHOULD A PROBE BE CHANGED?

In general, the probe should be changed when there is a noticeable deterioration in image quality. There are no hard and fast rules as to how many scans can be made or how many different samples can be studied with a single probe tip. The nature of the sample studied and the resolution required are key factors in determining how long a probe tip will last before it has to be changed. Some samples, e.g., hard surfaces with edge-shaped features, cause a tip to deteriorate more rapidly.

Streaks on an image are often an indication that the tip has picked up small contaminants. At times the contamination may fall off of its own accord; sometimes it can be removed with a puff of air from a squeeze bottle.

To get the most usage out of your cantilevers consider stepping them through stages of scan quality. Bring out a brand new cantilever only when it is necessary to scan a surface requiring the highest resolution of the instrument. Also, refrain from using a new cantilever on a surface of unknown topography. It is very easy to dull the tip when the surface has unexpected features and the scan parameters are not set correctly for the surface. When a cantilever shows unacceptable wear in high resolution scans, continue to use it in larger area scans of surfaces with larger features. A new cantilever will not produce a noticeably better scan of a larger, rough surface than a slightly dull cantilever. Seriously dull and damaged tips can still be used to train any new and inexperienced users of the microscope that come along. (After all, they will probably crash a cantilever or two while learning.) Damaged tips are also useful for experimental imaging in radically different ways.

5.9   A WORD ABOUT SAMPLES

Atomic force microscopy can be used to study the surface of most solid samples. In most cases one simply places the sample on the stage, positions it at low magnification, engages the probe and sample, and begins the scan. An image of the sample's surface profile is then generated. But some samples may require special consideration. These include the following:

1. Ferromagnetic samples, which can be attracted by a magnet, may have to be held down because they may be attracted to the magnet used in the probe holder. One way to hold samples down is with double-sided adhesive tape. Under best conditions, the Z-axis response will be about 3500 Hz, while the error response will be 25000 Hz. Under conditions where the PID gains must be reduced to prevent oscillation in portions of the image, the error component will still provide the full bandwidth, and detail in the image will not be lost, even at the highest scan speeds.

2. Samples on which an electrostatic charge builds up may be difficult to scan. In some cases an indication that charge has accumulated on the sample can be seen during the approach. The sample may strongly attract or repel the cantilever. This will be seen in the **Beam Align** window as either an upward or downward movement of the red spot as the probe tip comes close to the sample. Similarly, this will be seen in the **Engage** window during the engage process as a steady upward drift in the *Error* voltage display as the tip approaches the sample.

In other cases, effects of charging are seen after the probe and sample are engaged and the system is in feedback. The *Scanner Z Voltage* trace in the **Engage** window will drift up or down randomly rather than remain as a steady line. Or while scanning, friction between he moving probe and the surface will cause the probe to steadily charge and then suddenly discharge, producing a sudden step downward in the scan image at multiple locations.

There are various ways to circumvent the electrostatic charging problem. If the sample is a conductor it can be placed on a grounded stainless steel block and glued in place with a small amount of conductive paint placed along the sample edge. This creates a conductive path between the sample and the block. A non-conducting sample which shows charging effects can be made conductive momentarily by fogging the surface with a film of water vapor.

Another trick for dissipating static charge is to place the sample in a high humidity environment, e.g., by surrounding the scanning head and sample with a shroud enclosing a beaker of water. In some cases, simply wiping the sample with a slightly moistened tissue will work. Antistatic ion guns are also an effective means of eliminating static charge.

3. Extremely shiny, mirror-like samples may trigger a phenomenon known as "false feedback," in which the feedback loop triggers before the probe tip actually makes contact with the sample. This problem rarely happens, but if you suspect it may be occurring with your sample, a slight adjustment of the laser alignment or the tilt of the cantilever can remove the false laser signal.

6   Motor Control, Camera View

6.1   HARDWARE DESCRIPTION

Q-250 MiniStage

The range of movement for the MiniStage is ±5 mm.   The position precision of the MiniStage, considering only the reduction ratio of the stepper motors and the lead-screws, is ±0.397 μm. But with the added mechanical limitations of the drive mechanism the positioning accuracy is actually only about ±25μm.

It is possible to move the MiniStage manually with the knobs located behind the x and y motors. Note, however, that if the stepper motor knobs are manually turned the software's record of the stage position will no longer be correct.

Q-400 Rotary Stage

The Q-400 sample stage freely rotates 360º, and it can travel radially from the center of the 8-inch vacuum chuck to a point just inside the outer edge of the chuck.

The pressure requirements of the vacuum chuck are minimal; any vacuum source with an absolute pressure below 300 mbar (5psi) will be sufficient. The details of the vacuum connection arrangement will vary between installation sites, depending on the needs of the user and the vacuum facilities available.   The best arrangement, if possible, is to tap into an already existing vacuum line from a remotely located pump. This will ensure that there is no pump-related noise in the SPM image. If instead a local vacuum pump system must be used it will be necessary to restrict the acoustic and vibration pathways that will carry noise from the pump to the interior of the AVIC.

There are four rotatable plugs— in effect, little valves—along the radial groove in the surface of the vacuum chuck (Figure 6-1).   The tops of the plugs have grooves which can be rotated with a medium-size flat head screw driver. When the vacuum chuck is used to hold disk shaped samples set the plug positions to match the diameter of the disk being held.   The plug furthest from the center of the chuck falling under the disk surface should have its groove set perpendicularly to the radial groove in the chuck (vacuum stop), and all of the remaining plugs closer to the vacuum inlet should be set parallel to the radial groove (vacuum open).

Some model Q-400 systems include one or more disk centering stubs for the center of the vacuum chuck. For example, systems intended for CD or DVD inspection include two centering stubs, plus an edge-rest centering guide for centering disks which do not have a hole in the middle.
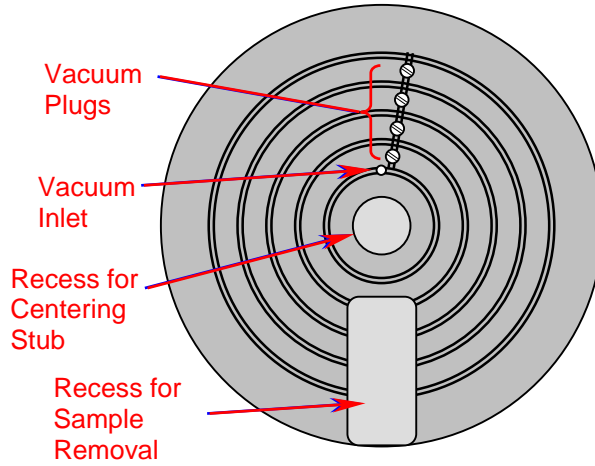
Figure 6-1   Vacuum chuck, centering stub, and vacuum plugs.

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6.2   MOTOR CONTROL SOFTWARE

Probe
Position

The video camera window and the probe and stage movement controls are located in the **Probe Position** window shown in Figure 6-2. The various controls are described below.
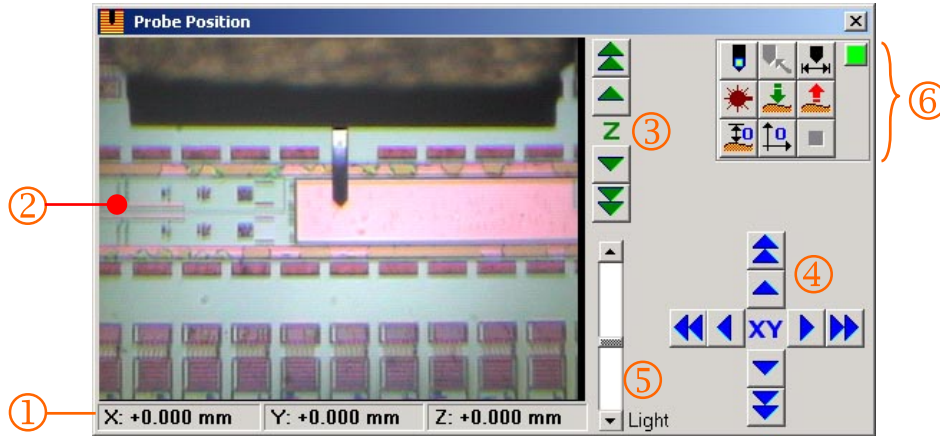
Figure 6-2   Probe Position window with probe and stage controls displayed.

① **Probe/Stage Coordinates**   These are the readouts for the stage position and the vertical position of the probe.

- The stage coordinates are greyed when either a motorized stage is not installed or the origin of the stage coordinates has not yet been set.

- The probe Z coordinate is greyed when the origin of the z axis has not been set.

❖Note: When the stage or z position motors are moved with motor controls *outside* of the **Probe Position** window (e.g. during the engage process) the coordinate readouts will only show the updated values when **Probe Position** has the Windows operating system focus. Clicking on this window gives it the system focus.

② **Video Camera View**   The probe is shown against the surface background.

③ **Z axis Motion Controls**   Pressing these control buttons moves the probe up and down as indicated.

When the Slow/Single Step buttons are pressed momentarily the Z motor will execute a single step and then stop. When they are held down continuously the Z motor will move continuously at a slow pace after the initial single step.

❖Note: If either the upper or lower z-axis limit switch becomes active the background of the buttons pointing in the direction of the limit will turn red. Moving the stage in the opposite direction will remove the limit condition.

④**Stage Motion Controls**   Pressing the control buttons moves the probe along the stage axis as indicated.

When the Slow/Single Step buttons are pressed momentarily the motor will execute a single step and then stop. When they are held down continuously the motor will move continuously at a slow pace after the initial single step.

❖Note: If a limit switch becomes active along one of the axis of the stage the background of the buttons pointing in the direction of the limit will turn red. Moving the stage in the opposite direction will remove the limit condition.

⑤**Camera Illumination**   Moving the slider changes the brightness of the LED camera illumination light.

The camera has a built-in automatic gain control (AGC) feature, so as the illumination brightness is increased, at some point the camera view will not appear any brighter even though the LED intensity is greater.

⑥**Toolbar Controls**
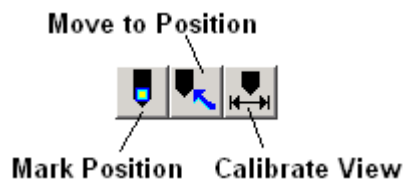
With these controls the translation stage may be configured so that a surface feature appearing in the video camera view can be repositioned under the probe by simply clicking on it. Further information is given in Section 6.2.2.

 Turns on/off the AFM mode laser. This control will be disabled when the instrument is configured for STM operation.

 Opens the **Engage Window**, used to lower the microscope probe onto the sample surface.

 Withdraws the scanner a short distance away from the sample surface.

This button has two functions: (i) to set the origin of the z-axis, and (ii) to move the probe to the origin of the z-axis. Refer to Section 6.2.1 for details.

This button has two functions: (i) to set the origin of the translation stage, and (ii) to move the probe to the origin of the z-axis. Refer to Section 6.2.1 for details.

Stops all the stepper motors. Note: This function is not available in this version of the software.

Toggles between showing/hiding the stage controls in the **Probe Position** window.

- When the controls are visible the size of the camera view is fixed. When the controls are hidden the size of the camera view can be adjusted by clicking-and-dragging on the corners of the window.

- Separate values are stored for the position of the **Probe Position** window when it is in the 'show controls' and 'hide controls' states. Therefore, switching between the show/hide states will also switch between two positions for the window.

6.2.1 Setting the Motor Control Origins

There are several software features which automatically move the scanner and/or the sample stage. They are listed in Table 6-1.

Software Window	Feature
Scan Sequence	Automatic repositioning of scanner and surface scanning.
Engage	Standard engage at z=0.
Probe Position	Move to scanner origin.
	Move to sample stage origin.

Table 6-1 Software features which invoke automatic stage movement.

These software features are disabled until the origin of the motor axis are set. Instructions for doing this are given in the sections below. The software does not store this information when it is shut down, so the motor axis origins must be reset each time the ScanAtomic software is started.

Setting the Scanner Origin

Probe
Origin

To set the z-axis origin for the scanner, open the **Probe Position** window, move the probe to the desired position near the sample surface, and press the *Probe Origin* toolbar button.   The z coordinate readout at the bottom of the **Probe Position** window will switch from greyed text to black text to indicate that the origin has been set.

To automatically move the stage to the origin position hold the keyboard Ctrl key down and press this same button.

Setting the Translation Stage Origin

This software feature is enabled when a motorized translation stage is installed. (Ref. Section 2.6)

Stage
Origin

To set the stage origin, open the **Probe Position** window, move the stage to its center position, and press the *Stage Origin* button.

The Q250 MiniStage is centered when the four edges of the top movable plate are aligned with the edges of the fixed bottom plate.   The Q400 rotory stage is centered when the vacuum chuck is rotated to position the sample removal recess toward the operator, and the middle of the vacuum chuck is positioned under the cantilever in the probe holder.

The stage coordinate readout at the bottom of the **Probe Position** window will switch from greyed text to black text to indicate that the origin has been set.

To automatically move the stage to the origin position hold the keyboard Ctrl key down and press the *Stage Origin* button.

6.2.2 Using the Video Positioning Tools

Overview

There are two steps to initializing this software feature:

- First, the camera view must be calibrated so that the width and height of the camera view, in millimeters, are known quantities. This calibration is stored by the system, and remains valid as long as the magnification of the camera optics is not changed.

- Second, the position of the end of the probe needs to be marked in the camera view. This step needs to be repeated every time the cantilever is changed or repositioned in the probe holder.

Once the camera view has been calibrated and the probe position has been marked a surface feature appearing in the video camera view may be positioned under the probe by simply clicking on it. The position accuracy for the MiniStage and the RTheta stage is approximately ± 25 μm.

❖Note: The *Move to position* toolbar control is disabled when the software is initially started, and is enabled when the probe position is marked.

Calibrating the Camera View

❖*Note: These instructions assume a motorized XY translation stage is installed. If instead a rotary stage is installed use the rotation axis control where the instructions call for X-axis movement. The calibration is most accurate when the radial position of the probe is set to the edge of the stage.*

Using the X stage controls, move a distinct surface feature just out of the field of view of the camera on the left side of the view. Then slowly move this feature to the right so that it just appears on the left edge of the camera view. Note the X coordinate of the stage. Now slowly move this feature to the right edge of the camera view. The change in the X coordinate of the stage gives the width of the camera view in millimeters. Click the *Calibrate View* button and enter this distance in the popup dialog box.

The camera view is now calibrated. The calibration value is stored in the software records. This procedure need not be repeated unless the adjustment of the camera optics is changed.

Marking the Probe Position

Click on the *Mark Probe* toolbar button to activate it. Then click on the camera view of the probe at the location of the probe point. This point is underneath the surface being viewed, and must be estimated based on the manufacturer's cantilever geometry data. Typically it is approximately half the width of the cantilever away from the end of the cantilever.

A fiducial mark (small blue square) will be momentarily superimposed on the cantilever when it is clicked, as a visual confirmation of the point which has been chosen.

The probe position is now set. This step must be repeated every time the cantilever is changed or repositioned in the probe holder.

❖Note: When the *Mark Probe* tool is activated a second or subsequent time the position of the last mark setting will be indicated by the momentary appearance of the same fiducial mark. If this position is satisfactory then it is not necessary to reset it. Just deactivate the *Mark Probe* tool by clicking on it again.

6.3   PROGRAMMED SCANNING
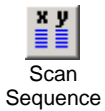
Scan
Sequence

The **Scan Sequence** control software automates the process of taking multiple images of a sample.   The access point for this software window is found in the toolbar of the **Realtime I** window (but not **Realtime II**).
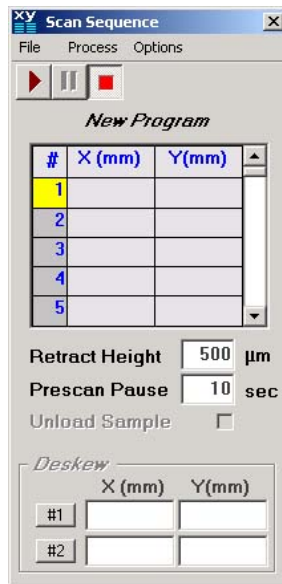
There are controls in this window which auto-matically move the sample stage and the probe. To avoid damaging the scanner be sure you are aware of the obstacles which the probe may encounter, and plan the use of these controls accord-ingly.

The basic steps for setting up and running a scan sequence are outlined in section 6.3.1. Section 6.3.2 gives additional information about the control options in the **Scan Sequence** window.

6.3.1 Basic Steps for Performing a Scan Sequence

1. Open the **Probe Position** window and set the origin of the sample translation stage (Ref. Section 6.2.1).

2. Place the sample on the stage and engage the probe with the surface. Open the **Probe Position** window again and set the origin of the z-axis of the scanner (Ref. Section 6.2.1)

3. Open the **Scan Sequence** window.   Enter the stage coordinates in the coordinates table for each scan to be performed. The coordinates may be entered in one of three ways:

   - Manually, just by typing in the numbers.

   - Automatically, by using the **Probe Position** stage controls to position the cantilever over each feature of interest on the sample, and then clicking one of the row index numbers in the **Scan Sequence** coordinates table to transfer the stage coordinates into the table.

     ❖Note: This can also be done in reverse: Holding the Ctrl-Shift keys down on the keyboard and clicking a row index number will automatically move the stage to the table coordinates position.

   - From memory, by navigating to **Scan Sequence** > *File* > *Load Program* to retrieve a set of coordinates you have previously entered and stored. This also retrieves your previous settings for *Prescan Pause*, *Retract Height*, and *Unload Position*.

   ❖Note: The scan sequence terminates at the first row in the coordinate table containing blank entries.

4. Set *Prescan Pause*. The *Prescan Pause* entry determines how long the system will pause after the probe has been engaged onto the surface before the surface scan begins. This delay allows time for the mechanical creep in the system to decay, so the creep distortion in the image will be minimized.   A recommended minimum setting for this is about 10 seconds.

5. Set *Retract Height*.   The probe *Retract Height* is the distance the probe will be raised above the $z = 0.000$ mm position when the stage moves from one stage coordinate position in the table to the next.

   The scanner may be seriously damaged if *Retract Height* is set incorrectly. The correct value depends on the roughness of the surface, the height of any obstacles on the surface, and the inherent tilt of the vacuum chuck. Make the *Retract Height* small to limit the time it takes to engage the probe with the

surface, but not so small that the probe may hit any portion of the surface when the stage is translating.

6. Activate the *AutoSave* software feature (**Scan Sequence** > *Process* > *Setup Autosave*). This will determine which data are recorded at each stage coordinate position. Refer the instructions in Section 5.2 for more information about Autosave.

Start
Program

7. The scan sequence is now ready to be executed . Press the *Start Program* button to start the process. The *Stop* button can be used to terminate the scan sequence early.

6.3.2 More Information about Scan Sequence Controls

Saving Programs (File > Save Program)

The **Scan Sequence** control settings can be stored for re-use. The files are saved as text files with the extension '.pgm'. They contain the coordinate table entries and the settings for the *Retract Height*, *Prescan Pause*, and *Unload Position*.

Scan Angle Tracking   (Options > Scan Angle Tracking)

This option is enabled on systems equipped with a rotary stage. When this option is checked the value of scan parameter *Scan Direction* at the **SPM Scan Configuration** window will automatically be adjusted as the stage is rotated so that the probe will scan across the sample features in the same relative orientation. For example, when the stage is rotated to 0º, *Scan Direction* will be set to 0º ; when the stage is rotated to 90º, *Scan Direction* will be set to -90º; and when the stage is rotated to 180º, *Scan Direction* will be set to -180º.

Post Scan Delay (Options > Set Post Scan Delay)

At the completion of each scan in the scan sequence the probe is raised to the *Retract Height* position and the stage is moved to the next set of coordinates in the table. If the post-scan delay factor is set to a value greater than zero the system will remain in this position for the specified amount of time before continuing with the sequence. In this way images of a surface may be separated by up to an hour.

Moving the Stage for Quick Sample Exchange (Options > Set Unload Position)

At the completion of the entire scan sequence the probe is raised to the *Retract Height* position one last time. If it is desired to have the probe move from this position to some final position where it is easier to change

the sample, enter the coordinates with this menu control. Checking the *Unload Sample* checkbox enables the unloading operation to this position.

Deskewing

The deskewing option is not available with this version of the software.

The pause state in the scanning sequence is generated during the deskewing setup. The *Pause* button is disabled in this version of the software.

7   *Working with Images*

7.1   SAVING AND LOADING IMAGE FILES

7.1.1   Saving Images in .AFM Format

Save Image As... saves the image to a storage device (Hard drive, flash memory, etc).

Clicking *Save Image As...* after a new image data has been acquired will first open the **Summary Data** dialog box to allow you to enter descriptive information about the image in the *Comment, Keyword* and *Description* input fields. Text entered in the *Comment* section will appear under the image when it is viewed with the **Search Image Files** window discussed in Section 7.1.4. After the **Summary Data** dialog box is closed the **Save Image As…** dialog box will open. Select a file directory and assign a file name to the image, then proceed to save the data.

When re-saving a previously saved image which has been modified in some way, (e.g. by applying some form of tilt removal) *Save Image As...* will bypass the **Summary Data** dialog box and directly open the **Save Image As…** dialog. If, however, you want to change the file's **Summary Data** contents before re-saving the image, you must do the following extra step. Go to the *File* menu in the software's main window and click *Show Image Summary*. The dialog box which appears will show the original **Summary Data** contents. Any of this information may be changed before re-saving the image.

7.1.2   Exporting Image Data

The main menu option   **ScanAtomic** *> File > Export Image as...* can be used to export image data to other applications in the following formats:

- **.TIF**   Saves the image data in the TIFF 6.0 file format.

  ❖Note: The normal image color palette is transformed into a 256-color gray scale palette. To reapply a color palette to the image, open the file in a graphics application such as Photoshop and re-render the image with a new palette.

- **.TXT** Saves the image data as a text file. Each text line contains the x,y,z values of a point in the image. Refer to the first several lines of the text file output for further information about the file format.

7.1.3 Loading Image Files

Open File

From the main window, click *Open* under the *File* menu to bring up the **Load Image File** dialog box. Navigate to the disk drive and folder of the desired image file. Note that only .afm images will appear in the file list.

7.1.4 Searching through the Image Files

Search Files

The **Search Image Files** window provides a convenient way to locate image files in your system.

When the **Search Image Files** window is initially opened a file dialog box will appear on top of the window. Use this dialog box to navigate to any image file in any folder where you wish to begin your search. When the dialog box is closed the selected file will be displayed in the upper left corner of the **Search** window, followed by up to twelve of the subsequent images in the folder. These are presented in the individual color palettes with which they were saved. Appearing below each image is its file name, resolution in pixels, and any information entered in the *Comments* box when the image was initially saved.   The tools for browsing, loading, and deleting image files are outlined below.

Re-Open Load Previous/Next Delete
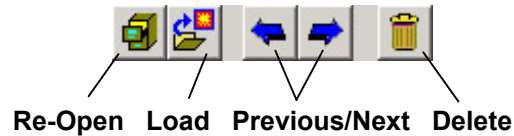
- **To view more images in a folder**   Click *Next* in the toolbar to see the next twelve images in the folder. Click *Previous* to show the previous twelve images.

- **To load images:**

    o **...Loading a single image**   Double-click on a picture or name. The image data will be loaded and the **Search** window will automatically close.

    o **...Loading a group of images** Hold the Ctrl key down and select 1 - 5 of the images by clicking on them. The border of an image and its associated text will change to blue when it is selected. Clicking the *Load* button will load the selected images into the image buffer, with the last selected image being placed "on top" in the sequence. The **Search** window will automatically close. The

"top" image will be visible in any of the SPM software windows. The other images may be accessed via the *Next/Previous* toolbar controls found throughout the software.

- **To search through a different folder**   Press *ReOpen* to locate and open a new folder.

- **Deleting images**   Hold the Ctrl key down and select 1 - 5 of the images by clicking on them. The border of an image and its associated text will change to blue when it is selected. Press the *Delete Files* toolbar button. Deleted images will be sent to the Windows Recycle Bin, and may be recovered if necessary.

7.1.5 Image File Summary Data Window

The **Image File Data Summary** window appears when a new image is saved to the hard drive. This allows you to enter descriptive information about the image in the *Comment*, *Keyword* and *Description* input fields.   Text entered in the *Comment* section will appear under the image when it is viewed with the **Search Image Files** window discussed in Section 7.1.4.

The *Scan Details* panel summarizes all of the instrument parameters associated with how an image was obtained. Refer to Figure 7.1.

To review the **Data Summary** information for the image currently being viewed, go to **ScanAtomic** > *File* > *Show Image Summary*. Many of the ScanAtomic software windows also allow you to quickly access this information by just right-clicking on the image.

The contents of the *Comment*, *Keyword* and *Description* text components can be changed at any time.   Click the *Save Changes* button to make the changes permanent.
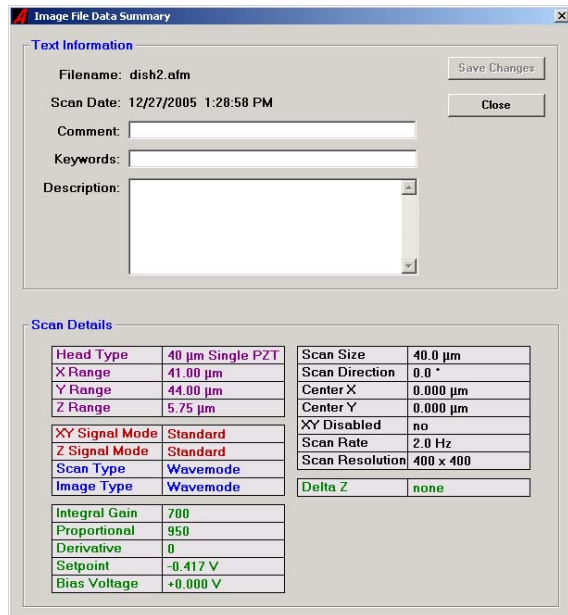
Figure 7-1 The Image File Data Summary window.

7.2   IMAGE GRAPHICS

The **Image Graphics** window (Figure 7-1) has tools for presenting image data in 2D or 3D format, either with "true color" palette Z scaling, or one of three different shading representations.

3D Rendering

Each of the shading modes has two controls to adjust the shading effect: *Contrast* and *Z Color*. The *Contrast* control increases or decreases the rate-of-change in the contour coloring in response to the local slope of the surface. The *Z Color* control shifts the overall coloring of the surface to levels which are higher or lower in the palette scheme.

The shading controls appear when one of the shading modes— Light Shading, Sunrise, or Slope Shading— is activated. See, for example, Slope Shading below.

❖Note: The *Contrast* and *Z Color* settings made in the **Image Graphics** window determine how the image is rendered in slope shading format throughout the software.

❖Note: Additional controls for rotating the image and changing its vertical scaling are accessed by moving the mouse to the lower-right corner of the window to activate a pop-up control panel.
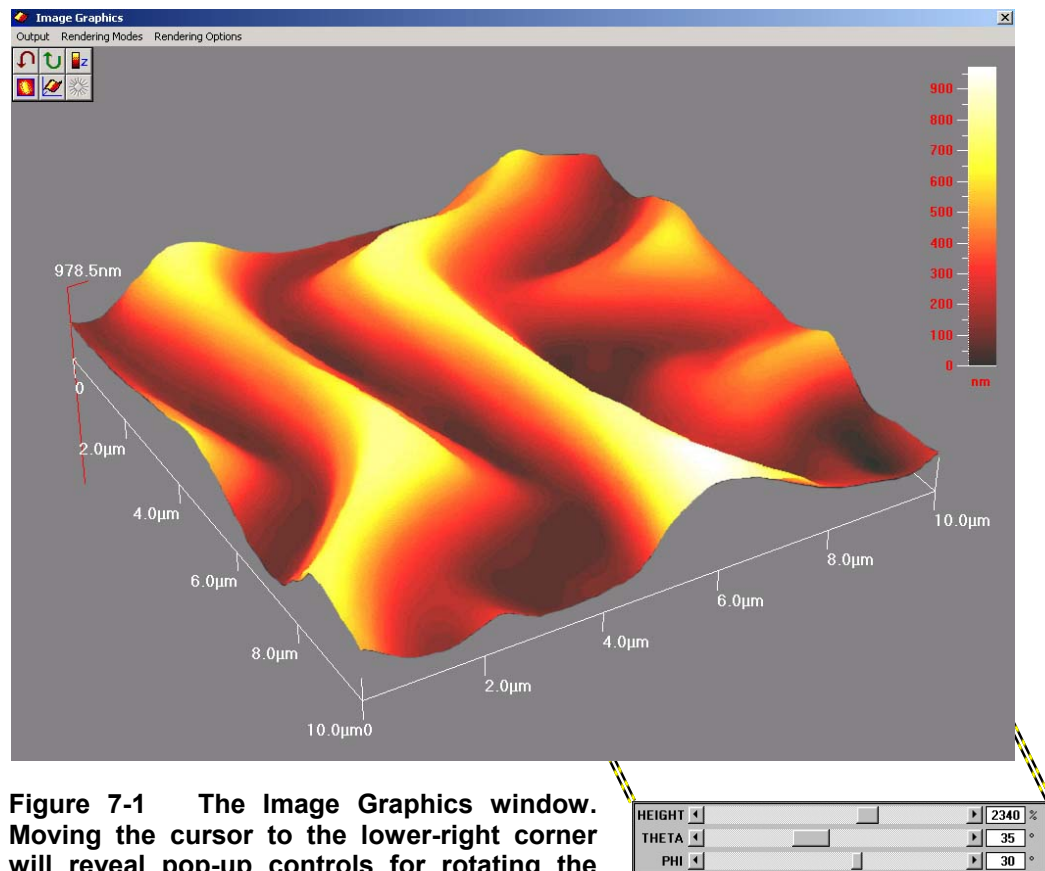
Figure 7-1   The Image Graphics window. Moving the cursor to the lower-right corner will reveal pop-up controls for rotating the image and changing the vertical height.

7.2.1 Rendering Modes

The *Rendering Modes* menu contains several graphics options for presenting the image data in different ways.

- **Scan Line** represents the image data with a wire mesh running only through the x axis of the data.

- **Grid** connects adjacent data points to form a wire mesh running along both the x and y axis.

- **Z Color** is a three-dimensional view of the image with height differences scaled in color. This is the default setting for newly created images.

- **Top-View** displays a top-down view of the image.

- **Slope Shading**   displays the image as if it were illuminated and viewed from above. The *Contrast* and *Z Color* scroll bars determine the way that slope shading is applied to the data. Note that the *Contrast* and *Z Color* settings made here determine how the image is rendered in slope shading in all other windows of the software.

- **Light Shading** displays a view of the image from above, but with the illumination placed at a user designated location. This mode of image presentation also allows the user to vary the image contrast and brightness.

- **Sunrise** is similar to *Light Shading*, but the light source direction is set to the east, and the mathematics of the shading ignores the slope in the Y direction. This is quicker to use, and small line-to-line disturbances caused by probe vibration do not show up in the image. This method of shading gives the most pleasing images since the surface detail can be seen, but the height contour is also visible.

- **Print Mode** allows you to quickly present an image with a white background.

7.2.2 Rendering Options

- **Show Z Scale**-- the Z palette and associated scale.

- **Show Scale Axis**-- the axis running along the edge of the image.

- **Show Contours--** generates contour lines of equivalent Z-height on the image. This command is only available with a top-view image. The user can select one of four contour patterns consisting of either 16, 10, 6 or 4 lines. For each selection *n*, the lines are spaced by a distance equal to *1/(n+1)* times the total height of the color bar scale.

- **Change Background Color** opens a color selection palette for changing the screen's background color.

7.3   CHANGING THE COLOR PALETTE

**Palette
Selection**

With the **Palette Color** design window the rendering palette may be set to one of the previously stored palette files, or an entirely new palette may be created. This window may be accessed at many points in the software via the *Palette Selection* toolbar button.
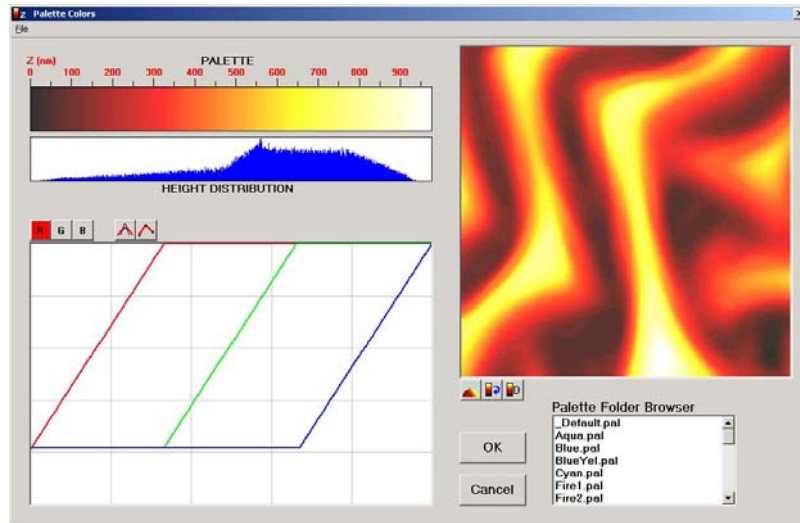
Figure 7-2 The Palette Color design window.

Applying Predefined Palettes

- Clicking an entry in the *Palette Folder Browser* in the lower-right corner of the widow will instantly change the palette scheme to one of the predefined palettes located in the software's "Palettes" folder. The selected palette may be deleted from the palette folder by pressing the keyboard *Delete* key.

- Clicking the *Restore Palette* button will return the palette to the original color scheme applied to the image when the **Palette Color** window was opened.

- Clicking the *Default Palette* button will apply the software's default palette to the current image. The default palette is assigned the special name _Default.pal, and it may also be loaded via the *Palette Folder Browser*. The definition of the default palette color scheme can be changed with the *Set Default Palette* command under the *File* menu.

  ❖Note: The *Default* palette is used by the scanning software to render new images. If the *Apply default palette to new scans* menu option in the **Realtime** window is is activated then all new scan images will be rendered with this palette.

Menu Options

- *Load Palette* brings up a dialog box for loading a new palette from the "Palettes" folder, or elsewhere in the computer files.

- *Save Palette As...* brings up a dialog box for saving the current color palette. Choose a file name followed by the extension ".pal". The default folder for storing palettes is the "Palettes" folder included with the software.

- *Load Default Palette* loads the default palette. The default palette is assigned the special name _Default.pal, and it may also be loaded via the *Palette Folder Browser*. The definition of the default palette color scheme may be changed with the *Set Default Palette* command.

- *Set Default Palette* assigns the palette currently being viewed in this window to be the new default palette.

Creating New Palettes

The *Color Graph* at the lower-left portion of the **Palette Color** window provides a graphical method for creating customized palettes.

To change the palette in a freehand fashion choose one of the primary colors with the *RGB* buttons above the graph, and then with the mouse cursor, draw the new curve shape in the graph area. The changes to the palette will appear instantly in the palette display above the graph and in the image itself to the right.

To create a palette using connected line segments, activate the line segment tool. This places three straight line segments in the graph area. Choose one of the primary colors to edit with the *RGB* buttons, as before. The endpoints of a line segment are moved by clicking and dragging. New segment endpoints may be added by clicking in the middle of a line. Endpoints may be removed by first clicking on the point to select it and then pressing the keyboard Delete key.

Kinks in the *RGB* color curves may be removed by pressing the *Smooth* button one or more times. The smoothing is applied to all three colors simultaneously.

7.4   REFINING THE IMAGE

7.4.1   Removing Tilt

The following tilt removal functions are found under the *Tilt Removal* pull-down menu in the **Realtime** window. An image modified by these functions can be restored to its original condition by clicking the *Previous* toolbar button.

- **Edge Fit** calculates the equation of a plane defined by the average slopes between the top/bottom edges, and the left/right edges of the image, and then subtracts it from the image data. In favorable circumstances *Edge Fit* will remove most of the tilt in a surface, slightly modify the appearance of the over-all curvature, and generally emphasize any small features present. *Edge Fit* does not work well if the edges of the image are not on the desired plane. For example, tilt will remain when a diffraction grating is scanned if the left edge of the image falls in a trough and the right edge falls on a crest.

- **Saddle** will remove a 45-degree saddle distortion that is missed by the *Parabolic* option.

- **Histogram/H** calculates a histogram of the height distribution of each scan line in the image. The peak of the histogram represents the most common vertical height of data in the scan line. This is the baseline value which is subtracted from each scan line in the image.   Note that there is no change in X-axis tilt with this method.

  Histogram/H works well in situations where the probe is prone to jog up or down by a fixed amount after it moves over a deep hole or tall particle. It also can be used to remove the effects of thermal drift, which causes the image to tilt along the y-axis. *ME* images and *Phase* images are often greatly improved by *Histogram/H* subtraction.

- **Histogram/V** works the same as *Histogram/H*, except the calculations are performed along the vertical lines of the image data.   This generally produces a poor image unless the scan line direction is intentionally rotated along the vertical axis before it is applied.

- **Horizontal L/L** calculates the average heights of individual scan lines in the horizontal direction and forces them to a common value.   This can be used as a filter to remove "jumps" or "roller coasting" along the y-axis of the image. However, it may introduce dark or bright streaks if the surface contains many prominent features or holes. *Histogram/H* frequently works better.

- **Vertical L/L** works the same as *Horizontal L/L* except the calculations are performed along the vertical lines of the image data.   This generally

produces a poor image unless the scan line direction is intentionally rotated along the vertical axis before it is applied.

- **Parabolic** tilt removal fits a paraboloid section (a three dimensional surface) to the image contours, and then subtracts this from the image data. This is the most frequently used tilt removal method for irregular surfaces. It works best where the features of interest are small compared to the overall tilt and curvature of the surface.

- **Parabolic L/L** calculates, on a line-by-line basis, a parabolic fit to each scan line in the image. Each of these parabola sections is subtracted from the image data. The effect is to remove the line-by-line tilt and curvature in the image along the horizontal axis. This is unlike the *Histogram/H* and *Horizontal L/L* methods, which only shift each line up and down, but do not attempt to flatten the line along the horizontal axis.

- **Three-Point** tilt allows the background plain of the surface to be specified as the user sees fit. A general theorem of geometry is that three points define a plane; selecting *Three Point* in the *Tilt Removal* menu activates a process of graphically selecting the three points in the image which correspond to the desired plane. The user places the cursor in succession at each of the three points in the image, left-clicking each time to leave a feducial mark behind. After the third point is selected the tilt removal is automatically applied and the image is redrawn.

- **Polynomial Segment** breaks the horizontal lines of an image into a series of short segments which are fitted with a polynomial of a specified order. From this, a new image is formed by subtracting the z values of the original image from the "background" contours of the polynomial segments. The result is a highly flattened image with only the fine details of the topology remaining.

  Values for the polynomial order and segment length are entered in a pop-up input box which appears each time *Polynomial Segment* option is selected.

(Blank Space)

7.4.2 Removing Image Streaks and Spots

The *Streak Removal* and *Spot Removal* tools improves the quality of an image by removing small imperfections in otherwise good data.

Streak Removal

Streak
Removal

Selecting the *Streak Removal* tool changes the mouse cursor to a cross-hair. Position the cursor at the upper left corner of the streak to be removed and click-and-drag the cursor to the lower right corner. The area to be removed will be outlined by parallel lines. When the cursor is released the image data within the outline will be removed. It will be replaced by a linear interpolation between the image data along the top edge of the outline and the bottom edge of the outline.

Spot Removal

Spot
Removal

Selecting the *Spot Removal* tool changes the mouse cursor to a cross-hair. Position the cursor a short distance above the upper-left corner of the spot to be removed, and then click-and-drag the cursor to a point which is a short distance below the lower-right corner of the spot. As the cursor is moved a rectangular region around the spot will be outlined. When the cursor is released the central region of the rectangle will be replaced by a graded average between the surface profile on the perimeter of the rectangle and the pre-existing height profile of the surface within the rectangle.   The graded averaging will gradually fill small surface holes, or flatten small bumps.

(Blank Space)

7.4.3 Retouch Filters

Like the streak and spot removal tools in the **Realtime** toolbar, the objective of these filters is to remove the unwanted image defects which compromise otherwise good image data.

This control window is accessed via **Realtime** > *Retouch > Retouch Filters…*.
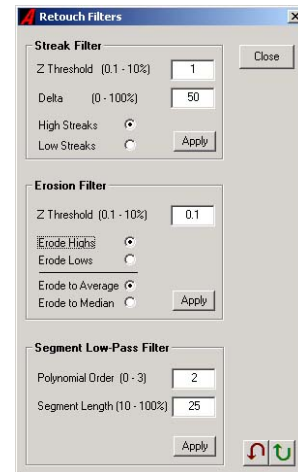
Streak Filter

Image streaks may be removed manually using the *Streak Removal* tool. This generally produces satisfactory result, but if the image is covered with many small streaks the manual technique becomes tedious. The *Streak Filter* attempts to locate and remove image streaks in an automated fashion.   Parameters:

- **Z Threshold.....** This is the minimum vertical step transition from one scan line to the next beyond which the software identifies the scan line as being on the edge of a streak, rather than being an acceptable gradual change in the surface topology. The value is specified as a percentage of the vertical range of the image. A typical value is 1%.

- **Delta.....** Parameter *Z Threshold* is adjusted to locate the edges of streaky regions. In addition to this, a second threshold parameter *Delta* is adjusted to discern if a segment of image data marked above and below as being "within the streak zone" needs to be removed. The value of *Delta* is specified as a percentage change in the height of a line with respect to its nearest neighbors. A typical value is 5%.

- **High/Low Streaks.....** High and low scan line streaks may be removed independently. In almost all instances the results are more satisfactory if the high streaks are removed before the low streaks.

Erosion Filter

This filter applies an erosion algorithm to 3x3 pixel regions of an image. When the center of the 3x3 region varies from the average of the perimeter pixels by more than the *Z Threshold* value the value of the pixel at the center of the region is

changed. The new value may be either the median or average of the perimeter pixel values. Parameters:

- **Z Threshold.....** This is the difference between the given pixel's value and the average of its 8 nearest neighbors beyond which the pixel's value will be altered. The threshold is specified as a percentage of the vertical range of the image. A typical value is 1%.

- **Erode Highs/Lows.....** High and low spots may be eroded independently. In almost all instances the results are more satisfactory if the high spots are eroded before the low spots.

- **Erode to Average/Median.....**   When the center of the 3x3 region exceeds *Z Threshold* the value may be replaced by either the average of the perimeter values or the median of the perimeter values. Eroding to the average is computationally fast, but it tends to smooth the edges of sharp features in an image, and this is not always satisfactory. Eroding to the median is computationally very slow, but it tends to retain the sharp edges in an image.

Segment Low-Pass Filter

The action of this filter is the opposite of the *Polynomial Segment* tilt removal method (Ref. Section 7.4.1). The horizontal lines of an image are broken into short segments, and the segments are fitted with a polynomial of a specified order. A new image is formed with the z values from the fitted polynomial curves. The result is an image with the fine details of the topology removed. This low-pass filtering technique is an alternative to matrix low-pass filtering and FFT low-pass filtering. Parameters:

- **Polynomial Order.....**   the order of the polynomial used to fit the local curvature of the horizontal line segments.

- **Segment Length.....**   the length of the fitting segments, defined as a fraction of the image width.

❖Note: The *RT Topology Map* surface leveling feature uses this filter to produce the a scanner's background topology map.

7.4.4 Magnifying the View: Soft Zoom

Soft Zoom creates a new image by cropping a small image out of a larger one. The new image data are generated by interpolating between the old image points. This is used most frequently to align some specific features in the larger image with the horizontal and vertical edges of the image frame. For example, if the tracks in a CD image run a few degrees from horizontal it is possible to level the tracks by aligning the *Soft Zoom* cropping window with the tracks in the image.

Soft Zoom

The steps are as follows:

1. Click on the *Soft Zoom* tool in the **Realtime** window. The mouse cursor will change to a cross-hair when it is moved over the image area.

2. Move the cursor to the center of the desired cropping region.

3. Click and drag the mouse pointer away from the center. A cropping square will form with its center at the selected point. The square may be rotated as well as sized. Keep in mind that the edge of the square to which the mouse cursor is attached will form the right-hand edge of the final cropped image.

4. Release the mouse button when the desired image size and orientation is reached. The new interpolated data will immediately appear on the screen.

5. If the new image does not seem right in some way, click *Previous* in the menu bar to revert to the original image.

7.5   MATRIX FILTERING

Matrix filters are small square arrays of numbers (array dimensions N x N) which are convolved with the image data array to produce a new image. That is, for each small NxN region of the image, the values of the filter numbers are multiplied by the z values of the corresponding image points, and the NxN products are summed. The sum replaces the value of the original image point at the center of the N x N region.

Matrix filters can be designed to reduce image noise, sharpen surface features, locate feature edges, and so on.   Several common filter types are installed into the software's Matrix Filter folder when the software is installed into your computer. They can be applied to an image by simply selecting them from the drop-down list under the *Matrix Filter* menu heading in the **Realtime** window.

Matrix Filter Editor

The **Matrix Filter Editor** window (**Realtime** > *Matrix Filter* > *Filter Editor*) is used to create and modify filters.
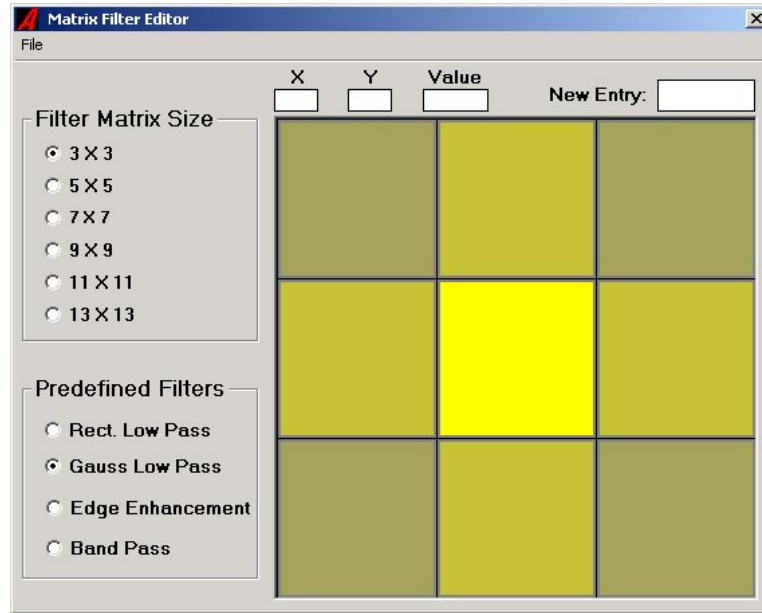
Figure 7-3 The Matrix Filter Editor window.

Predefined Filter Types

Four common filter types with dimensions ranging from 3x3 to 13x13 may be created instantly by selecting the appropriate radio buttons on the left side of the editor window.

The value of any filter element may be examined by hovering the mouse cursor over the element. The *X*, *Y* and *Value* boxes at the top of the window indicate the row and column indexes and the value of the filter element.

Saving a filter into the SPM software's Filter Folder will make it accessible from the *Matrix Filter* menu control, found in several windows in the software.

Custom Filters

First select the desired *Filter Matrix Size*. Then to change an element in the matrix, enter the new number into the *New Entry* text box and then click the element square. The maximum allowed value is 100 (rendered yellow), the minimum allowed value is -100 (rendered blue). Values near 0 are rendered grey. Several elements of the filter may be modified to the same new value by clicking repeatedly in the filter array.

7.6   FOURIER TRANSFORM FILTERING

The objective of Fourier filtering is to remove unwanted interference and noise from the image. Interference often appears as periodic lines in the image, whereas noise appears as specks or dots scattered randomly throughout the image. A two-dimensional Fourier transformation performs a mathematical operation on the spatial image data to re-express it in the frequency domain. In the frequency domain the frequency components of the noise are often distinct from the frequency components of the desired image information. This fact can be exploited by erasing the noise frequency components from the transform and then re-transforming this back into the spatial domain to recover the 'cleaned' image topology.

7.5.1 Predefined Filters

The predefined FFT filters listed below can be applied to an image by simply selecting them from the drop-down list under the *Fourier Filter* menu heading in the **Realtime** window.

The adjustable parameters for the these filters are accessed with the *Filter Parameters* dialog box. Open the **Fourier Transform Filtering** window and then navigate to   *FFT Filter > Filter Parameters...* (Ref. Section 7.5.2)   The functions of the various parameters are discussed under the filter type headings below.

PSD Filter

The PSD filter works in the following fashion. First, the scaling factor

$$S = Log(\text{Larger} (\text{Threshold} * (Re^2 + Im^2), 1))$$

is computed for each point in the FFT spectrum , where Re is the real component of the FFT and Im is the imaginary component of the FFT.

Threshold is a power of 10 attenuation factor equal to $10^{\wedge}(-Cutoff\ Threshold)$. The parameter *Cutoff Threshold* is the only user adjustable parameter for the filter.

Next, Re and Im are multiplied by S to produce the filtered FFT spectrum. Finally, the Fourier transform is inverted to generate the filtered version of the original surface image.

The PSD filter is particularly suited to emphasizing any periodic 2 dimensional periodic structure in a surface.

AC Line Frequency Filter

This filter works in the following fashion: The *Fundamental Frequency* and *Bandwidth* parameters, in time units of Hz, are converted into the corresponding spatial frequencies of the Fourier transform of the image. The conversion is based on the scan size of the image and the scan speed used to obtain the image. The resulting spatial frequency values are used to erase the portions of the FFT data which match the time frequency and bandwidth criteria. The filtered FFT spectrum may then be inverted to generate the filtered version of the original surface image.

- If the *Odd Harmonics* option is selected then the same erasure process is carried out for frequencies of 3, 5, etc. times the fundamental.

- If the *Even Harmonics* option is chosen then the same erasure procedure is carried out for frequencies 2, 4, etc times the fundamental.

The "AC Line" part of this filter's name is derived from its primary use: to remove unwanted periodic electrical noise appearing in an image which was picked up from the electrical equipment operating in a laboratory. The *Fundamental Frequency* parameter is typically set to 60 or 120 Hz in locations with 60 Hz electrical power, or 50 or 100 Hz in locations with 50 Hz electrical power. The factor of two difference between the values for the fundamental frequency is attributed to the fact that in some circumstances the noise is proportional to the AC line voltage, while in other circumstances it is proportional to the rectified version of the AC line voltage.

The setting of the *Bandwidth* parameter depends on the sharpness of the offending noise pattern in the FFT. Typically the a bandwidth of 10 Hz is sufficient.

❖Note: The *AC Line Frequency* filter will be unsuccessful in circumstances where the periodicity of the noise falls in the vicinity of major frequency components of the underlying image, which makes it difficult to disentangle the noise from the image by simple FFT transform erasure. In particular, avoid imaging scan rates which make the periodic noise appear as nearly vertical lines in the scan image. Switch to a slightly higher or lower scan rate which will tilt the periodic noise pattern closer to the 45º line of the image.

Spatial Bandpass Filter

The *Spatial Bandpass* filter sets the Fourier transform components at spatial frequencies below the *Lower Limit* and above the *Upper Limit* to zero, leaving the rest of the components unchanged. The effect is to capture a annular segment of the FFT. The filtered FFT is inverted to generate the final filtered version of the scan image.

The limits of the *Spatial Bandpass* filter are expressed as a percentage of the maximum spatial frequency range along the coordinate axis. For example, if a

scan image has a size of 10 μm the FFT will have the range of $\pm$ 255/(10 μm) = $\pm$ 25.5 μm^{-1} along the coordinate axis. Bandpass settings of 10% and 50% will capture the Fourier transform components between 2.55 μm^{-1} and 12.7 μm^{-1} in the spectrum.

❖Note: The bandpass filter limits are expressed in terms of a percentage of full-scale rather than in absolute μm^{-1} units because this allows the filter to be applied in a way which is independent of the scan size.

❖Note: By setting the *Lower Limit* to zero and adjusting only the *Upper Limit* the filter will act as a low-pass filter. Conversely, by setting the *Upper Limit* to 100% and adjusting only the *Lower Limit* the filter will act as a high-pass filter.

7.5.2 The Transform Filtering Window

The **Transform Filtering** window is used to:

- View the FFT transform of image data.
- Measure spatial and time frequencies in the FFT spectrum.
- Adjust the predefined FFT filter parameters, and apply these filters to the image data.
- Manually modify the FFT spectrum and then retransform it to create a modified surface image.

Fourier
Transform
Filtering
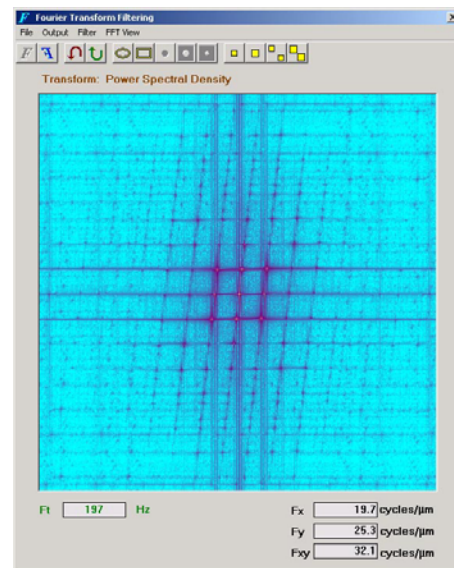
Figure 7-4 The Fourier Transform Filtering window.

Menu Controls

File > Export FFT as...   The FFT data being displayed— the power spectrum, real component, or imaginary component— may be exported as either a TIFF file or an ASCII text file. Note that when the data are stored in ASCII format the horizontal scale factor listed in the header of the file will be the width and height of the original image L in microns. The maximum spatial frequency along the x and y axis of the transform will be $\pm$255/L.

FFT Filter

- **Filter Parameters...** Opens the **Filter Parameters** dialog box.

- **PSD** Applies the power spectral density filter. If this filter is applied when a surface image is displayed, the image will automatically be Fourier transformed, then filtered, and then retransformed back to show the new surface image.   If this filter is applied when a Fourier transform is displayed then the only action will be to apply the filter to the transform.

- **AC Line Frequency**   Applies the *AC Line Frequency* filter. If this filter is applied when a surface image is displayed, the image will automatically be Fourier transformed, then filtered, and then retransformed back to show the new surface image. If this filter is applied when a Fourier transform is displayed then the only action will be to apply the filter to the transform.

- **Spatial Bandpass**   Applies the *Spatial Bandpass* filter. If this filter is applied when a surface image is displayed, the image will automatically be Fourier transformed, then filtered, and then retransformed back to show the new surface image. If this filter is applied when a Fourier transform is displayed then the only action will be to apply the filter to the transform.

FFT View

- **Power Spectrum** Displays the sum of the squares of the real and imaginary components of the FFT transform data. This control is enabled after performing the FFT operation.

- **Real Component**   Displays the real component of the FFT transform data. This control is enabled after performing the FFT operation.

- **Imaginary Component** Displays the imaginary component of the FFT transform data.   This control is enabled after performing the FFT operation.

- **Select Palette** Selects which palette will be used to render FFT data. The appearance of the transform may be adjusted by changing the rendering palette.

❖Note: The vertical scales of the Real FFT, Imaginary FFT, and PSD spectra are not normalized. For example, the PSD calculation is performed by first calculating the FFT of the image data, with the image data in the form of integers scaled from 0 (lowest point on surface) to 32767 (highest point on surface). The resulting numbers in the real and imaginary parts of the FFT are

then squared and added together to generate the PSD spectrum. No other scaling factors are applied.

❖Note: The vertical scaling in an FFT image is logarithmic. This makes the lower amplitude components of the spectrum visible along with the high amplitude components.

❖Note: Images are resampled to a pixel resolution of 512 x 512 prior to performing the FFT, therefore the FFT has the same 512 x 512 resolution.

Toolbar Controls

F **FFT Transform**   Performs a Fast-Fourier Transform of image data and presents the results in the form of the power spectral density. The *FFT Transform* control is available whenever a topology image is displayed in this window. See also the FFT View section, above.

Inverse FFT Transform   Retransforms the Fourier data back to normal topology data. This control is enabled whenever FFT data are displayed in this window.

Previous/Next Buffer Image Steps forward and backward through the 5-level image ring buffer. Note that FFT data cannot be stored in the ring buffer, so the *Previous/Next* controls will not allow you flip between FFT and normal surface image views of surfaces.

Ellipse Boundary   Select this control to draw an elliptical boundary on the FFT spectrum. This boundary is used by the low-pass and high-pass cutoff filter controls. The *Ellipse Boundary* control is enabled when FFT data are displayed.

Rectangle Boundary   Select this control to draw a rectangular boundary on the FFT spectrum. This boundary is used by the low-pass and high-pass cutoff filter controls. The *Rectangle Boundary* control is enabled when FFT data are displayed.

High Frequency Cut   This control is enabled when an elliptical or rectangular boundary has been drawn on the FFT data. Selecting *High Frequency Cut* will set the amplitudes of all frequency components outside the boundary to zero

Low Frequency Cut   This control is enabled when an elliptical or rectangular boundary has been drawn on the FFT data. Selecting *Low Frequency Cut* will set the amplitudes of all frequency components inside the boundary to zero.

Gaussian Frequency Cut This control is enabled when an elliptical or rectangular boundary has been drawn on the FFT data. Selecting *Gaussian Cut* will gradually taper the amplitudes of the high frequency components down to zero, following the amplitude profile of a Gaussian curve. The advantage of a *Gaussian Cut* over a *High Frequency Cut* is that the abrupt clipping of spectrum components produced by a *High Frequency Cut* tends to produce oscillation artifacts along the edges of the *Inverse FFT Transform* image. A *Gaussian Cut* does not introduce oscillation artifacts.

Small/Large Eraser These controls are enabled when FFT data are displayed. By clicking and dragging with the mouse the amplitudes of the frequency components underneath the eraser are set to zero.

Small/Large Conjugate Eraser These controls are enabled when FFT data are displayed. By clicking and dragging with the mouse the amplitudes of the frequency components underneath the erasers in the normal and conjugate positions are set to zero.

Frequency Display

- **Fx, Fy**   When frequency data are displayed the position of the mouse cursor on the frequency spectrum will be converted into the corresponding spatial frequency coordinates along the x and y axis of the spectrum. The frequency components are presented in units of cycles per μm.

  ❖Note: A useful way to interpret the frequency units is as follows: If the original topology image size is 10 μm, the frequency range of the FFT spectrum will be $\pm$ 255/(10 μm) = $\pm$ 25.5 μm^{-1}.   If the mouse cursor is positioned halfway along the positive x-axis of the spectrum, the x-axis frequency readout will be 12.8 μm^{-1}. So if the original 10 μm topology image was of a grating with a line pitch of 12.8 lines per μm, and the grating lines were oriented parallel to the y-axis of the scan,   this surface structure would manifest itself in the FFT spectrum as a bright streak along the x = 12.8 μm^{-1} frequency coordinate.

- **Fxy**   This is the frequency position of the mouse cursor along the radial direction. $Fxy = Sqr\ [\ (Fx)^2 + (Fy)^2\ ]$

- **Ft**   When frequency data are displayed the horizontal position of the mouse cursor on the spectrum is converted into the corresponding time frequency value in Hertz.

  For example, if a scan is performed at a scan rate of 2 Hz, the x-axis of the transform can be interpreted as spanning a frequency range of $\pm$ 255/(0.5 seconds) = $\pm$ 510 Hz. If unwanted 50 Hz electrical noise is picked up by the scanning electronics this will produce a series of lines in the surface topology image. With a scan rate of 2 Hz there will be (½ 0.5 sec) = 0.25 seconds to acquire the data in one scan line of the image— the retrace of the probe takes the remaining 0.25 seconds. In this time (50 Hz)*(0.25 s) = 12.5 noise lines will appear in the surface image. In the FFT view of the image the 50 Hz electrical noise will appear as a bright streak at the 50 Hz coordinate position along the x-axis, and probably at the harmonic frequencies of 100 Hz, 150 Hz, etc as well.

7.7   PRINTING WINDOWS

A *Send To Printer* function is available under the *Output* menu of most of the ScanAtomic windows. This function automatically scales and orients the printout so that the window image fills the maximum area available on the paper.

Alternatievely, windows in the SPM software may be printed by first clicking anywhere on the window to give it the Windows operating system's focus, copying it into the Windows clipboard with the key-press sequence *Alt-Print Screen*, and then pasting it into a Windows-based application such as Paint or Microsoft Word.

7.8   EXPORTING TO GRAPHICS APPLICATIONS

A *Send To Editor* function is available under the *Output* menu of most of the ScanAtomic windows. This function copies the current window image into the Windows clipboard and then start an external editor application. The editor may be set to any graphics-enabled program which can deal with bitmap (.bmp) images. Examples include Microsoft Paint, Microsoft Word, Adobe Photoshop, and Paint Shop Pro.   Once the graphics application has been initiated, the application's *paste* or *insert* control is used to transfer the clipboard contents into a workspace or document.

At Ambios the editor program is initially set to Paint. To change the editor, go to the ScanAtomic program's main window and navigate to **ScanAtomic** *File > Select Editor*. This will bring up a file browser window. Locate the desired application and press *OK* in the browser window.

7.9   NEXT / PREVIOUS TOOLBAR CONTROLS

Most subwindows within the ScanAtomic software have undo/redo capability up to the five most recent changes. Past image information is held in a 5-level ring buffer. Most operations applied to an image (leveling, smoothing, palette changes, etc.) will cause the current image data to be pushed into the ring buffer before the modifications are applied. Selecting *Previous* from the menu will retrieve the previous image data and place it into the z-buffer for image processing. Selecting *Next* from the window menu reverses the operation: the current z-buffer is pushed back into the ring buffer and previous image file is brought back into the z-buffer. The diagram below summarizes the relationship between the various image buffers in the software.
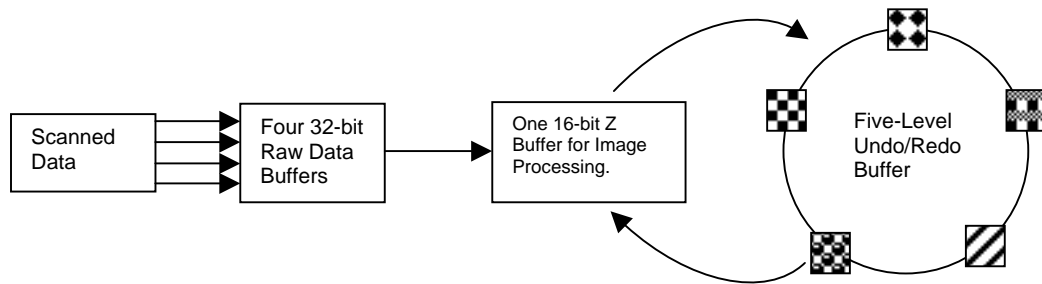
Figure 7-5 The relation between the four 32-bit data buffers, the 16-bit image processing buffer, and the five-level storage ring which stores past versions of the data held in the image processing buffer.

❖Note: Partial scan data may be recovered. When a scan is terminated before completion the previous completed scan is always returned to the z-buffer, but the partially scanned image can be recovered by clicking *Next*.

8   Image Analysis

8.1   HISTOGRAM ANALYSIS

The **Histogram** window is used to explore the spatial characteristics of the surface topology in a statistical manner.

Histogram
Analysis
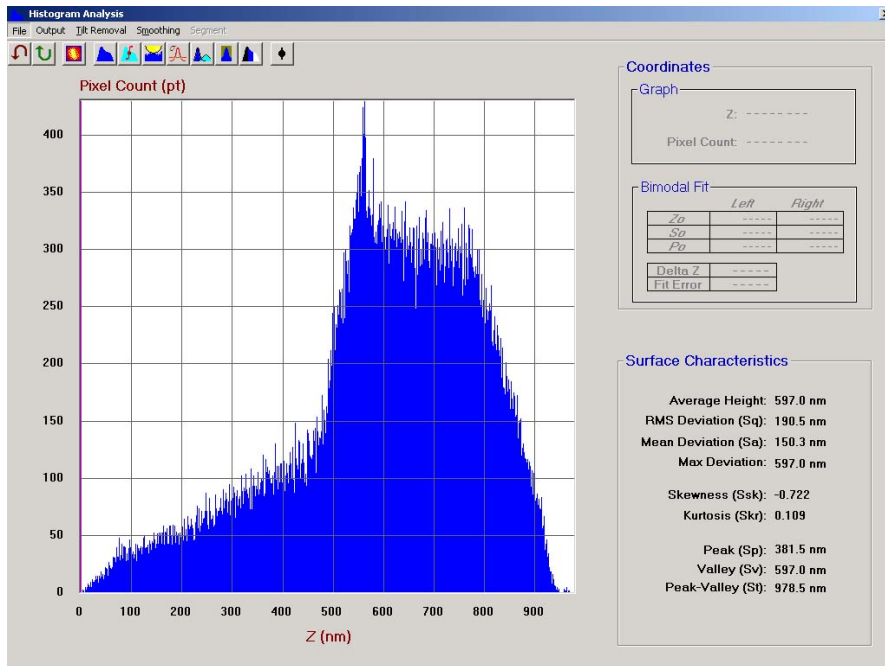
8.1.1 Menu Controls

File > Export Graph Data

Histogram, Histogram Integral and Bearing Ratio graph data may be exported as text files.   The respective file extensions are: *.hist.txt*, *.hint.txt*, and *.habt.text*

Tilt Removal

See: Post-scan surface leveling methods Section 7.4.1.

Smoothing

3, 5, and 9 Pixel The data are averaged over intervals of 3, 5, or 9 pixels along the x-axis to produce a smoothed image.

Segment

When the *Histogram Segmentation* mode is active this menu is enabled. (Ref. Section 8.1.2)

- **Flat Palette** The colors of the Low, Middle, and High image segments match the region colors on the histogram.

- **Graded Palette** This combination of three color palettes makes the distinction between the Low, Middle, and High segments of the image clear, while at the same time allowing the eye to get a sense of the underlying surface topology. The assignments are: 1) Low image segment— a grey scale palette running from black to mid-gray. 2) High image segmen— a grey scale palette running from mid-grey to white. 3) Middle image segment— the full range of the color palette assigned to the image.

- **Custom Flat Palette** The colors of the Low, Middle, and High image segments are user-selectable.   The colors are chosen with the Segment Colors menu controls.

- **Apply segment palette to image** The color palette assigned to the image while the Histogram Segmentation mode is active is temporary. Applying this option will replace the image's original palette with the temporary palette.

8.1.2 Toolbar Controls

Next/Previous Move through the image ring buffer for undo/redo operations.

Histogram Generates a histogram of the height data in an image. The number of levels in the histogram is fixed at 600.

Surface Image Displays the surface image.

Histogram Truncation Clicking on this control activates/deactivates the histogram truncation mode. When the truncation mode is active, clicking-and-dragging across the histogram will select the z-range of the image data to truncate. When the mouse button is released at the end of the click-and-drag operation the data will be truncated: image points with heights above the top of the selected range will be truncated to the height value of the top of the range; image points

with heights below the bottom of the selected range will be truncated to the height value of the bottom of the range.

❖Note: When image data are truncated the image data in the truncated regions are considered "suspect data". For this region the lowest and highest levels of the histogram data (bins 0 and 599) are not included in the following calculations: *Histogram Integral*, *Gaussian Fit*, *Bearing Ratio*, and *Bimodal Match*.

Histogram Segmentation Clicking on this control activates/deactivates the histogram segmentation mode.   When the segmentation mode is active the histogram will be separated into three contiguous colored regions.   The corresponding regions of the surface topology will appear in a small image at the upper-right corner of the **Histogram Analysis** window. The boundaries of the regions may be moved by clicking and dragging on the histogram with the mouse. The *Segment Dimensions* panel beneath the surface image lists information about the volumes and surface areas defined by the segment boundaries. The segment palette colors applied to the surface image may be changed via the *Segment* menu.

Coordinate Cursor   Clicking on this control activates/deactivates the coordinate cursor. When the coordinate cursor is active the Graph Coordinates panel will automatically track the position of the cursor.

Histogram Integral   This is the integral of the histogram distribution, starting from the point in the histogram corresponding to the lowest valley in the surface and summing upward. The vertical scale of the graph represents 0 - 100% of the surface area. For example, at the 20% point, 20% of the surface has an elevation below this level, and 80% is above.

Gaussian Fit   Superimposes onto the histogram plot a Gaussian fit to the data. This is calculated from the average height and Sq. (Ref. Section 8.1.3)

Bearing Ratio   The bearing ratio curve is the integral of the histogram distribution, starting from the point in the histogram corresponding to the highest peak in the surface and summing downward. The vertical scale of the graph represents 0 - 100% of the surface area. For example, at the 30% point, 30% of the surface has an elevation above this level, and 70% is below.

Bimodal Match   When this toolbar button is pressed the software will attempt to fit the histogram data with two Gaussian curves. If the distribution appear to be two overlapping Gaussians the software will attempt to fit the profile based on this premise.   If the distribution appear to be two widely spaced Gaussians then the software will attempt to fit the profile based on this premise. If the software fails to see the histogram as fitting either of these distribution

extremes it will place two Gaussian peaks on the histogram without attempting to fit the data.

The Gaussian peaks are graphically overlaid on the histogram graph.   They have handles to allow manual adjustment of their individual height, position, and width. The fit parameters for the bimodal fit are listed in the *Bimodal Fit* display panel.

8.1.3 Numerical Display Panels

Segment Dimensions

- **Area   Material (µm²) / (%)**

  This is the projected area of the surface in a given segment: That is, each pixel in an N x N pixel image of an L x L scan area is taken to represent an area of L² / N². The number of pixels falling within the bounds of a segment is summed and then multiplied by this factor to produce the projected area value. Note that this definition differs from the "true" surface area, which would be a summation of area segments following the actual contours of the surface.   The difference is illustrated below: projected area in red, "true" area in blue.

  The percentage value (%) is the projected area of a segment expressed as a percentage of the total scan area.

(A) Projected Surface Area   (B) "True" Surface Area
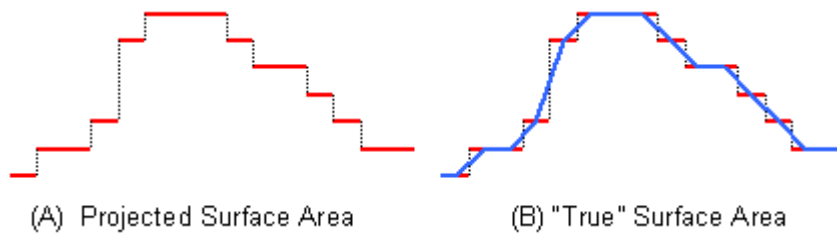
- **Volume   Material / Void (µm³)**

  The figure below graphically defines what is meant by *Material* and *Void* for a segmented image. (A) shows a cross-section through a hypothetical image.   The cross-section appears 'blocky' to emphasize the pixilated nature of the data in any image. In (B) the image has been segmented into *Low*, *Middle*, and *High* regions. The volume of material in a segment is represented by the blocks with solid shading. The volume of empty (void) space in a segment is represented by the blocks with textured shading. The software counts the blocks in the *Material* and *Void* spaces for each segment to arrive at the µm³ volumes listed for each space. Note that the

bottom of the *Low* segment is determined by the lowest pixel in an image, while the top of the *High* segment is determined by the highest pixel in an image.

(A) SURFACE TOPOLOGY

Zmax

Zmin
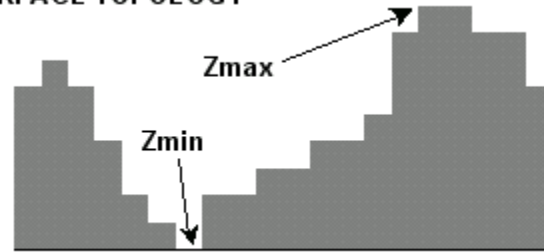
(B) SEGMENTED SURFACE

High

Middle

Low
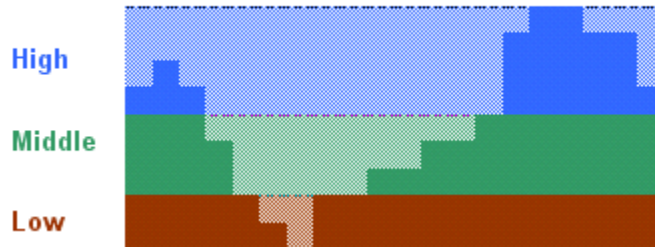
Coordinates

- **Graph**   The horizontal and vertical coordinates of the cursor position on the graph.

- **Bimodal Fit**   The parameters for the left and right Gaussian curves are defined by the distribution height H equation

$$H = P_o \exp[\ -(Z - Z_o)^2/(2S_o)^2]$$

    where P_o is the peak value of the curve and Z_o is the z-axis position where the curve peaks. Parameter S_o would be the standard deviation of a true Gaussian distribution, but more generally may be viewed as a measure of the width of the peak.

- **Delta Z**   The distance between the two peaks. Delta Z = Abs[(Z_o)left - (Z_o)right]

- **Fit Error**   A figure of merit for how well the bimodal fit matches the histogram distribution. It is the average absolute error between the data and the fitting function.

Surface Characteristics

These surface roughness parameters are computed in the **Histogram Analysis** window whenever histogram data are displayed.

❖Note: To get meaningful results for any surface roughness measurement it is important to make sure that the scan size is large enough to capture a representative sample of the topography of interest, and equally important to make sure the image topology is flattened in an appropriate way to remove all extraneous tilt and curvature.

- **Average Height**   The lowest point in the image is assigned the height of zero, and all other points in the image are higher than zero. The average height of the sample points is based on this reference arrangement.

$$\bar{z} = \frac{1}{N} \sum_{n=1}^{n=N} z_n$$

- **S$_q$ (Root Mean Square)** The standard deviation of the Z values in the image.

$$S_q = \sqrt{\frac{1}{N} \sum_{n=1}^{n=N} \left(z_n - \bar{z} \right)^2}$$

- **S$_a$ (Average Roughness)** The mean or average roughness. It is the average deviation from the mean surface plane.

$$S_a = \frac{1}{N} \sum_{n=1}^{n=N} \left| z_n - \bar{z} \right|$$

- **S$_{sk}$ (Skewness)**   A measure of the symmetry of the variation of the histogram profile about its mean line. Surfaces with a positive skewness have fairly high spikes that protrude above a flatter average. Surfaces with negative skewness have fairly deep valleys in a smoother plateau. More random surfaces (Gaussian) have a skew near zero.

$$S_{sk} = \frac{1}{NR_q^3} \sum_{n=1}^{n=N} \left(z_n - \bar{z} \right)^3$$

- **S$_{kr}$ (Kurtosis)** This is a measure of the spikiness of the histogram profile about its mean line, or equivalently, it is a measure of the area under the histogram's tails compared to those of a Gaussian fit to the data having the same standard deviation. A true Gaussian distribution has a kurtosis of 0. A positive kurtosis implies a sharply peaked distribution; compared to the Gaussian fit there is a relative shift in the distribution toward the tails. A

negative kurtosis implies a flat-topped distribution; compared to the Gaussian fit there is a shift in the distribution away from the tails.

$$S_{ku} = \frac{1}{NR_q^4} \sum_{n=1}^{n=N} (z_n - \bar{z})^4 - 3$$

- **S_p (Maximum Peak)** The maximum height or highest peak of the profile roughness above the mean plane.

- **S_t (Maximum Peak to Valley)** The sum total of the maximum peak and maximum valley measurements.

- **S_v (Maximum Valley)** The lowest point below the mean image plane.

8.2   DIMENSION ANALYSIS

Dimension Analysis
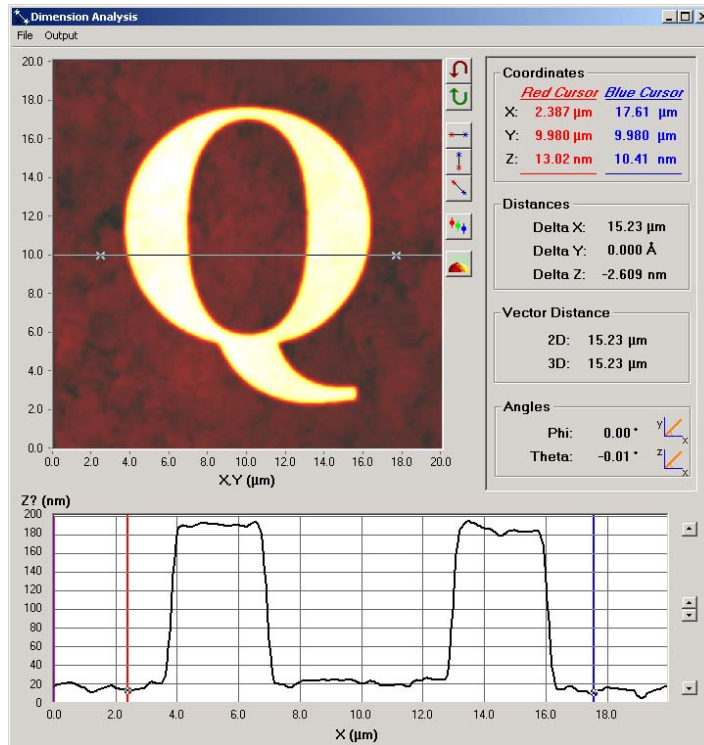
Toolbar Controls

Next/Previous   Move through the image ring buffer for undo/redo operations.

Shading   Turns on/off the slope-shading image rendering option.   Use the **Image Graphics** window to adjust the *Contrast* and *Z Color* slope-shading controls.

Section Detail   Transfers the cross section line being viewed in this window to the **Section Detail** window, and then opens that window.

Horizontal Section   Places a horizontal section line across the center of the scan image and draws the section graph.

Vertical Section   Places a vertical section line across the center of the scan image and draws the section graph.

Diagonal Section   Clicking this control activates the section-line drawing tool. When the tool is active, click-and-drag a line across the surface image to create a new section line of arbitrary length and direction. The tool will automatically de-activate after the section line is drawn.

❖Note: The red and blue cursor markers appearing on the section graph may be moved by clicking and dragging the corresponding cross marker along the section line. Also, the section line may be moved by clicking on the section line itself and dragging the line to a new position.

❖Note: Holding the Shift key down while drawing a *Diagonal Section* line will constrain the line to a horizontal path.

Numerical Display Panels

Coordinates

X, Y, Z   These are the coordinates of the two markers placed on the image cross-section line. They correspond to the Red and Blue cursors placed on section graph at the bottom of the screen. The coordinate system used has the origin placed in the lower-left corner of the image, the x-axis horizontal, the y-axis vertical, and the z-axis indicated by the colors in the color palette.

Distances

Delta X, Delta Y, Delta Z   These are the differences between the x, y, z coordinates of the two markers placed on the image cross-sectioning line.

Vector Distance

Preliminary definition: Let L be a straight line connecting the x,y,z coordinates of the two markers placed on the surface image.

2D   The 2D distance is the length of the projection of L onto the x,y plane. Mathematically the 2D distance is given by

$$2D = Sqr [(X1 - X2)^2 + (Y1 - Y2)^2].$$

3D   The 3D distance is the length of L . Mathematically the 3D distance is given by

$$3D = Sqr [(X1 - X2)^2 + (Y1 - Y2)^2 + (Z1 - Z2)^2].$$

Angles

(Refer to the definition of line L above.)

Phi   The *2D* distance between the marker points, as defined under "Vector Distances" above, is the length of the projection of L onto the x,y plane. Phi is the angle of this projected line with respect to the x-axis of the coordinate system. Mathematically Phi is given by

$$Phi = arctan \ [\ (Y1 - Y2) / (X1 - X2) \ ].$$

The value of *Phi* is always translated into the positive angular range of 0 - 90º.

Theta   *Theta* is the angle of L with respect to the xy plane.   Mathematically *Theta* is given by

$$Theta = arctan \ \{ \ (Z1 - Z2) / Sqr \ [\ (X1 - X2)^2 + (Y1 - Y2)^2 \ ] \ \}.$$

Theta falls in the angular range of +90º to -90º, depending upon which of the markers is in the higher position.

(Blank Space)

8.3 SECTION DETAIL

This is an extension to the **Dimension Analysis** window. It has additional tools for probing the 2D characteristics of an image.

Section
Detail
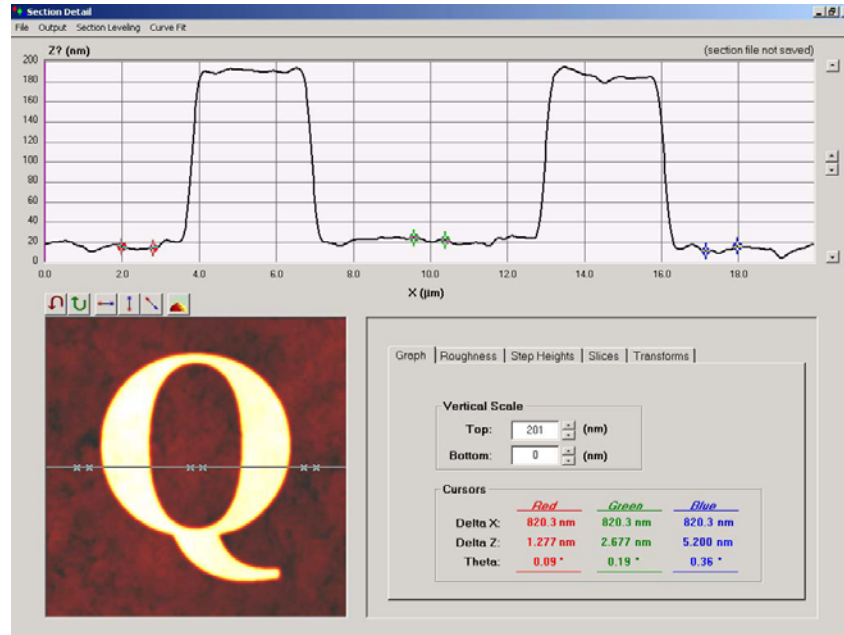
Menu Controls

File > Save/Load Section Data

Section data may be stored and retrieved. The data are stored as a text file with the file extension *.xsec.txt*. Power spectral density data may be exported. The data are stored as a text file with the file extension *.psd.txt*.

Section Leveling

• **Linear**   The section data are fit with a least-squares line, and the linear fit is subtracted from the data.

• **Parabolic**   The section data are fit with a least-squares parabola, and the parabolic fit is subtracted from the data.

• **Red Cursor Selection**   The coordinates of the two red cursors define a line which is subtracted from the section data.

- **Undo Leveling** After any of the three section leveling options is applied to a cross-section this control is enabled. It returns the section data to their previous values.

Curve Fit

The results of each of the curve fits below are posted in the upper-left corner of the section graph. The data are unchanged.

- **Line** The section data are fit with a least-squares line.

- **Parabola** The section data are fit with a least-squares parabola.

- **Periodic Step** The data are fit with a periodic rectangular profile which slopes linearly up or down.

  The output parameters for *Period Step* are: *Period*, *Duty Cycle*, and *Height*. The duty cycle is expressed as the ratio of the length of the high segment of the period to the length of the low segment. The goodness-of-fit criteria used in the curve fit is the "least absolute error", not the "least squares error". The *Periodic Step* fitting algorithm produces meaningful results only if it is applied to section data which has a truly periodic contour, or if it is applied to single surface step, which can be interpreted by the software as a segment of a longer periodic contour.

Toolbar Controls

Next/Previous Move through the image ring buffer to provide undo/redo capability.

Shading Turns on/off the slope-shading image rendering option. Use the Image Graphics window to adjust the Contrast and Z Color shading parameters.

Horizontal Section Places a horizontal section line across the center of the scan image and draws the section graph.

Vertical Section Places a vertical section line across the center of the scan image and draws the section graph.

Diagonal Section   Clicking this control activates the section-line drawing tool. When the tool is active, click-and-drag a line across the surface image to create a new section line of arbitrary length and direction.   The tool will automatically de-activate after the section line is drawn.

❖Note: The red, green, and blue cursor markers appearing on the section graph may be moved by clicking and dragging the corresponding cross marker along the section line. Also, the section line may be moved by clicking on the section line itself and dragging the line to a new position.

❖Note: Holding the Shift key down while drawing a Diagonal Section line will constrain the line to a horizontal path.

Tab Controls

Graph

Vertical Scale   The upper and lower limits of the section graph may be adjusted to specific values.

Cursors   Three cursor pairs appear on the section line graph: a red pair, green pair, and blue pair. For each cursor pair, the vertical and horizontal distances between the markers, and the angle *Theta* of a line running through the markers, are computed. *Theta* is measured with respect to the horizontal axis of the section graph.

Roughness

Standard roughness parameters for the section line are computed when the *Measure* button is pressed.   *Measure* also superimposes onto the graph a graphical representation of the reference line used for the computations, and the highest and lowest points in the section line. The reference line used to compute the surface roughness may be set to either a horizontal line representing the average (mean) height of the section profile or a user-selected reference line determined by the positions of the red cursor markers.

The definitions of the cross-section roughness parameters are the 1-dimensional analogs of the 2-dimensional quantities specified in Section 8.1.3.

❖Note: To get meaningful results for any surface roughness measurement it is important to make sure that the scan size is large enough to capture a representative sample of the topography of interest, and equally important to make sure the image topology is flattened in an appropriate way to remove all extraneous tilt and curvature.

Step Heights

When *Measure* is pressed the average height of the data between each cursor color pair is calculated and shown graphically on the section line graph. These three heights are used to calculate three step heights: the step height between the red and green averages, the step height between the red and blue cursor averages, and the step height between the blue and green averages. The step heights are tabulated under the *Delta* column. The low and high levels of each step are tabulated under the *Average Low* and *Average High* columns, respectively.

Slices

Pressing *Measure* creates a set of equally spaced horizontal cross-sections through the image data. The resulting roughness parameters for each line are tabulated. The *Slices* tab is enabled only when a topology image is being viewed, and will be disabled for all other types of image data such as *Phase* and *Lateral Force*.

Transforms

Pressing *Measure* with the *Section Line* radio button selected will calculate the power spectral density (PSD) curve for the cross section line and graph the results. Alternatively, with the *Image* radio button selected, pressing *Measure* will calculate the power spectral density curve for every scan line in the image, and the average of the PSD curves will be graphed.

The slope of a segment of the PSD curve can be estimated by positioning the cursors to the endpoints of the segment and pressing the *Cursor Slope* button. The slope value is for the line passing through the cursor points.

❖Note: The vertical scale of the PSD is not normalized. The PSD calculation is performed by first calculating the FFT of the scan line data, with the transform being applied to image data numerically expressed in micrometer units. The real and imaginary numbers produced by the FFT routine are then squared and added together to generate the final PSD spectrum. No additional scaling factors are applied.

8.4   IMAGE MATH

The **Image Math** window has software controls for mathematically comparing, manipulating, and modifying surface images as complete objects.

Image Math
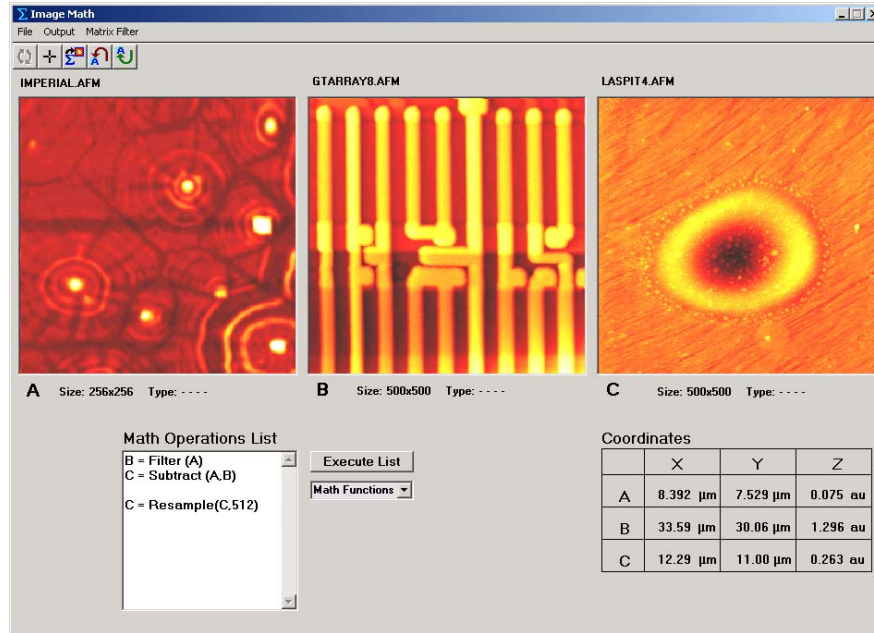
8.4.1 Menu Controls

❖Note: For the control options under the *File* and *Output* menu headings one of the three image bins A, B, or C must be selected to determine which bin the operation will be applied to. Select a bin by clicking on the image space. The border of the bin will be highlighted in blue to indicate it has been selected.

File > Keep Image

Selecting one of the images by clicking on it and then applying the *Keep Image* command will transfer the selected image to the main image buffer of the software, and then the **Image Math** window will be minimized, but not closed. In this way the selected image may be viewed or process by the other analysis windows in the software. The functionality is identical to the *Transfer* toolbar button.

Matrix Filter

- **Matrix Filter Editor...**   Refer to Section 7.5.

- **…List of Filters…**   This list is populated with the filters stored in the Matrix Filter folder of the ScanAtomic software. Place a check mark next to the filter you wish to be applied when the *Filter()* math operation is applied. Refer to section 8.4.1 for further information about the *Filter()* math operation.

8.4.2 Toolbar Controls
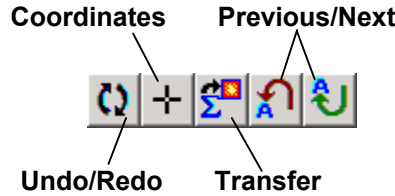
Undo/Redo   Allows alternating back and forth between the contents of image bins A,B,C before and after the instructions in the *Math Operations List* have been executed.

Coordinates   When this tool is highlighted, clicking at any point in one of the images will place an identically positioned fiducial mark in each of the images, and also update the x,y,z coordinate data shown in the *Coordinates* table. This is useful for comparing the topology details in multiple images.

Transfer   Selecting one of the images and then pressing the *Transfer* button will transfer it to the image processing buffer of the software. The **Image Math** window will be minimized but not closed. In this way the selected image may be viewed or process by the other analysis windows in the software.

Bin-A Previous/Next   Moves the 5-level image buffer contents in and out of image bin A. (Ref. Section 7.9)

❖Note: The contents of an image bin may be copied to one of the other two bins by a drag-and-drop operation with the mouse.

8.4.3 Math Operations List

Math Operations List

B=Filter(A)	
C=Subtract(A,B)	Execute List
C=Resample(C,512)	Add (a,b) ▼
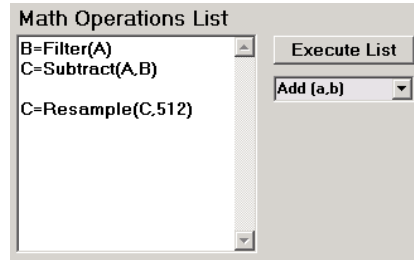
Pressing the *Execute List* button processes the math operations listed in the *Operations List* text box up to the point where the first blank text line is encountered. For quick reference purposes, the available math operations are given in an adjacent drop-down list. Selecting an entry in the drop-down list will insert the function text in the *Operations List* text box at the location of the text cursor. A detailed description of each function is given below.

The syntax to be followed when entering math instructions into the list is

<p align="center">Destination = Function (Operands)</p>

where Destination is the letter of the bin where the result of the operation will be placed and Function is one of the functions listed below. Operands may be bin letters and/or dimension numbers, depending on the function type.

❖Note: The instruction syntax is not case sensitive. Upper or lowercase letters can be used.

The instruction list shown in the picture above serves as an illustrative example. In the first line B=Filter(A) a matrix filter will be applied to image A and the results will be placed in image B. In the second line C=Subtract(A,B) the contents of B will be subtracted from A and the result will be placed in C. Because the third line in the list is a blank line, the next line in the list C=Resample(C,512) will not be executed.

Function Summary

- **Invert(a)**   Inverts the image along the z axis. High features become low; low features become high.

- **Rotate(a)**   Rotates the image 90° CCW.

- **Copy(a)**   Creates a duplicate of an image.

- **Filter(a)**   Applies the matrix filter selected under the *Matrix Filter* menu list.

- **Mirror(a)**   Applies the coordinate transform x$\rightarrow$ -x to the image.

- **d/dx(a,n)**   Takes the derivative of the image topology along the x axis. Parameter n specifies the size of the fitting interval to compute the derivative. The minimum value is 1, corresponding to 1 point to the right and left of the center point. The maximum value is 1/10 of the image pixel resolution. For example, the maximum allowed fitting interval would be 30 points to the right and left of the center point for a 300 x 300 pixel image.

- **Resample(a,n)**   Increases or decreases the pixel resolution of an image by interpolation. Parameter n specifies the new resolution of the image. Allowed values for n are in the range of 100 - 1024.

- **ResizeX(a,n)**   Expands or compresses the image along the x axis to the new size n in μm . For example, if a value of $n = 0.8$ is applied to a 1 μm x 1 μm image, the image will be compressed to 80% of its original size along the x axis, with the remaining 20% of the image space being filled in by a blank flat plane. The shape of the image along the y axis will not be affected.

- **RescaleXY(a,n)**   Changes the xy size of an image. Parameter n specifies the new x and y horizontal size of the image in units of μm.

- **RescaleZ(a,n)**   Changes the z height of an image. Parameter n specifies the new vertical height of the image in units of μm. If n is negative the image will be rescaled and inverted.

- **Add(a,b)**   On a pixel-by-pixel basis, the z value of two images are added together to produce a new image.

- **Subtract(a,b)**   On a pixel-by-pixel basis, the z value of b is subtracted from a to produce a new image.

9   *Standard System Calibration*

Calibration is a procedure which sets the ability of the instrument to accurately measure distances along the X, Y and Z axis using standards of known accuracy. The properties of the piezoelectric scanner (PZT) change with age, temperature and use. Hence, calibration must be performed periodically.

System
Calibration

The calibration procedures described in this chapter apply to the *Standard* mode of operation. If your system hardware includes the metrology option, the calibration procedures for the *Metrology* mode of operation are given in Manual Supplement 11. The noise and thermal drift tests given at the end of this chapter apply to all SPM systems.

9.1   X AND Y AXIS CALIBRATION

The xy motion of the scanner is calibrated by scanning a grating with a known line pitch and using the spacing of the lines in the image to generate the required calibration parameters. The goal of the calibration software is to adjust the calibration parameters to produce an image of the grating in which the line pitch is constant within a specified nonlinearity tolerance and the pitch is precise within a specified pitch tolerance.

The software generates the calibration parameters iteratively: it automatically scans the grating, calculates new calibration parameters from this image, and then rescans the grating with the new parameters to see if the nonlinearity and pitch tolerances have been met.   This procedure is repeated until the tolerances are met.

In the simplest and quickest calibration scheme, calibration scans at just one scan size, speed, and direction are used to calibrate both the x and y axis of the scanner. The software then extrapolates from these numbers to move the scanner correctly at larger or smaller scans, faster or slower scans, and scans which are rotated from the original calibration direction. The calibration instructions given in section 9.1.1 are for the quick calibration scheme. The resulting scanning performance is adequate for most applications.

There are also several advanced calibration options which improve the scanner performance in some circumstances. These options are discussed in section 9.1.2. The scanner performance is improved by creating a matrix of calibration values at different scan sizes, speeds, and directions so that the calibration data are interpolated rather than extrapolated to control the scanner motion.

9.1.1 Basic X,Y Calibration Procedure

1. Locate the calibration grating shipped with your system. It normally is placed in the scaner shipping box. Table 9.1 below lists the gratings included with the standard scanner types.

Scanner Range (µm)	Grating (µm)
20	1.1
40	1.1
80	2.0
200	6.67

Table 9-1 Gratings shipped with the standard scanner types.

Other gratings may be substituted if desired. The general rule is that the spacing of the lines in the grating should be in the range of 1/50 to 1/5 of the scanner range. For example, a 40 µm scanner may be calibrated with a grating having a line spacing in the range of 0.8 µm to 8 µm.   Gratings with a line pitch at the lower end of this range are preferred.

2.   The grating provided for the 20, 40, and 80 micron scanners is usually in the form of a plastic replica film mounted on a glass slide. For the other scanner types the grating lines are engraved into the surface of a 0.5 square glass block. In any case, place the grating under the scanner with the lines of the grating oriented along the y-axis of the scanner as shown below.
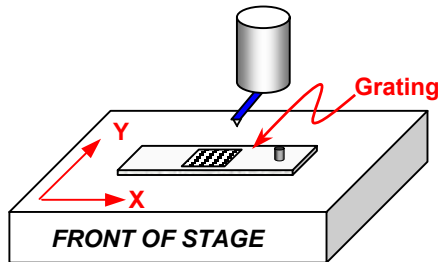
**Figure 9-1
The calibration slide with the grating oriented for x-axis calibration.**

3. The calibration may be performed with either *Wavemode* or *Z Height* scans, though it is generally easiest to use *Z Height*. Engage the probe with the grating surface and image an area on the surface corresponding to the nominal range of your scanner, e.g., 40 µm for a 40 micron scanner, 80 µm for an 80 micron scanner, etc.

- Verify that the surface area selected is free of defects. If any large defects are found move to a different area of the grating and try again.

- Verify that the lines in the grating fall within ±4° degrees of the y-axis of the scanner. For example, refer to the grating image in Figure 9.1. The pitch spacing along the x-axis varies with the cosine of this angle, so keeping the rotation under 4° keeps the pitch error under 0.25 %.

4. Open the calibration software window and select the *Auto XY* control tab. In the *Parameters* panel you will see that there are several options for how the xy motion of the cantilever may be calibrated.   The calibration method followed here is the simplest one, with all the options switched off.   Setup the *Parameters* panel as follows:

- Uncheck all of these calibration options: *Separate small grating*, *Orthogonal scans*, *Small*, and *Fast.*

- If the scanner is being calibrated for the very first time on your system (e.g. it was not calibrated at Ambios) check the *Start with... Default calibration* option.   Otherwise check the *Start with... Current calibration* option.

- In the *Grating Line Spacing* box enter the pitch of your calibration grating.

- Set the *Large Scan Size* entry to the nominal xy range of the scanner: 20, 40, 80, or 200 microns.

- Set the *Slow Scan Speed* to either 1 Hz or 2 Hz .

- The *Maximum Iterations* entry determines how many times the software will rescan the grating in attempting to reach the range and nonlinearity tolerance values. It normally only takes two iterations to reach the tolerance values, but it is generally best to set *Maximum Iterations* to 4 to allow for the worst-case conditions.

- For 20, 40, and 80 micron scanners set the *Nonlinearity Tolerance* and *Pitch Tolerance* values to 1%. For the 200 micron scanner set the *Nonlinearity Tolerance* to 2% and the *Pitch Tolerance* to 3%.

5. Now press the green *Start* button.   This initiates the x-axis portion of the calibration sequence:

- The software automatically makes these **SPM Configuration** adjustments: *Scan Resolution* = 400, *Center X* = 0, *Center Y* = 0, *Scan Direction* = 0º.

- If the system is setup for contact-mode imaging the software automatically sets the *Scan Type* to *Broadband.* If the system is setup for intermittent-contact mode imaging the software automatically sets the *Scan Type* to *BB Wavemode.* This is done because the image produced by *Broadband* / *BB Wavemode* generally picks-up the grating lines more distinctly than *Z Height* / *Wavemode*, improving the performance of the calibration algorithm.

- The calibration software scans the surface and displays the scan in the upper-right panel of the **Calibration** window. Note: Any RT tilt-removal features which were active will be deactivated for the calibration scans.

- The *Scan* panel shows the current *Size*, *Speed*, and *Angle* of the scan underway, and indicates which iteration this scan represents in the search for parameters which will put the scanner calibration within tolerance.

6. At the completion of each scan the tilt and curvature in the grating image are removed, the image is smoothed, and then the image is broken down into approximately 8 horizontal segments to which sine and cosine curves are fitted. These are plotted as a series of green and magenta sinusoids on top of the image panel. From these curves the phase of the grating undulation is integrated and plotted as a series of green diagonal lines. If the calibration procedure works correctly the green lines will fall nearly perfectly on top of one another, as shown in Figure 9-2.
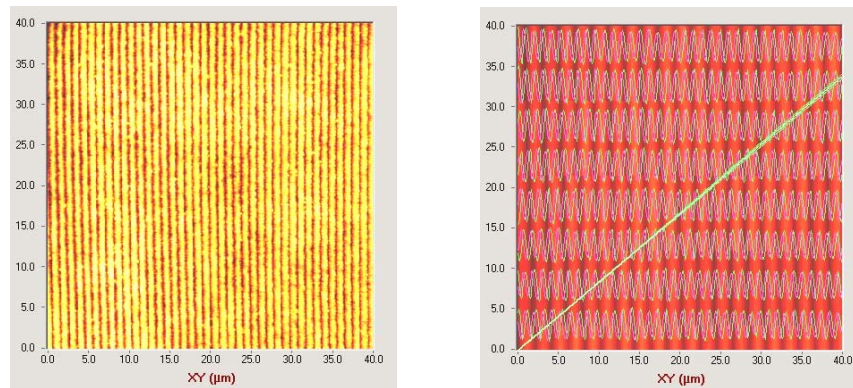
Figure 9-2   Left: Scan of a 1.1 µm calibration grating. Right: The sinusoids calculated by the software quantify the shape of the grating contours.   The phases of these waves are integrated to determine how the scanner is moving as it scans. The integrated phase is represented by the diagonal green lines. If the motion is linear, and constant from the beginning to the end of the scan, the green lines will be straight and overlap one another as shown here.

❖Note: If the green lines diverge wildly on the righthand side of the image this indicates that calibration algorithm has failed to integrate the phase correctly.   The calibration procedure will fail in this circumstance.   The usual cause of this problem is that the calibration image has insufficient high/low contrast in the grating profile, either because the tip is too blunt or the grating lines are too close together. If this happens you should stop the calibration and try using a probe with a sharper point.

7. The *Results* panel shows the calibration results for the most recently completed scan. As each scan is completed these numbers will be updated. You should observe that the *Nonlinearity* and *Average Line Pitch* values gradually improve with each iteration, until they eventually fall within the tolerance values specified in the *Parameters* panel. The *Expansion Range* parameter indicates the actual maximum range available to the scanner along the axis being programmed. Typically this will be 5% to 10% more than the nominal xy range of the scanner.

8. Once the x-axis has been calibrated to within the specified tolerance the probe will automatically be retracted, and you will be instructed to rotate the grating by 90º in preparation for the y-axis calibration. After you have rotated the grating engage the probe with the surface again and scan the surface to verify that:

- The selected scan region has no defects.
- The grating lines fall with ±4º of the x-axis.

9. Now press the yellow *Continue* button. This initiates the y-axis portion of the calibration sequence. The program will proceed in a similar fashion to the way the x-axis was calibrated. The primary difference is that you will notice that the scan image will automatically be rotated by 90º prior to fitting the sinusoids and integrating the phase. This is just a matter of programming simplicity; exactly the same calibration algorithm is used for the y-axis as for the x-axis.

Additional Information

The calibration data are stored in the spm.ini file. A separate group of calibration data are stored for each head type, so that multiple scan heads may be supported by the microscope system.

It is important to give the microscope sufficient warm-up time prior to running the calibration software to minimize the effects of thermal drift on the scans. Ideally the microscope stage is housed in an enclosure (e.g. the AVIC) and left switched on for at least one hour prior to calibration.

If for some reason you wish to skip the x-axis calibration steps and proceed directly to the y-axis calibration, hold the keyboard Ctrl key down when clicking the *Start* button.

9.1.2 Advanced X,Y Calibration Features

If circumstances warrant their application, the advanced calibration software features which were switched off in the section 9.1.1 procedure may be switched on. They work independently of one another, so the options may be switched on/off independently. The overall procedure outlined in 9.1.1 still holds— i.e., the grating is used to calibrate the x-axis first, and then the y-axis— the primary difference is that when additional calibration options are switched on more scans will be performed by the system, and the overall calibration time will increase. The options are described below.

Orthogonal Scans

For most scanning applications the *Scan Direction* parameter is left fixed at 0º, which means that the x-axis is always the "fast" scan direction (the probe moves quickly from side-to-side) and the y-axis is always the "slow" scan direction (the probe moves slowly down line-by-line). This is exactly the way the scanner is calibrated in section 9.1.1.

When the *Scan Direction* is rotated, however, this leads to an error in the scanner calibration. In the worst cases— scans at 90º or 270º— the calibration values will be applied in reverse: the fast x-axis calibration data will be applied to what has become the slow direction, and the slow y-axis calibration will be applied to what has become the fast direction. This may lead to scan dimension errors of 5% to 15% depending on the scanner type.

By checking the *Orthogonal Scans* option the software will calibrate the x-axis and the y-axis as both the slow and the fast scan direction. This is done by performing calibration scans at both 0º and 90º. When the instrument is calibrated in this way, as *Scan Direction* is rotated the software will automatically interpolate between these two calibration data sets, thus removing the 5% to 15% dimensional error problem.

Small Scans

In the procedure of section 9.1.1 the scanner was calibrated at one scan size. When the instrument is calibrated in this way, as you use the microscope the software extrapolates from this data set to control the motion of the scanner at smaller and larger scan sizes. This method works very well for the 20 and 40 micron scanners, but for the 80 and 200 micron scanners there may be a small error introduced at very small scan sizes.

By checking the *Small* scan option the software will calibrate the x and y axis of the scanner at both a large and small scan size. When the instrument is calibrated in this way, a surface scan performed between these two calibration points will use

interpolated calibration numbers. When the surface is scanned at a scan size below the smaller calibration range the calibration will be an extrapolation once again, but the distance of the extrapolation will be much smaller and less prone to error.

The *Small* scan option gives you the additional choice of calibrating with the same grating at both the large and small scan sizes, or using separate gratings for the large and small scans. The advantage of using just one grating is simplicity and speed. It is not necessary to swap gratings and pick a clean scanning region every time the grating is switched. The advantage of using two separate gratings is that there is more freedom to choose the size of the small scan calibration point. For example, with a 40 micron scanner you could use the 1.1 µm calibration grating to calibrate the instrument at both 40 µm and 6 µm. It is not possible to use the 1.1 µm grating to calibrate below about 6 µm because there would be too few grating lines in the scan image to produce a reliable calibration result. But if a separate finer pitched grating is available you could calibrate at a scan size much less than 6 µm.

In short, there are two small scan calibration options. They affect the calibration procedure in the following way:

One Grating

   a) Check *Small* scans.

   b) Select a grating with a pitch of approximately 1/40 the nominal xy range of the scanner. Enter the pitch of this grating in the *Grating line spacing* parameter box.

   c) Enter the nominal scanner xy range in the *Large Scan* box.

   d) Do not check *Separate small grating*. Enter in the *Small* parameter box a distance which will produce an image containing no less than 5 complete grating lines with the grating selected in step (b).

Two Gratings

   a) Check *Small* scans.

   b) Select a <u>Large</u> grating with a pitch of 1/50 to 1/5 the nominal xy range of the scanner. Enter the pitch of this grating in the *Grating line spacing* parameter box.

   c) Enter the nominal scanner range in the *Large Scan* parameter box.

   d) Select a <u>Small</u> grating with a finer pitch than the <u>Large</u> grating.

   e) Check *Separate small grating*. Enter the pitch size of this grating in the adjacent text box.

   f) Enter in the *Small* size parameter box a distance which will produce an
       image containing no less than 5 complete grating lines with the <u>Small</u>
       grating.

   g) Note that when the green *Start* button is pressed the calibration sequence
       begins with the <u>Large</u> calibration grating.   As the calibration process
       continues you will be prompted to switch between the <u>Large</u> and <u>Small</u>
       gratings as they are needed by the software.

Fast Scans

In the procedure of section 9.1.1 the scanner was calibrated at one scan speed.
When you use the microscope, the software extrapolates from this data set to
control the motion of the scanner at faster and slower scan speeds. This method
works very well for the 20 and 40 micron scanners, but for the 80 and 200 micron
scanners there may be a small error introduced at very fast scan speeds.

By checking the *Fast* scans option the software will calibrate the x and y axis of
the scanner at both a fast and slow scan speed. When a surface is scanned at a
scan speed between these two calibration points interpolated values will control
the scanner motion. When the surface is scanned at a scan speed greater than the
faster calibration point the calibration will be an extrapolation once again, but the
distance of the extrapolation will be much smaller and less prone to error.

9.2   Z AXIS CALIBRATION

There is only one z-axis calibration factor in the software. It specifies the
maximum z motion of the probe when the maximum z-axis voltage swing is
applied to the PZT. A separate value is stored for each head type, so that multiple
scan heads may be supported by the system.

There are two different procedures available for calibrating the z-axis of the
scanner. The first procedure, *Calibration with a Sloped Surface*, gives a good
general-purpose calibration of the system, and works particularly well when
objects larger than 1 μm are being imaged. The second procedure, *Calibration
with a Step Height Standard*, gives the most accurate results because the
instrument can be calibrated with a step height comparable to the height of the
surface features in your samples.

❖Note: Ambios only ships step height standards with metrology systems.
Owners of standard SPM systems may purchase step height standards directly
from Silicon-MDT, VLSI Standards, etc.

❖Note: It is possible to manually change the z-axis calibration value. Open the **Advanced Configuration Parameters** window (**ScanAtomic** > *Utilities* > *Advanced Configuration Parameters*) and check the *Enable Diagnostic Software* option. Then open the **SPM Calibration** window and select the *Std Utility* tab panel. The value is changed via the *Z-axis Calibration Constant* entry box.

Calibration with a Sloped Surface

Locate at the calibration glass slide provided with your instrument (Ref. Figure 9-1). When this slide is placed on the translation stage upside-down, so that it is supported by one edge of the glass and the metal post (Figure 9-3), the surface of the glass slide will have a 10% slope. The 10% sloped surface is used to calibrate the z-axis of the scanner via the previously performed xy calibration. Provided the xy axis are calibrated correctly, in a scan of this surface we know that for every 10 μm of motion along the direction of the glass slope, the surface must rise 1 μm. This known vertical change is used to calibrate the z-axis of the scanner.

1. Withdraw the scanner about 10 mm above the sample stage and place the calibration slide underneath the probe, parallel to the y-axis, as show here:
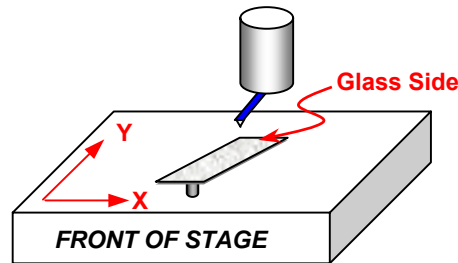
Figure 9-3 The glass slide properly positioned under the scanner for z-axis calibation.

2. Lower the probe onto the surface, wait a minute or two for the system components to settle, and then scan the surface at a rate of 1 – 2 Hz. The scan size should be set to approximately 10x the vertical range of the scanner. (Refer to Table 9-2) For example, the scan size should be set to 40 μm for a "40 μm scanner" with a nominal 4 μm z range.

❖Note: All RT tilt removal features (Ref. Section 5.3) must be turned off for this procedure to work correctly.

3. Open the **Calibration** window and press the vertical cross-section button to produce a section view of the image running directly along the 10% slope. The section line should look like a fairly straight, upward sloping line, as shown in Figure 9-4. Move the red cursor markers on the section graph to the far ends of the curve as shown in the figure.

Vertical Section

Figure 9-4 Vertical cross-section of the 10% sloped surface.

4. Select the *Two Pt XYZ* tab panel. Under the *Measured Distance* column there
    will be a readout for the horizontal distance between the red cursors, labeled
    Delta Y. The vertical distance between the red cursors, based on the system's
    current calibration, is shown next to the *Delta Z* label.

5. We know that the actual vertical distance between the red cursors is $1/10^{th}$ of
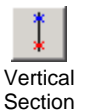   the *Delta Y* value. Enter this number in the textbox under the *Known Distance*
    column for the *Delta Z* row. Be sure to use the correct units when entering
    this number.

6. Under the *Calibrate Axis* column the Z button will now be enabled. Press this
    button and the Z axis will be calibrated. A message box will appear asking
    you to confirm that the newly computed Z range for the scanner is reasonable.
    The table below lists the nominal vertical ranges of the standard scanner types.
    If the result you obtain is wildly different from these values the usual reason is
    either (a) the *RT tilt* removal options were not turned off when the surface was
    scanned, or (b) the cross-section line chosen runs sideways to the surface slope
    rather than directly up the slope.

Scanner XY Range (µm)	Z Range (µm)
20	2
40	4
80	8
200	8

**Table 9-2   Nominal vertical and
horizontal ranges for the standard
scanner types.**

Calibration with a Step Height Standard

The important factors to consider when calibrating your scanner with a step height
standard are:

- Choose a step height standard which is similar to the height of the features of interest in your samples.

- Always take small, slow scans of the calibration grating to minimize the amount of creep error in the calibration image. Only two or three grating lines are needed in the calibration image.

The step height calibration procedure is given below.

1. Orient the grating under the probe with the grating lines aligned parallel to the y-axis of the scanner, as shown here:
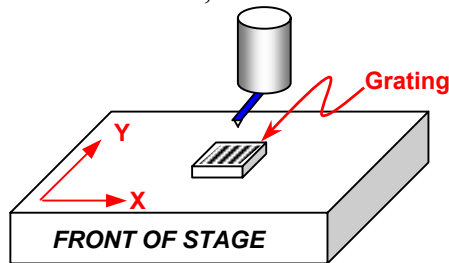
**Figure 9-5
The step-height grating oriented for z-axis cal-ibration.**

2. Place an intermittent-contact cantilever into the probe holder and setup the microscope for *Wavemode* scanning. Lower the probe onto the surface. Scan 2-3 lines of the grating at a slow scan speed, typically 1Hz.

3. Flatten the image using the *3-Point* tilt removal method (Ref. Section 7-4).

4. Open the **Calibration** window. Press the *Horizontal Section* button to create a horizontal cross-section running perpendicularly through the grating lines, as in Figure 9-6. Move the red cursor markers on the section graph to the top of a step; move the blue cursor markers to an adjacent trough, as shown in the figure.

Horizontal
Section
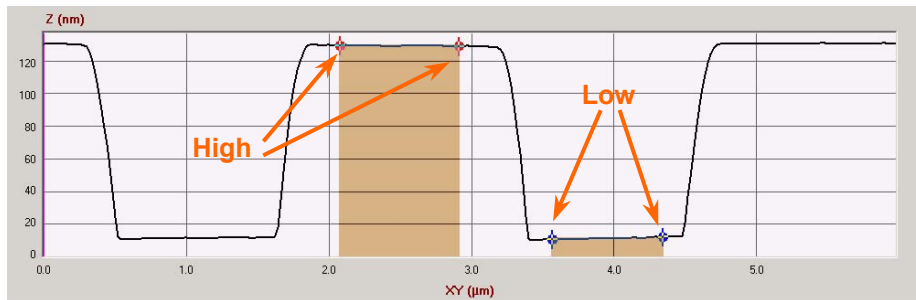
Figure 9-6 Horizontal cross-section of a step height standard with the cursors positioned to measure the step.

5. Select the *Two Pt XYZ* tab panel. Under the *Measured Distance* column click the *Measure* button next to the R_z-B_z text box. The average of the data points between the markers is used to compute the step height distance. The value is posted in the adjacent textbox.

6. Under the *Known Distance* column, along the R_z-B_z, row, enter the manufacturer's step height value for the grating. Be sure to use the correct units when entering this number.

7. Under the *Calibrate Axis* column the Z button will be enabled. Press this button to calibrate the Z axis.

❖Note: When the z axis of a scanner is calibrated with a step height standard it is not unusual for the calibration result for the nominal z range of the scanner to be significantly less than with the sloped surface method. The apparent reduction in range can be as large as a factor of 2, depending on the scanner type. The source of this discrepancy is the difference in how the piezoelectric material responds to a small voltage change versus how it responds to a large voltage change. When calibrating the piezo tube with the 10% sloped-surface, the tube is expanded and contracted over close to its full voltage range, i.e. about 400 volts. This gives a true value for the full range of the scanner. When calibrating the piezo tube with a step height standard, however, the voltage change applied to the tube is much less, typically in the range of 4 to 40 volts. The piezoelectric material will move a smaller distance when it experiences small voltage changes than it will for large voltage changes.

9.3   IMAGE NOISE TEST

This test can be performed at any time with any type of probe. It is a good way to track down sources of image noise and to quantify the results of any steps you take to reduce the noise. The basic idea is to disable the XY movement of the scanner during a scan so that the probe point stays over the same position on the surface throughout the scan. Any vertical movement appearing in the scan must therefore be due to some sort of noise, and not to features of the surface.

When this image noise test is performed, be aware of the fact that the data produced are dependent on several factors beyond just noise present in the system. The proportional, integral, and derivative gain settings, the scan rate, and resolution settings, and whether the scan is performed in *Wavemode* or *Z Height* mode are all important factors. If you wish to keep a running record of the noise level of your system you must use the same parameters each time. Also note that, all other factors being equal, the image noise level is always lower in *Wavemode* than in *Z Height* mode.

The steps for measuring the image noise are given below.

1. At the **SPM Configuration** window check *XY Disabled.* Depending on the type of cantilever in the probe holder, select either *Z Height* or *Wavemode* for *Scan Type*. If the probe is not already in surface contact, lower the probe to the surface and wait approximately 20 seconds for the microscope to stabilize.

2. Go to the **Realtime** window and activate the *L/L Parabolic* tilt removal option, found under the *RT Options* menu. Start the scan.

3. The fuzzy image appearing on the screen is a visual representation of the vertical image noise of the system. When the scan is completed, remove any tilt in the image with the *Parabolic* tilt removal method.

4. Open the **Histogram** window. The number of interest is Sq (rms deviation) shown in the *Surface Characteristics* panel. This is a quantified measure of the vertical noise of the system. The noise level achieved will depend on the extent to which the instrument is shielded from mechanical, acoustic and airflow disturbances. An excellent noise level would be one less than 1 Å rms.

5. If there is any periodic structure in the noise image— in particular, any diagonal banding in the image— this is an indication that one of the sources of noise is periodic. Likely suspects include fan noise, motor noise, AC power line noise, and resonant vibration of the PZT scanner. To track down the culprit it is helpful to have its number… that is, the frequency of the periodic noise. This can be determined by going to the **Fourier Transform Filtering** window and examining the frequency spectrum. When interpreting the frequency information keep in mind that aliasing may occur during the data sampling.

6.   As a final step, return to the **SPM Configuration** window and uncheck *XY Disabled* when you are through.

9.4   THERMAL DRIFT TEST

Long-term thermal drift is generally caused by the slow process of heating and cooling the various components of the scan head and stage. The heating (or cooling) is generally due to variations in room temperature, by the slow heating produced by the warm video camera, and the slow heating produced by the camera illumination light inside the scan head. The stepper motors on the system are not a source of heating because they are switched off except for the brief time intervals when the scan head or stage is being moved. The video camera is perhaps the worst offender, because it is the warmest component in contact with the scanner body.

To measure the vertical thermal drift, lower the probe onto a flat surface and wait 20 seconds for the instrument to stabilize. From the main software window go to *Utilities >Advanced Scan Parameters* and check *Enable Diagnostic Software*. Then go to *Utilities > General* to open the **General** utilities window. In the *Vertical Drift* panel press *Start*. A graph will be slowly generated showing the vertical position of the probe as a function of time. Because the probe is nominally not moving, any deviation of this graph from a straight line is a measure of the relative shift between the PZT and the sample stage. Every 120 seconds the graphing process will automatically restart, with the initial height redefined as zero each time.

9.5   LOW FREQUENCY NOISE TEST

The image noise test in section 9.3 is useful for detecting and analyzing image noise with frequencies above a few tens of Hz. Because the *L/L Parabolic* tilt removal option removes lower frequencies from the image, however, this test will not give information about the lower frequency noise sources in the scanning environment, such as building resonances.

To measure low frequency noise, lower the probe onto a flat surface and wait 20 seconds for the instrument to stabilize. From the main software window go to *Utilities >Advanced Scan Parameters* and check *Enable Diagnostic Software*. Then go to *Utilities > General* to open the **General** utilities window. In the *Z Noise* panel press *Start*. Samples of the z position of the probe over 7 second intervals will be converted into a frequency spectrum and displayed in the graph area. As additional data are obtained from each subsequent 7 second interval the new data are averaged with the previous data to improve the signal-to-noise ratio of the frequency spectrum.

10   Surface Force Measurements

10.1 OVERVIEW

A variety of measurements can be performed with the **Surface Force** software. Besides the basic function of exploring the interaction force between a cantilever tip and a surface, the **Surface Force** software may also be used to perform nanomechanical indentation/scratch measurements, to set the scanning force for contact mode scans, to determine the amplitude of vibration in intermittent-contact scans, and to do simple forms of lithography involving indentation and scratching.
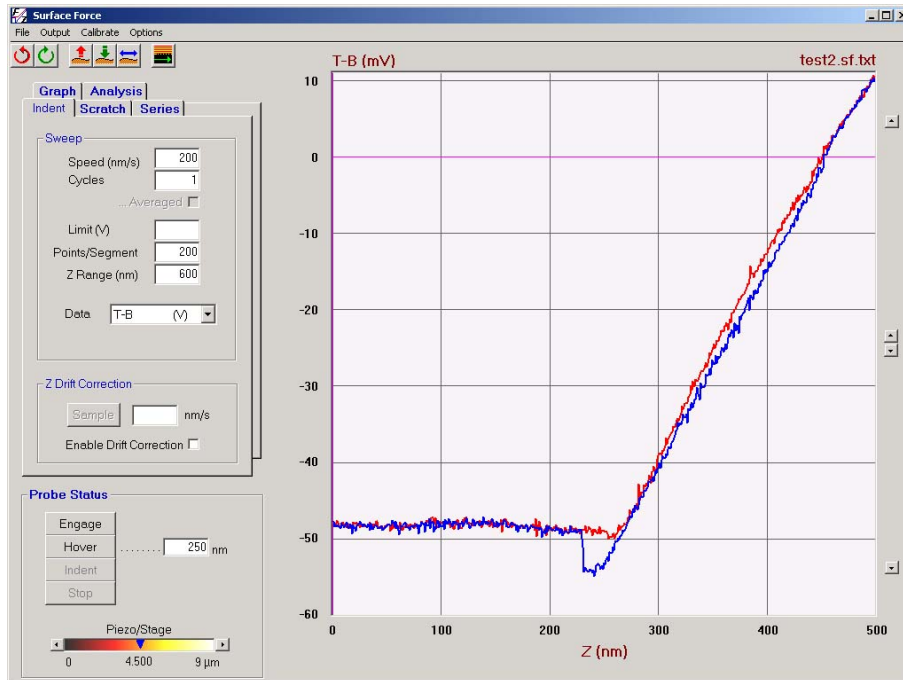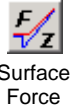
Surface
Force

Here is the usual sequence of steps that would be followed in a **Surface Force** measurement:

1. Scan the surface to see if the region selected meets the needs of the measurement to be performed.

2. Open the **Surface Force** window with the probe engaged with the sample surface.

3. In the *Probe Status* panel, set the hover distance to a height which will bring the probe out of contact with the surface when the hover mode is

activated. Then press the *Hover* button to activate the hover mode. This switches off the Z feedback circuitry and raises the probe off of the surface.

4. Position the probe over the desired point on the sample surface using the **Move Probe** control window.

5. Setup the parameters for the type of measurement to be performed (scratching, indenting, force profiling, etc).

6. Press the *Indent/Scratch* button in the *Probe Status* panel to perform the measurement.

7. Finally, press the *Engage* button in the *Probe Status* panel to return the probe to normal surface contact, ready to scan the surface again.

Most of the measurements performed with the **Surface Force** software require the cantilever optics to be calibrated. Instructions for calibrating the optics, and for performing several common types of measurements, are given in the *Measurements* section (10.3) of this chapter.   It is best to read through the Controls section (10.2) first, however, to become familiar with the various controls in this window and where they are located.

❖Note: With a metrology-equipped system the *XY Mode* at the **SPM Configuration** window may be set to either *Standard* or *Metrology*. If the system is set to *Metrology* mode the **Surface Force** software will use the xy position sensors to accurately position and move the probe. Regardless of the *Z Mode* setting, however, the **Surface Force** software does not use the metrology sensor to control the z position of the probe. The accuracy of the z position of the probe depends upon the accuracy of the *Standard* mode z-axis calibration of the scanner.

10.2 CONTROLS

Menus

File   The graph data generated in this window may be saved and reloaded later. The data are saved as a text file with the file extension ".sf.txt".

Output   The graphical contents of this window may be printed or sent to an external program which can manipulate bitmap images. Refer to Section 7.7 and 7.8 for more information.

Calibration

- <u>Calibrate Photodetector</u>   A measurement of the photodetector T-B voltage as a function of probe height Z is used to generate a calibration factor to convert the T-B signal into an equivalent deflection of the end of the cantilever in microns. Refer to Section 10.3.2 for instructions on performing the calibration.

- <u>Enable Auto Zeroing</u>   One of the parameters which is set when the cantilever optics are calibrated is the zero-point voltage. This parameter is adjusted so that when the probe is out of surface contact the corresponding T-B voltage is interpreted as zero deflection.   Slow variations in the temperature of the scanner will cause the photodetector T-B voltage to drift, which will also cause the zero-point voltage to drift. One way to correct for the drift is to just recalibrate the cantilever optics periodically. Another method is to check the *Enable Auto Zeroing* software option, so that the software automatically interprets the initial photodetector signal at the beginning of each measurement as the zero-deflection level.

❖Note: Be aware that when the *Enable Auto Zeroing* feature is active it is important to verify that the *Hover* distance is set sufficiently high to raise the probe out of surface contact at the outset of each measurement. Nonsense results will be obtained otherwise.

- <u>Set Spring Force Constant</u>   This is the force constant of the cantilever, in units of Newtons of force per meters of deflection of the end of the cantilever— or equivalently nN/nm, or μN/μm. A typical value for the force constant is found on the cantilever manufacturer's data sheet. It is also possible to estimate the force constant from a measurement of the resonance characteristics of the probe. Refer to Section 4.6.1 for further information.

Options

- <u>Move Probe</u>   This control opens the **Move Probe** window. (Ref. Section 10.4)

- <u>Adjust Setpoint</u>   This control opens a small dialog box to enter a new value for the z-feedback *Setpoint*.   Functionally, this is the same as changing *Setpoint* at the **SPM Configuration** window or the **Realtime** window. The primary difference is that here, provided the cantilever optics and force constant are set correctly, the *Setpoint* may be adjusted in physically significant terms such as scanning force or vibration amplitude. Refer to Section 10.3 for further information.

- <u>Split Un/Loading Data</u>   The loading and unloading data generated by a force-distance sweep of the probe are combined into one data array, which may be stored into a disk file, graphed, recalled from a disk file, etc., as one unit. In some instances it is more convenient to split the data set into separate loading and unloading arrays, and corresponding separate graphs.   This control performs the splitting operation.

Toolbar Controls

Previous/Next Graph   The *Previous/Next Graph* toolbar controls function in an analogous way to the *Previous/Next Image* controls found throughout the software. As new data sweeps are performed, or graph files are loaded from the hard drive, the older files are pushed into a 12-level storage buffer. By pressing the *Previous/Next* buttons it is possible to flip between the different data sets.

Withdraw   Withdraws the probe a short distance from the sample surface.

Engage   Opens the **Engage** window. (Ref Section 3.7.2).

Move Probe   Opens the **Move Probe** window. Allows graphical positioning of the probe within the surface scan area. (Ref Section 10.4).

Realtime Scan   Opens the **Realtime** window. (Ref. Section 3.7.2)

Probe Status Panel

Engage

When the *Engage* button is highlighted the probe is engaged with the surface and the feedback circuitry is enabled. In this state the surface can be scanned in the usual way.

Figure 10-1 Probe Status

Pressing the *Engage* button when the *Hover* button is highlighted will activate the feedback circuitry and engage the probe with the surface. The blue arrow in the *Piezo/Stage* color bar will move to indicate the change in position.
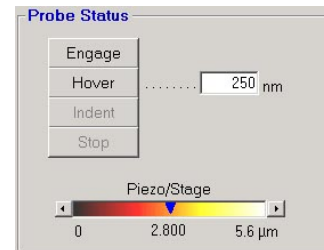
Hover

When the *Hover* button is highlighted, the z-feedback is disabled and the scanner is contracted by the distance specified in the adjacent textbox.

Pressing the *Hover* button when the *Engage* button is highlighted will deactivate the z-feedback circuitry and retract the scanner by the specified distance. The blue arrow in the *Piezo/Stage* color bar will move to indicate the change in position.

❖Note: When the hover distance is set to, say, 250 nm this does not mean that the separation between the cantilever tip and the surface will be 250 nm in the hover state. For example, when the system is operating in contact mode there is a certain distance the scanner must retract before the cantilever will un-bend and the

probe tip will lose contact with the surface. This reduces the actual hovering separation between the cantilever tip and the surface.

❖Note: While the *Hover* state is active the hover height may be changed without re-engaging the probe by simply changing the entry in the textbox and pressing the keyboard *Enter* key.

Indent/Scratch

This button switches between the *Indent* and *Scratch* functionality, depending on which of the measurement tab panels is selected. When the *Indent* tab is selected the indent functionality is enabled. When the *Scratch* tab is selected the scratching functionality is enabled. When the *Series* tab is selected the functionality may be scratching or indenting, depending on which measurement *Mode* is selected at the top of the *Series* tab panel. The *Indent/Scratch* button is disabled when the *Graph* or *Analysis* tabs are selected.

Stop

A measurement sweep or sweep-sequence may be terminated early by pressing this button.

Piezo/Stage

This is a graphical indication of the expansion/contraction state of the scanner. The left-to-right scale of the color bar represents the available expansion/contraction range of the scanner. The blue pointer on this scale indicates where the current z position of the scanner falls in this range.

When the pointer is near the left edge of the color bar the scanner is near is maximum expansion; when the pointer is near the right edge of the color bar the scanner is near its maximum contraction. The arrow buttons at the right and left ends of the color bar are equivalent to the single-step up/down buttons found in the **Engage** window. Stepping the z position motor up and down while the **Surface Force** window is in the *Engage* state will move the blue pointer along the color bar. In this way the current z position of the scanner may be adjusted to change the amount of contraction or expansion range available for a particular measurement.

Indent Panel

Sweep

- Speed This is the speed with which the probe is loaded and unloaded during an indentation measurement. Note that higher sweep speeds have the advantage of reducing the effects of scanner drift on the data obtained, but on the other hand, slower sweep speeds allow the software more time

to average the data signal at each sample point, reducing the noise in the measurement.

- Cycles   An indent measurement is performed when the *Indent* button in the *Probe Status* panel is pressed. For *Cycles* settings greater than 1 the same measurement will be repeated at the same point on the surface, with each completed data set being pushed into the *Previous/Next* data buffer before the next measurement begins.

- ...Averaged   When this is checked, the repeated measurements performed when *Cycles* is set to a number greater than 1 will be averaged to produce a single, final data set. This software feature is currently unavailable.

Figure 10-2 Indent Panel

- Limit   When the *Limit* entry box is empty, the indent process will load the probe up to the z position specified by the *Z Range* control, and then unload the probe. When the *Limit* box is not empty the indent process will load the probe up to the z position specified by *Z Range* <u>unless</u> the *Limit* value is reached first, of in which case the loading process will stop at the *Limit* value.

  For example, consider a measurement of the tip indentation force as a function of the z position of the probe. Suppose *Z Range* is set to 500 nm and *Limit* is set to 2 µN. If the cantilever force reaches 2 µN when the z position is only 450 nm the loading process will end at the 2 µN point and the unloading process will begin.

  ❖Note: The *Limit* setting affects *T-B (V), Deflection (µm), Force (µN), Lateral (V)*, and *Phase (º)* measurement sweeps when the signal rises <u>above</u> the *Limit* setting.   The *Limit* setting affects *Amplitude (V)* and *Amplitude (µm)* measurement sweeps when the signal falls <u>below</u> the *Limit* setting.

- Points/Segment   This is the number of points stored in the data file for the loading segment, equivalent to the number of points in the data file for the unloading segment. Values between 200 and 500 are typical.

- Z Range   In the typical loading/unloading process, when the *Indent* button is pressed the probe is moved from the *Hover* position down toward the surface by a distance *Z Range* (loading), and then the probe is moved back up to the *Hover* position (unloading). The actual distance moved may be modified by the *Limit* control setting, however.
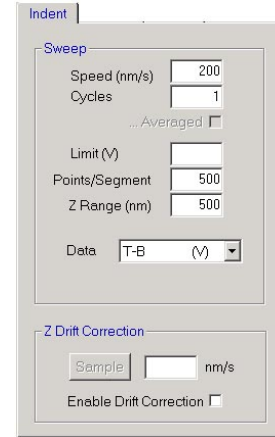
- <u>Data</u>   These are the signals which may be recorded in the indentation sweep. They are tabulated below.

Data Signal	Vibration	Description
T-B (V)	Off	Photodetector Top-Bottom signal
Deflection (µm)	Off	Z movement of cantilever tip
Force (µN)	Off	Force at cantilever tip
Lateral (V)	Off	Torsional movement of cantilever tip
Amplitude (V)	On	Peak vibration amplitude, uncalibrated
Amplitude (µm)	On	Peak vibration amplitude, calibrated
Phase (º)	On	Relative phase of vibration

Table 10-1

The Vibration column indicates whether the cantilever is vibrating during the measurement. The vibration on/off condition is independent of the *Scan Type* setting made at the **SPM Configuration** window. When the cantilever vibration is switched On the cantilever will vibrate at the most recent frequency setting made at the **Wave Configuration** window.

Refer to the *Measurements* section of this chapter (10.3) for examples of how the different data signals are used.

Z Drift Correction

- <u>Sample</u>   The *Sample* button is enabled when the probe is in the *Engage* state. When this button is pressed a brief measurement of the z position of the probe as a function of time will be made, and from the slope of this data a value for the vertical drift rate of the scanner will be calculated and posted in the adjacent text box. Note that the entry in the text box may be set manually as well.

- <u>Enable Drift Correction</u>   Any drift in the z position of the scanner over the course of a loading/unloading measurement will introduce a small error in the z coordinates of the data set (the horizontal axis of the graph). The curves may be stretched outwardly or compressed inwardly, depending on the direction of the drift. The extent of the correction depends upon the temperature stability of the instrument, how much settling time has elapsed since the probe was engage with the surface, and the relative speed of the indentation measurement as compared to the rate of z drift.

  When the *Enable Drift Correction* control is checked, the drift rate posted in the text box will automatically be applied to the z coordinates of the data set at the completion of the scan, correcting the error to first order.

  ❖Note: The z drift correction feature may also be used to compensate for the effects of creep in the scanner, which causes a similar shift error in the slope between the loading and unloading curves. The typical correction factor applied for this purpose would be of order -1 to -10 nm/s.

Scratch Panel

Sweep

- <u>Load Rate</u>   The rate which the probe is loaded onto the surface from the *Hover* state. Loading proceeds up to the specified initial force (or indentation depth) of the probe tip. See *Initial/Delta* below.

- <u>Scratch Rate</u>   Once the tip has reached the initial force (or indentation depth) for the scratch process, this is the rate which the tip will be dragged laterally across the surface during the scratch measurement.

- <u>Initial/Delta</u>   *Initial* is the initial condition the system reaches before beginning the scratch measurement— either a certain load force of the tip or a certain indentation depth of the tip, as determined by the selection made in the adjacent drop-down list. *Delta* is the change in this parameter over the course of the scratch. For example, if *Initial* is 2 µN and *Delta* is +1 µN then the load force will increase linearly from 2 µN to 3 µN over the course of the surface scratch. Negative *Delta* values are also valid.
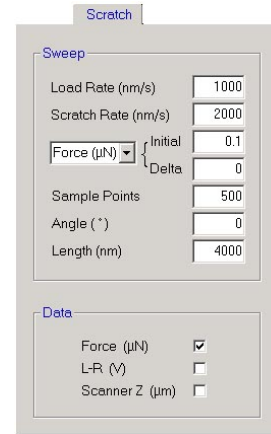
Figure 10-3 Scratch Panel

- <u>Force (µN), Depth(nm)</u>

  o Selecting *Force (µN)* produces a surface scratch with a controlled force between the probe tip and the surface. From the *Hover* state the probe is loaded onto the surface at the *Load Rate* up to the *Initial* force value. Then the scratch is performed at the *Scratch Rate* through a distance *Length* along the surface direction *Angle*. With the *Delta* force setting the scratch force may be programmed to remain constant, increase, or decrease along the scratch line, depending upon whether *Delta* is set to zero, a positive value, or a negative value, respectively.

  o Selecting *Depth (nm)* produces a surface scratch with the probe following a programmed path along the sample surface.   The scratch is performed in a two-pass process. Refer to Figure 10-4 below. In the first pass, starting from the initial *Hover* state, the probe is engaged with the surface in the normal way for surface imaging and then the probe is moved along the scratch path to record the surface profile along that line (*i-iii*).   The first pass concludes with the tip being returned to the initial xy position for the scratch and lifted back to the *Hover* z position (*iv*). In the second pass, the tip is loaded onto the surface until the tip of the probe is pushed below the nominal sample surface by the distance specified by the *Initial* parameter (*v-vi*).   This initial depth position is determined by calculating the difference between the upward deflection of the cantilever Z_C and the

downward movement of the scanner Z_S, i.e., Z_C changes less than Z_S as the surface is elastically or plastically deformed. The scanner trajectory to be followed in the scratch process is determined by mathematically shifting the recorded surface profile down to this depth level. The scanner then moves along this path (*vii*).

❖Note: In general this does <u>not</u> lead to a scratch with a constant depth.
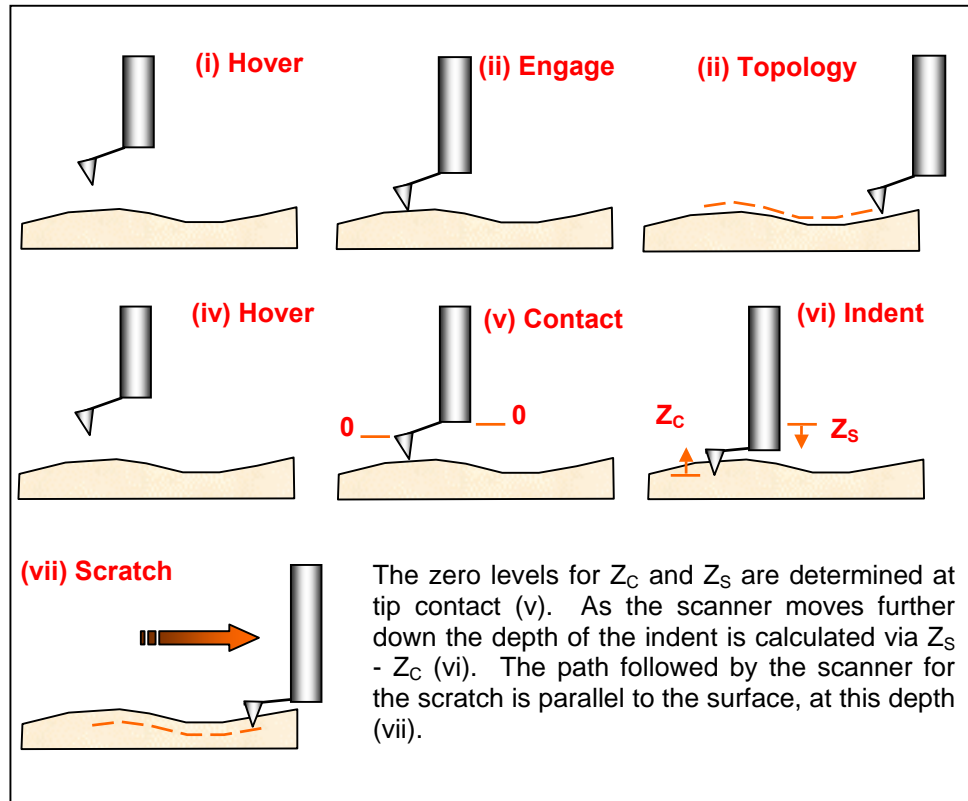
Figure 10-4 The steps in performing a Depth-controlled scratch.

- <u>Sample Points</u>   This is the number of measurement points in the data sets produced by the scratch. Typical settings are in the range of 200-500 points.

- <u>Angle</u> The scratch may run along any direction in the xy plane.

❖Note: The angle specified here is with respect to the relative coordinate system, as defined by the **SPM Configuration** settings (Ref. Section 10.4.2). For example, if *Scan Direction* is set to 0º and *Angle* is set to 0º the scratch will run along the positive x-axis of the microscope <u>stage</u>. A scan of the scratch will run along the x-axis of the scan <u>image</u>. On the other hand, if *Scan Direction* is set to 90º and *Angle* is set to 0º the scratch will run along the

positive y-axis of the microscope <u>stage</u>. An AFM scan of the scratch will, however, still run along the x-axis of the scan <u>image</u>.

- <u>Length</u>   The length of the scratch.

Data

- <u>Force</u>   This is the load force of the probe tip against the sample surface, as determined by the vertical deflection of the cantilever. The cantilever optics and cantilever force constant must be set properly to obtain accurate force data.

- <u>L-R</u>   This is the torsional force on the probe tip, as determined by the L-R photodetector signal. The units of this measurement cannot be calibrated in terms of force or torque, however.

- <u>Scanner Z</u>   As a surface is scratched the z position of the scanner will vary as necessary to track the specified force profile or depth profile. By recording the *Scanner Z* signal during the scratch the path of the scanner may be examined for clues as to how the probe interacts with the surface material over the course of the scratch. The vertical position at the beginning of each scratch is defined as $z = 0$.

Series Panel

- <u>Mode</u>   The *Series Panel* may be setup to perform a series of surface indentations or a series of scratches. The selection is made via the *Mode* control.

- <u>X(µm), Y(µm)</u>   When *Mode* is set to *Indent Surface*, these are the center coordinates for each of the indentations. When *Mode* is set to *Scratch Surface*, these are the coordinates of the starting point for each scratch.

❖Note: The coordinates specified here are with respect to the relative coordinate system. (Ref. Section 10.4.2)

- <u>F(µN), Z(nm)</u>   When *Mode* is set to *Indent Surface*, the loading segment of the indentation will end when either the specified force *F* or loading distance *Z* has

Figure 10-5 Series Panel

been reached. The choice between indenting to a maximum force or distance is made via this drop down list box. Similarly, when *Mode* is set to *Scratch Surface*, the initial value of the loading force for the scratch *F* or the initial indentation depth for the scratch *Z* is specified here.
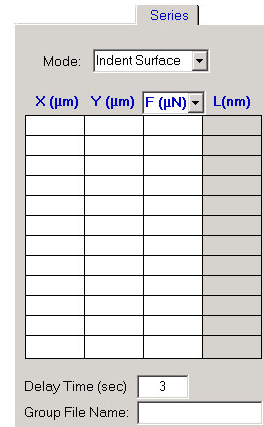
- L(μm) This column defines the length of the scratch to perform starting at each *X,Y* position.

- Delay Time Each time the software moves the probe to a new *X,Y* coordinate position it is best to have the system pause for several seconds prior to performing the next scratch or indentation to give the scanner time to stabilize. Adjust the *Delay Time* parameter for this purpose.

- Group File Name As the software moves through the scratch or indentation sequence each completed data set is pushed into the *Previous/Next* buffer before initiating the next measurement. If text is entered into the *Group File Name* textbox the data will also be saved in the ScanAtomic "Graphs" folder. The data are stored with a number appended to the end of the file name entered. For example, with *Group File Name* set to "My Test", the data sets would be saved as My Test 1, My Test 2, etc.

Graph Panel

Axis Scales

Top/Bottom define the vertical scale of the graph. *Left/Right* define the horizontal scale of the graph.

Options

- Show Setpoint   When the graph data being viewed have a vertical scale which is consistent with the meaning of the current **SPM Configuration** *Setpoint* value, checking this box will overlay a dashed orange line on the graph to indicate where the setpoint falls on the vertical scale of the graph. For example, if the graph data are for probe force *F* vs. probe displacement *Z*, the orange reference line will indicate the force equivalent of the current *Setpoint* voltage. Refer to sections 10.3.6 and 10.3.7 for details.

Figure 10-6 Graph Panel

- Automatic Y Scaling   When the *Automatic Y Scaling* control is checked the vertical scale of the graph will automatically scale to appropriate minimum and maximum values for the graph data. The change occurs immediately when the system is not performing an indentation or scratch measurement. It also occurs automatically at the endpoints of a measurement sweep when indenting and scratching.

- Match Scales   This sets the vertical and horizontal graph scales of the data sets in the *Previous/Next* buffer to match the scales of the graph currently being viewed. The change is only applied to identical measurement types. For example,

clicking *Match Scales* when viewing a Force vs. Z graph will make the graph scales of all the Force vs. Z data sets in the buffer match the one being viewed.

- Apply Data Smoothing   The graph data being viewed are smoothed to reduce noise. This is done by breaking the data into intervals of 5 points and fitting these data segments with a second order polynomial. Clicking this control repeatedly will gradually erode a noisy graph line into a smooth curve.

Analysis Panel

- Cursor Coordinates   The vertical and horizontal coordinates of the two cursors are posted here, along with the difference *Delta* between the coordinates. For indentation data sets, the cursors may be placed on either the loading or unloading segments of the data set by using the *Segment* control.

- Two Pt Slope   Calculates the slope of the line defined by the coordinates of the two cursors.

- LS Slope   Calculates the slope of the least-squares line fitting the data between the two cursors.

- Curve Area Calculates the area under the interval of the graph marked by the two cursors.
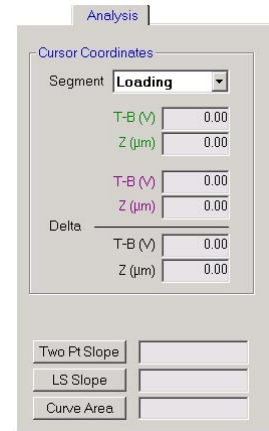
**Figure 10-7
Analysis Panel**

10.3 MEASUREMENTS

10.3.1   Selecting a Cantilever

There are several considerations which go into deciding which cantilever to use for a particular measurement, e.g., What cantilever tip materials (silicon, silicon-nitride, diamond, etc.) are strong enough for the forces the tip will be subjected to? Does the surface of the cantilever need to be coated or functionalized? How low of a spring constant will work in a weak-force measurement? Or at the other extreme, how high of spring constant may be require to provide sufficient tip surface pressure?

Perusing the published literature for research related to your own is generally the best way to answer these questions. The following order-of-magnitude examples provide some helpful hints.

Example (A)

Measurement Objective:
Achieve inelastic deformation of polycarbonate.
Order of magnitude of desired indentation: 100 nm in radius.
Cantilever deflection to achieve this indentation: 0.1 um.

Estimation of Force Constant
Spring force constant: $K \equiv$ Force/Distance
Yield pressure of polycarbonate: ~100 MPa
Required Force = Pressure * Area ~ 100 MPa * 10^{-14} m^2 = 10^{-6} N
$\Rightarrow$ K ~ $(10^{-6}N) / (10^{-7}$ m) = 10 N/m

❖Note: This spring constant is fairly large; If the tip material is silicon then it would probably be best to image the surface with this cantilever operating in Wavemode to avoid excessive wear of the probe tip during scanning.

Example (B)

Measurement Objective:
Determine pull-off adhesion of probe tip with surface.
Cantilever deflection to achieve the pull-off: 0.1 um.

Estimation of Force Constant
Spring force constant: $K \equiv$ Force/Distance
Estimate of tip contact area based on ideal tip radius: 1000 nm^2.
Estimate of contact force based on physisorption bond: 10^{-8}N
$\Rightarrow$ K ~ $(10^{-8}N) / (10^{-7}$ m) =0.1 N/m

❖Note: This spring constant is small, and it would be best to image the surface with this cantilever in *Z Height* mode because the quality of the resonance would not be sufficient for *Wavemode* imaging.

10.3.2 Calibrating the Cantilever Optics

❖Note: If the cantilever is to be operated only in intermittent-contact mode, with no indenting or scratching operations, then refer to the calibration instructions in Section 10.3.7.

A measurement of the photodetector T-B deflection signal as a function of probe height Z is used to generate a calibration factor to convert the T-B voltage signal into an equivalent deflection of the end of the cantilever in microns.   This procedure should be followed prior to *Deflection (µm)* and *Force (µN)* indentation measurements. It should be repeated every time the cantilever is changed or repositioned, or
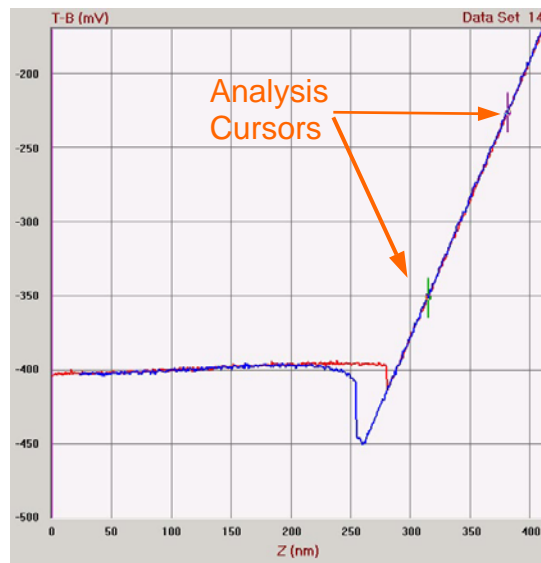

Figure 10-8 Optics calibration curve.

whenever the laser or photodetector position knobs are moved. The calibration is saved in the SAconfiguration file when the **Surface Force** window is closed.   The calibration values are recalled when the window is re-opened.

1. Engage the probe on a flat hard surface. Open the **Surface Force** window.

    Setup the *Indent* tab panel controls to perform a shallow indentation with the probe as illustrated in Figure 10-8. This indentation curve has sufficient non-contact data to clearly define the signal level when the probe is not in surface contact, and it also has sufficient coverage of the cantilever deflection to clearly define the slope of the indentation line.

    The parameters required to produce a shallow indentation curve vary considerably between probe types.   Examples for two very different probe types are given in the tables below.

    Table 10.2 settings are appropriate for a type CSC17 cantilever, which has a small force constant   (0.15 N/m).   With this cantilever the microscope is normally configured to image the surface with *Scan Type* set to *Z Height*.

    Table 10.3 settings are appropriate for a type NSC16 cantilever, which has a large force constant (40 N/m).   With this cantilever the microscope is normally configured with *Scan Type* set to *Wavemode* for surface imaging, but note that when *T-B (V)* , *L-R (V)* , *Deflection (µm)*, and *Force (µN)* data are obtained in the **Surface Force** window the cantilever vibration is automatically switched off during these measurements and the indentation is performed with a non-vibrating cantilever.

    (It is instructive to compare the differences in the *Hover* distances and *Z Range* distances in the two tables.)

Indent Tab Panel	
Speed	1000 nm/s
Cycles	1
Limit	No entry
Points/Segment	500
Z Range	1000 nm
Data	T-B (V)
Enable Z Drift Correction	Off or On
Probe Status	
Hover Distance	1500 nm

Table 10-2 CSC17 cantilever.

Indent Tab Panel	
Speed	100 nm/s
Cycles	1
Limit	No entry
Points/Segment	500
Z Range	400 nm
Data	T-B (V)
Enable Z Drift Correction	Off or On
Probe Status	
Hover Distance	50 nm

Table 10-3 NSC16 cantilever.

2. Press the *Hover* button to raise the probe out of contact with the surface. Press the *Indent* button to perform the measurement. If the resulting graph is not similar to Figure 10-8 then make corrective adjustments to the *Hover Distance* and/or *Z*

Range parameters and repeat the measurement. Increase the *Hover Distance* if the curve is not initially flat. Increase the *Z Range* and/or decrease the *Hover Distance* if the cantilever does not reach the surface and deflect by the end of the sweep.

3. Select the *Analysis* tab panel to access the green and violet graph cursor markers. Position the cursors along the indentation slope of the graph; it does not matter if the loading or unloading data segment is used.

4. Under the *Calibration* menu select *Calibrate Photodetector*. The calibration is now complete.

5. As a check to verify that the calibration is set correctly, select the *Deflection (µm)* option in the *Data* drop down list and press the *Indent* button again to produce a measurement of the cantilever tip deflection vs. scanner z position. The resulting graph should have the zero-deflection portion of the data curve fall along the zero-point of the graph's vertical scale, and the slope of the indentation portion of the curve should ideally be 1. The slope may be measured in the *Analysis* tab panel.

10.3.3 Surface Force and Indentation Measurements

The instructions in this section apply to both elastic indentations, where the goal is to measure the interaction force between the probe tip and the surface, and inelastic indentations, where the goal is to permanently deform the surface. Operationally, the only difference is how far the probe is pushed against the surface.

The task of calibrating the cantilever optics provides an introduction into how to operate the software and perform an indentation measurement. The steps listed below are intended to be a quick summary of the overall procedure.

1. Select a probe which is appropriate for the type of measurement to be undertaken.

2. Calibrate the cantilever optics following the instructions in Section 10.3.2.

3. Set the cantilever spring force constant: **Surface Force** > *Calibration* > *Set Spring Force Constant*. An approximate value for the spring force constant may be obtained from the manufacturer's data sheet. The force constant of diving-board shaped cantilevers may also be estimated using the utility in the **Wave Configuration** window. (Ref . Section 10.5)

4. In the *Indent* tab panel select which *Data* signal to measure: probe deflection, normal probe force, or lateral probe force.

5. If you wish to perform the indent to a specific downward Z position set the required value in the *Z Range* text box and leave the *Limit* box empty. If you

wish to perform the indent to a specific maximum *Force* set the value in the *Limit* text box, and put a sufficiently large entry in *Z Range* that the limit will be reached.

6. Set the loading *Speed*, the number of *Points/Segment*, and the number of indent *Cycles* to perform.

7. Press the *Indent* button in the *Probe Status* panel to perform the indent.

❖Note: As the data are measured they are given sequential provisional names Data Set 1, Data Set 2, and so on.

10.3.4 Scratch Measurements

1. Select a probe which is appropriate for the type of measurement to be undertaken.

2. Calibrate the cantilever optics following the instructions in Section 10.3.2.

3. Set the cantilever spring force constant: **Surface Force** > *Calibration > Set Spring Force Constant*. An approximate value for the spring force constant may be obtained from the manufacturer's data sheet. The force constant of diving-board shaped cantilevers may also be estimated using the utility in the **Wave Configuration** window. (Ref . Section 10.5)

4. Select the *Scratch* tab panel in the **Surface Force** window.

5. Refer to the description of the *Scratch* tab panel in Section 10.2. Select the scratch type, either to a controlled load force or along a fixed scratch profile. The choice is made by selecting either *Force(µm)* or *Depth(µm)* in the drop-down list.

6. Define the *Load Rate* for the indentation.

7. Define the *Scratch Rate*, scratch *Length*. Define the *Angle* of the scratch with respect to the x-axis of the scan image.

8. Select the data to record during the scratch: probe load *Force*, *L-R* lateral force, or *Scanner Z* movement.

9. Press the *Scratch* button in the *Probe Status* panel to perform the scratch.

❖Note: As the data are measured they are given provisional names and stored into the *Previous/Next* 12-level graph buffer. For example, if check marks are placed next to all three possible data types, and this is the third measurement you have made in the day, the graphs would be given the provisional names Data Set 3F, Data Set 3LR, and Data Set 3Z .   By using the *Previous/Next* toolbar buttons you can flip between the data sets.

10.3.5 Series Scratch/Indentation Measurements

1. If the objective is to produce a series of surface indentations, first use the *Indent* tab controls to perform a single indent of the surface to ensure that the parameters in the *Indent* panel are appropriate for the kind of measurement required. The settings made in the *Indent* panel for the indentation speed, points per segment, etc, will be applied to the series. Similarly, if the objective is to produce a series of surface scratches, first use the *Scratch* tab panel to perform a single scratch on the surface to ensure that the scratch parameters are set appropriately.

2. Open the *Series* tab panel. With the *Mode* drop-down list elect to perform either a series of scratches (*Scratch Surface*) or a series of indentations (*Indent Surface*).

Figure 10-9 Series Panel

3. In the left two table columns enter the *X,Y* coordinates for the series.   This would be the center point for indentations, or the starting coordinates for scratches.

4. In the third column of the table elect to make the scratch/indent to a specified load force *F (μN),* or indentation distance *Z(nm).*   The meaning of these two terms depends upon the *Mode* selected at the top of the *Series* panel:
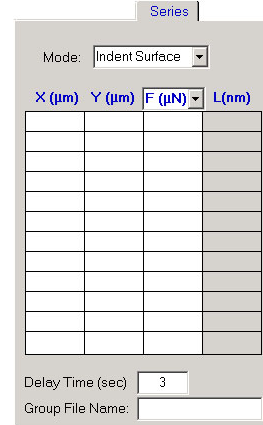
Indenting Mode

•   When *Z (nm)* is selected, the values in this column are inserted into the *Z Range* parameter box in the *Indent* tab panel and indents are performed up to these distances.

•   When *F (μN)* is selected the entry for *Z Range* in the *Indent* tab panel is ignored. Each indent is performed up to the load force *F* specified in this column.

Scratching Mode

•   When *F (μN)* is selected each scratch is performed with a controlled force between the probe tip and the surface. The entries in this column specify the initial force for each scratch. The force applied over the course of each scratch will change by the *Delta* value entered in the *Scratch* tab panel.

•   When *Z (nm)* is selected the probe follows a programmed path along the sample surface, as explained in section 10.2, *Scratch Panel*. The entries in this column become the *Depth* parameters for the initial indentation of the probe. The change in depth for each scratch is determined by the *Delta* value entered in the *Scratch* tab panel.

- The direction of each scratch is defined by the *Angle* parameter in the *Scratch* tab panel. The length of the each scratch is specified in the *L (µm)* column of the *Series* tab panel.

5. Decide which data should be recorded in the measurements. This would is done with the *Data* selection in the *Indent* tab panel for a series of indenations, or with the *Data* section in the *Scratch* tab panel for a series of scratches.

6. Set the *Delay* time factor to ≥3 seconds. This pause before each indent/scratch is performed gives the scanner time to settle at its new *XY* position.

7. Press the *Scratch Set* or *Indent Set* button in the *Probe Status* panel to start the measurement sequence. As the sequence proceeds the current row of instructions being processed in the table is highlighted in yellow.

8. As the software moves through the scratch or indentation sequence, each completed data set is pushed into the *Previous/Next* buffer before initiating the next measurement. If text is entered into the *Group File Name* textbox the data will also be saved in the ScanAtomic "Graphs" folder. The naming convention for the files depends upon the *Mode* setting:

- For a series of indentations, the data are stored with a number appended to the end of the file name. For example, with *Group File Name* set to "MyTest", the data sets would be saved as MyTest 1, MyTest 2, etc.

- For a series of scratches, the data are stored with a number appended to the end of the file name plus a letter group to indicate the data type. For example, with *Group File Name* set to "MyTest", and all three data types selected in the *Scratch* tab panel, the first set of files to be saved on the hard drive would have the names MyTest_ 1_Z , MyTest_ 1_LR , and MyTest_ 1_F.

(Blank Space)

10.3.6 Adjusting the Contact Scanning Force

1. Calibrate the cantilever optics. (Ref. Section 10.3.2)

2. Set the cantilever spring force constant: **Surface Force** > *Calibration* > *Set Spring Force Constant*.

3. In the *Indent* tab panel, select the *Force (µN)* option in the *Data* list. Perform a single indentation measurement to produce a graph similar to Figure 10-9.

   ❖Note: Figure 10-9 was created with a CSC17 cantilever using the parameter configuration shown in Table 10-4.   Notice how the *Limit* control was used to limit the maximum force to 150 nN, while the *Z Range* setting was set very high so that the *Limit* setting would take effect in the measurement.

Indent Tab Panel	
Speed	1000 nm/s
Cycles	1
Limit	0.150 µN
Points/Segment	500
Z Range	3000 nm
Data	Force (µN)
Enable Z Drift Correction	Off or On
Probe Status	
Hover Distance	1500 nm

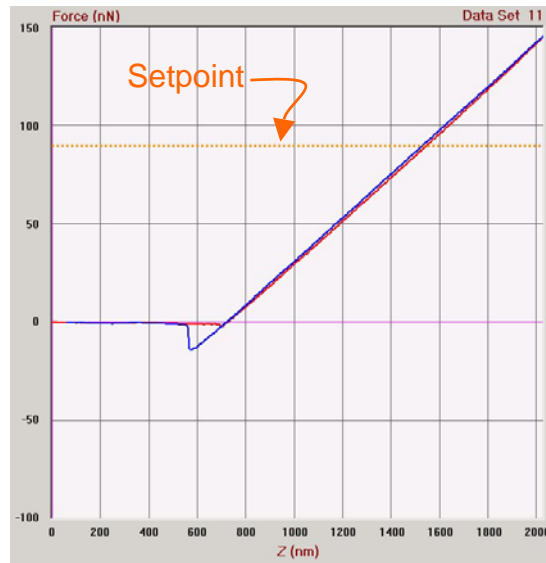**Table 10-4 Example setup for an CSC17 cantilever.**

Figure 10-9   The SPM setpoint displayed against a force-distance curve.

4. Select the *Graph* tab panel and check the *Show Setpoint* checkbox. A horizontal orange line will be overlayed on the graph to indicate the current setpoint force value. This is also shown in Figure 10-9. It may be necessary to change the vertical scale of the graph if the current setpoint force is higher than the range of the indentation force measurement.

5. To change the scanning force, open the setpoint adjustment dialog box: **Surface Force** > *Options* > *Adjust Setpoint*. The current setpoint value in nanoNewton units will be displayed in the dialog box when it is opened. Enter the new setpoint value in nanoNewton units and press OK.   The orange setpoint line will shift to the new force position. If the probe is engaged with

the surface when the setpoint is changed the blue arrow in the *Piezo/Stage* display bar will move to indicate the change in the scanner z position required to adjust the cantilever deflection.

10.3.7 Estimating the Cantilever Vibration Amplitude

To estimate the cantilever vibration amplitude the cantilever optics must be calibrated. This may be done as described in Section 10.3.2, but the method presented there is generally not applied when the cantilever is intended to be used in high-resolution *Wavemode* imaging because there is a chance of dulling the probe tip with the large contact force. The following instructions describe how to calibrate the cantilever optics with a vibrating cantilever. The assumption made here is that for every nanometer the scanner moves the cantilever toward the surface the amplitude of vibration decreases by one nanometer. This assumption is approximately true when the surface the cantilever is vibrating against is rigid, the cantilever is vibrated near its resonance frequency, and the Q of the cantilever vibration is large.

❖Note: The typical cantilever vibration amplitude is of order 100 nm, so more accurate results will be obtained if the scanner is calibrated with a ~100 nm step height standard prior to the optics calibration.

1. Engage the probe in *Wavemode* on a flat, clean, surface.

2. Open the **Surface Force** window and setup the *Indent* tab controls to produce an indentation curve similar to Figure 10-10. For example, the settings shown in Table 10-5 would be appropriate for an NSC16 cantilever. Notice how the *Limit* control is set to end the loading segment of the measurement when the amplitude reaches 0.05 volts. This prevents the cantilever tip from being over-stressed.

Indent Tab Panel	
Speed	1000 nm/s
Cycles	1
Limit	0.05 V
Points/Segment	500
Z Range	1000 nm
Data	Amplitude (V)
Enable Z Drift Correction	Off or On
Probe Status	
Hover Distance	200 nm

Table 10-5   Example setup for an NSC16 cantilever.
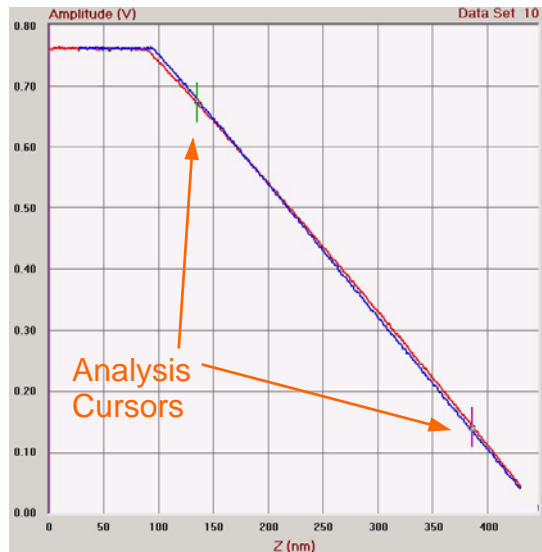

Figure 10-10 Optics calibration curve.

3. Press the *Hover* button to raise the probe out of contact with the surface. Press the *Indent* button to perform the measurement.

4. Select the *Analysis* tab panel to access the green and violet graph cursor markers. Position the cursors along the indentation slope of the graph; it does not matter if the loading or unloading data segment is used.

5. Under the *Calibration* menu select *Calibrate Photodetector*. The calibration is now complete.

6. To measure the vibration amplitude of the cantilever change the *Data* signal to *Amplitude (μm)* and press *Indent*.

10.3.8 Adjusting the Intermittent-Contact Damping Factor

1. Calibrate the cantilever optics with the method described in Section 10.3.7.

2. In the *Indent* tab panel, select the *Amplitude (μm)* option in the *Data* list. Perform a single indentation measurement to produce a data graph similar to Figure 10-11. The settings shown in Table 10-6 were used to produce this result with a NSC16 cantilever. Notice how the *Limit* control was used to end the loading segment of the measurement when the amplitude reached 10 nm. Usually *Limit* will be set to 10-50 nm to prevent the cantilever tip from being over-stressed.

Indent Tab Panel	
Speed	500 nm/s
Cycles	1
Limit	0.01 μm
Points/Segment	500
Z Range	1000 nm
Data	Amplitude (μm)
Enable Z Drift Correction	Off or On
Probe Status	
Hover Distance	200 nm

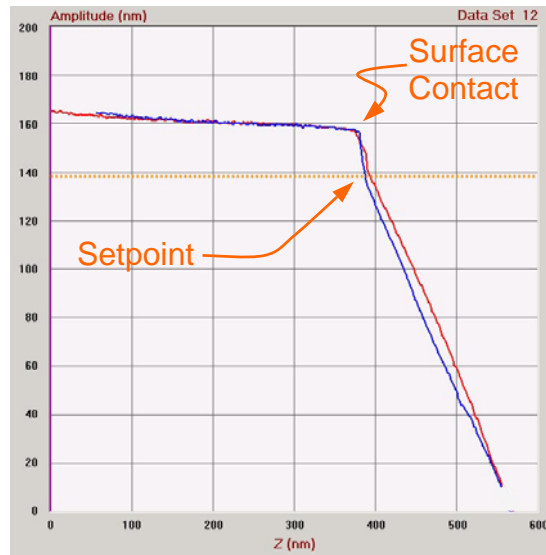**Table 10-6 Example setup for an NSC16 cantilever.**

Figure 10-11 The SPM setpoint displayed against a vibration amplitude curve.

3. Select the *Graph* tab panel and check the *Show Setpoint* checkbox. A horizontal orange line will be overlayed on the graph to indicate the current setpoint value. This is also shown in Figure 10-11. It may be necessary to change the vertical scale of the graph if the current setpoint position is higher than the range of the amplitude measurement.

4. The damping factor DF for intermittent-contact scanning is defined as

$$DF = 100\% * (Free\ Amplitude – Setpoint\ Amplitude) / Free\ Amplitude$$

where the Free Amplitude is the amplitude of vibration when the probe just begins to contact the sample surface. For example, in Figure 10-11

$$DF = 100\%*(160\ nm – 140\ nm) / (160\ nm) = 12.5\%.$$

The normal setting range for DF is 5% - 50% . This would correspond to a vibration amplitude of 150 nm to 80 nm in the example above.

To change the damping factor, open the setpoint adjustment dialog box: **Surface Force** > *Options* > *Adjust Setpoint*. The current setpoint value in nanometer units will be displayed in the dialog box when it is opened. Enter the new setpoint value in nanometer units and press OK.   The orange setpoint line will shift to the new vibration amplitude position. If the probe is engaged with the surface when the setpoint is changed the blue arrow in the *Piezo/Stage* display bar will move to indicate the change in the scanner z position required to adjust the damping factor.

10.3.9 Measuring the Dynamic Phase Shift

1. Open the **Wave Configuration** window and set the amplitude and frequency of vibration in the usual way for surface imaging.   As a general guideline, smaller vibration amplitudes increase the sensitivity of phase detection measurements. (Ref. Section 4.6)

2. At the **Wave Configuration** window, select the *XOR* phase detector and lock the phase detection operating point on the midpoint of the segment of the phase detection curve with negative slope. N.B. Selecting the midpoint of the positive slope line inverts the phase signal. (Ref. Section 12.2)

3. Open the **Surface Force** window. Using the technique described in Section 10.3.7 determine the value of *Z Range* at which the amplitude of vibration drops to zero. To minimize the risk of tip damage, the value for *Z Range* should not exceed this value during the phase measurements.

4. With the *Indent* tab panel controls set as in step 3, select the *Phase (º)* data signal and press the *Indent* button to perform the dynamic phase shift measurement.

10.4 POSITIONING THE PROBE IN THE SCAN AREA

10.4.1 The Move Probe Window

With the **Move Probe** window the cantilever point can be positioned anywhere within a scanned region by clicking on the surface image. The toolbar control to access this window is found in the **Surface Force** window and the **STM Spectroscopy** window.
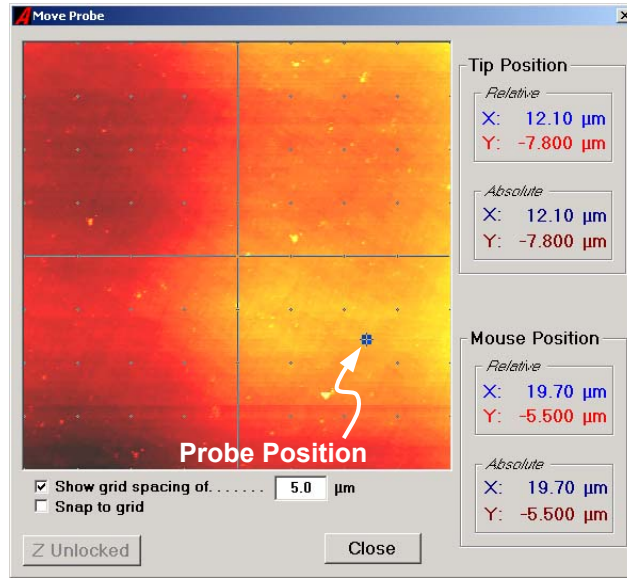
Move
Probe

Figure 10-12 The Move Probe window.

- The current position of the probe is indicated with the square feducial mark shown in Figure 10-12. (Except, of course, if the probe position falls outside of the image area. Then the feducial will not appear.)

- The right panels in the **Move Probe** window indicate the current position of the tip, and the position of the mouse over the scan image, in both the relative and absolute coordinate systems. These are defined in Section 10.4.2 below.

- The probe is repositioned with the offset DACs in the EIU electronics (the DACs responsible for creating the *Center X* and *Center Y* **SPM Configuration** adjustments). For the type 3 and 4 EIU electronics these are 12-bit converters, so the position resolution is 1/4095 of the scanner's xy range. For example, with a 40 µm scanner the xy position resolution is about 10 nm. For the type 5 EIU electronics the offset DACs are 16-bit converters, so the position resolution is 1/65535 of the scanner's xy range. Note: At the end of every complete (or incomplete) surface scan the offset DAC's are returned to their *Center X*, *Center Y* positions.

- The *Z Lock* button is used with the Hysitron Triboscope Interface to lock and unlock the Z position of the scanner.

10.4.2 Position Coordinates: Absolute vs. Relative

Two coordinate systems are used by the ScanAtomic software: *absolute* coordinates, and *relative* coordinates.

The *absolute* coordinate system is what is seen when looking at the cantilever through the video camera. A scanner can move the probe over a square area defined by the range of the scanner. For example, Figure 10-12(A) illustrates the range of an 80 μm scanner.   The center of the square is defined as the origin of the absolute coordinate system. For an 80 μm scanner the absolute x,y coordinates are bounded within ±40 μm. The +x-axis runs from left-to-right in the camera view, and the +y-axis runs from bottom-to-top.

Now imagine scanning a surface with the following **SPM Configuration** window settings: *CenterX = 10* μm, *CenterY = 10* μm, *Scan Dir = 30˚*, as sketched in Figure 10-12(B). When looking at the surface scan on the computer screen it is natural to think of a coordinate system lying on top of the image with the origin at the center of the image, the y-axis running vertically, and

Figure 10-12 The absolute and relative coordinate systems.

the x-axis running horizontally. This is an example of the *relative* coordinate system. The position and orientation of the relative coordinate system with respect to the absolute coordinate system is defined by the scan parameters *Center X*, *CenterY*, and *Scan Dir*.

So the relative coodinate system is defined by *Center X*, *CenterY*, and *Scan Dir*, but note that these three parameters may come from either (a) the current settings
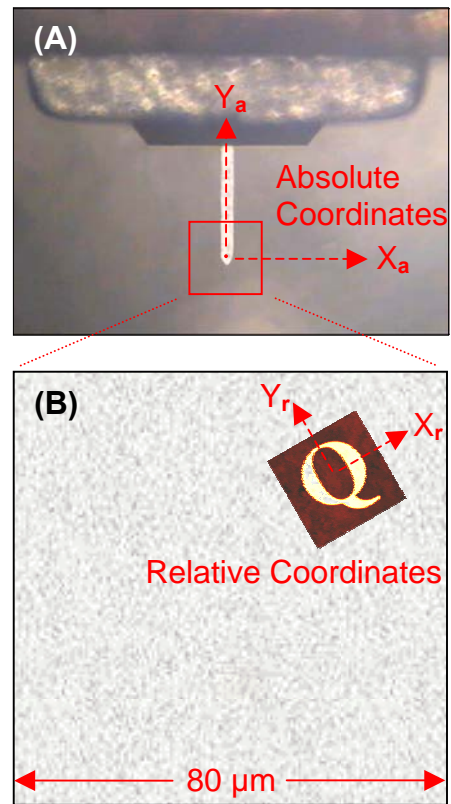
in the **SPM Configuration** window, or (b) the recorded values in the image file currently being viewed. To minimize the confusion, this convention is followed:

- In the *Series* tab panel in the **Surface Force** window, the coordinates being entered in the table are in the relative coordinate system defined by *Center X*, *CenterY*, and *Scan Dir* in the **SPM Configuration** window. This is the case regardless of which image is currently being viewed.

- When the probe is positioned with the **Move Probe** window, the relative coordinate system is defined by *Center X*, *CenterY*, and *Scan Dir* in the image file. If the the image coordinates do not match the **SPM Configuration** coordinates the software will automatically reset the **SPM Configuration** coordinates to match the image coordinates. A message box will appear if the coordinates are changed.

10.5 ESTIMATING THE CANTILEVER FORCE CONSTANT

The force constant calculated with this software utility is only valid for "diving board" style cantilevers; it is not valid for "V" shaped cantilevers. The method is attributed to Dr. J. E. Sader. Reference: Rev Sci Instr, **70**, 1999.

1. Open the **Wave Configuration** window (Ref. Section 4.6.1).   If you are using a contact-mode cantilever it will be necessary to momentarily switch the *Scan Type* setting to *Wavemode* to gain access the **Wave Configuration** window.

2. Perform a wide frequency sweep to locate the resonance peak, and then magnify this to a 10 kHz sweep by clicking on the resonance peak in the graph.

3. The Q of the cantilever is a central factor the the spring constant calculations. Because the Q of the cantilever is determined from the full-width-at-half-maximum (FWHM) of the resonance peak it is important to make sure that cantilever resonance is as sharp as possible. Try adjusting the probe holder tilt lever, and repositioning the laser spot on the back of the cantilever, to see if the sharpness can be improved.

4. While the 10 kHz sweep is being performed, select from the menu bar *Cantilever > Calculate Force Constant.*   The system will perform a slow-sweep through the vibration resonance, lock the resulting graph data, and determine the resonance frequency and the Q of the resonance from this data.   The resonance frequency and Q results, along with several other physical constants used to estimate the force constant of the cantilever, will be posted in a panel appearing on the righthand side of the **Wave Configuration** window (Figure 10-13).   The parameters are listed below.

Figure 10-13

- **Fluid Viscosity / Density**   The viscosity and density of the fluid the cantilever is vibrating in, typically air or water.

- **Cantilever Length / Width**   The length and width of a diving-board shaped cantilever. This information is provided on the manufacturer's data sheet.

- **Peak Frequency** The resonance frequency of the cantilever's vibration.

- **Quality Factor** Calculated as ratio of the FWHM frequency range divided by the resonance frequency.

- **Force Constant**   The result of applying the parameters listed above to Sader's method of estimating a cantilever's effective force constant.
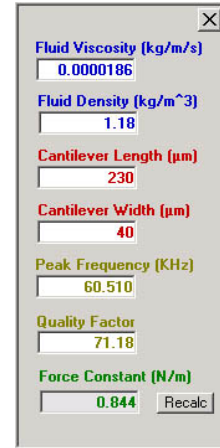
5. Check the entries in the *Force Constant Panel* to make sure they correspond to the physical shape of the cantilever being tested (Length, Width) and the fluid environment around the cantilever (Viscocity, Density).   Any of the six parameters in this panel may be manually changed. By pressing the *Recalc* button the *Force Constant* will be recalculated with the new values.

11 Lateral Force Imaging

11.1 INTRODUCTION

The *Lateral* imaging mode measures the torsional force on the cantilever produced by the friction between the probe point and the surface. The torsional force causes the cantilever to twist, and this is detected via the lateral shift in the direction of the laser light being reflected off of the back of the cantilever.

The degree of twisting is, in part, a reflection of the strength of the frictional force between the probe tip and the surface. In favorable circumstances this effect can be used to extract information about where different materials are located in the surface topography.   Unfortunately the twisting effect is also strongly influenced by the slope of the surface topology. This is shown schematically in Figure 11-1.

Scan Direction

High Friction
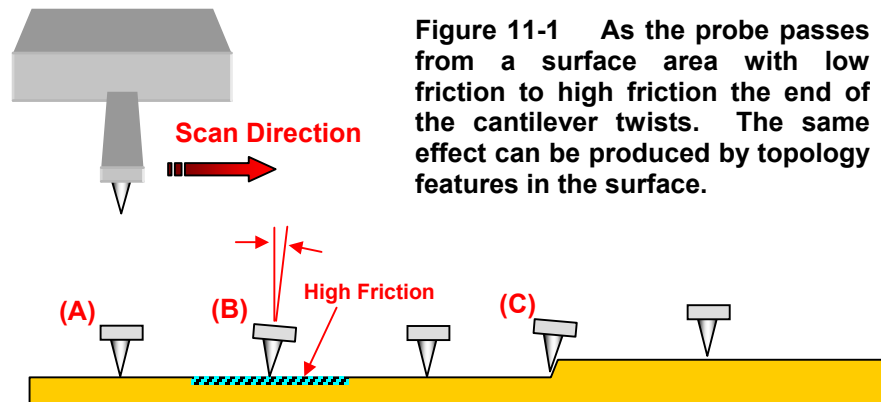
(A)   (B)   (C)

Figure 11-1   As the probe passes from a surface area with low friction to high friction the end of the cantilever twists. The same effect can be produced by topology features in the surface.

It is necessary to develop an intuitive feel for when the contrast seen in a lateral force image is due to actual material differences and when it is just due to undulations in the surface contour. A good place to start is with a sample which is known to be homogenous, so that it will be clear from the outset that any image contrast obtained could not be due to morphology.

For example, shown in Figure 11-2 are test images of a polycarbonate plastic replica grating. The plastic is known to be homogeneous, yet there is a great deal of image contrast in the lateral force image (C).   The image contrast in (C) correlates with topology images (A) and (B). This indicates how easy it is for surface roughness to produce an unwanted 'noise' signal in any lateral force scan. Notice in particular how the cantilever was momentarily twisted sharply by the steep surface edge marked in (C), producing a very bright feature in the image.
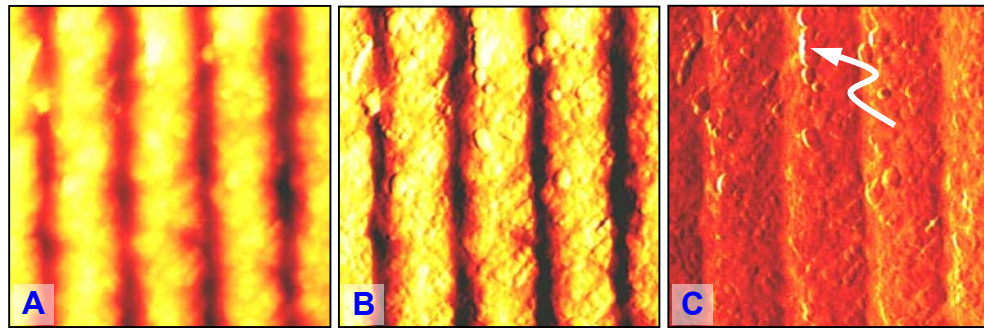
Figure 11-2   Topology of a plastic replica grating rendered normally (A) and with slope shading (B). The simultaneously obtained lateral force image is shown in (C). Scan size 4 μm.

As a counter example, Figure 11-3 is a case where the lateral image contrast does tell us something about the surface morphology. Regions where the teflon coating has worn away are only hinted at in the topology image, but the lateral force image makes the boundaries fairly clear. Notice how there is an underlying 'topology noise component' in the lateral force image, but the darker regions in the lateral force image clearly cross over wide areas of the topology.
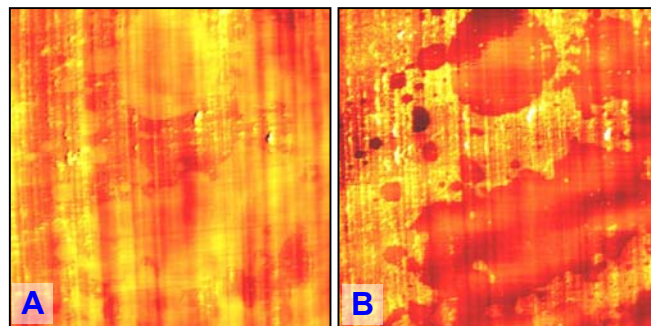
Figure 11-3

Topology image (A) and lateral force image (B) of a worn teflon coated razor blade. Scan size 17 μm.

11.2 PROCEDURE

The lateral force image signal is available when the instrument is configured for contact-mode operation. This would be for scan type settings of *Z Height*, *Lateral*, and *BiLateral*.

The instrument-specific factors which contribute to the strength of the lateral force signal are the scan speed, scan direction, the cantilever shape, and the cantilever load force.

- **Scan Direction**   The twisting effect on the end of the cantilever is greatest when the scan direction is set to 0º or 270º.

- **Scan Speed**   Increasing the scan speed increases the frictional force between the probe point and the surface, and increases the twisting effect.

- **Normal Load Force**   Increasing the normal load force between the probe point and the surface increases the twisting effect. Information about how the normal force can be adjusted via the *Setpoint* control is given in Section 10.3.6.

- **Cantilever Shape**   Contact mode cantilevers may be obtained with a variety of bending and torsional spring constants. In general, the longer and thinner the cantilever, the lower the torsional spring constant. This increases the cantilever's sensitivity to the lateral force signal, but it also decrease the cantilever's ability to produce good topology images. The standard contact mode cantilevers provided by Ambios are a good general purpose cantilever for topology and lateral force imaging. They have these characteristics: Length 460 μm, Width 50 μm, Thickness 3 μm, Bending Spring Constant 0.15 N/m.

The Z scaling units for lateral force images are arbitrary units (au). The actual frictional force experience by the probe point is not determined. The image results may be interpreted in a qualitative fashion by inferring that low values (dark areas within the color palette) are areas of lower friction, while high values (bright areas) are areas of higher friction. Semi-quantitative results may be obtained by calibrating the lateral force signal using a special calibration surface (Ref. M. Varenberg, I. Etsion and G Halperin in Rev. Sci. Instrum., **74** (2003) 3362-3367).

As a final note, the *BiLateral* scan type has the advantage of giving views of the surface topology and the lateral force signal for both the forward and reverse traces of the probe. In some instances the dual sets of image information can be used to help distinguish between lateral force image contrast caused by morphology and contrast caused by surface shape.

12 Phase Imaging

12.1 INTRODUCTION

In ideal circumstances *Phase Mode* can be used to differentiate between different materials in a sample surface. To understand how phase imaging works, first consider how the phase of the cantilever's motion varies when it is not in contact with the surface. Figure 12-1 shows the response of the cantilever to being externally vibrated at frequencies near its natural resonance frequency. The amplitude of the cantilever's motion peaks when driven at the resonance frequency, f_o. Note that at the resonance frequency the phase of the cantilever's motion with respect to the external source of vibration lags by 90°. In preparation for intermittent-contact imaging the vibrator frequency is normally locked at a point just to the left of the resonance, as indicated in the figure. At this frequency the phase shift is less than 90°— say, 60°.
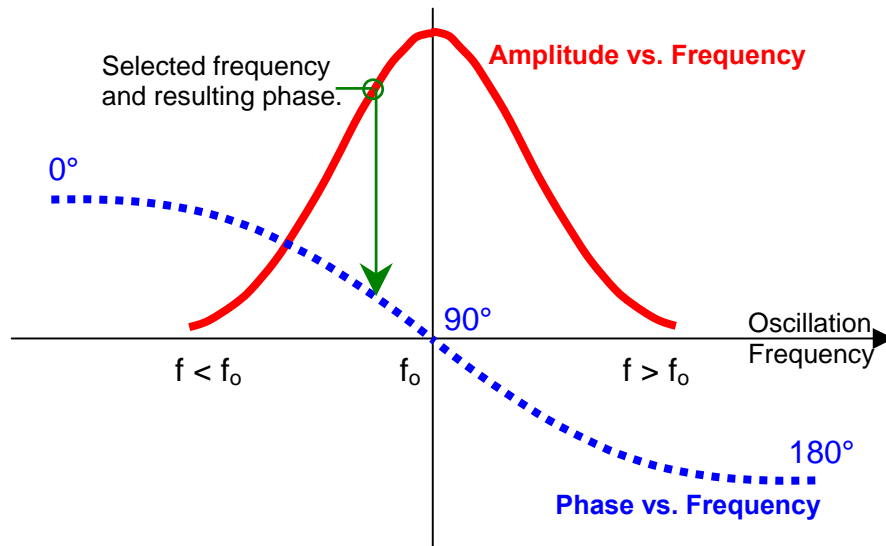
Figure 12-1 Cantilever response to a constant amplitude external vibrator as the frequency of the vibrator is swept across the cantilever resonance.

When the probe is lowered to the surface the effect of intermittent contact with the surface will be to both lower the amplitude of vibration and to modify the relative phase of vibration. The direction of the phase change will depend on the nature of the interaction between the probe and the surface. Assume for the moment that

the surface material is homogeneous everywhere. This would seem to imply that whatever phase shift the cantilever experiences would be constant as the probe is rastered, and therefore the phase image should look like an uninteresting flat plane of constant phase. But this is not the case. The phase will be influenced by the relative velocity of the probe tip with respect to the surface slope-- shifting slightly lower as the tip is rastered up a hill, and slightly higher when the tip is rastered down a hill. The phase will also be affected by changes in the adhesive force between the tip and surface, primarily around crevices. The images below of the calibration grating shipped with the system illustrate these effects.
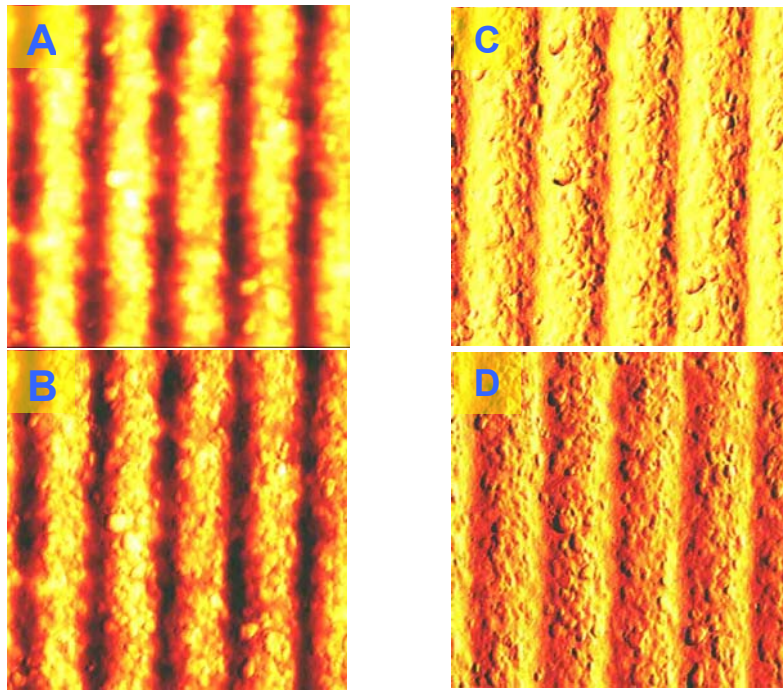

Figure 12-2   Image (a) is a topological view of a plastic replica grating. Image (b) is the same data rendered with slope shading to emphasize the small details in the surface. Images (c) and (d) are phase mode images of this same area as in (a). In image (c) the tip was rastered right-to-left; in image (d) the probe was rastered left-to-right. Compare the images to see how the slope in the surface topology creates phase shift contrast.

It follows that one must be careful to separate image phase contrast caused by topology from phase contrast caused by actual material differences. Figure 12-3 illustrate situations where the source of the contrast is clear. Both images show contamination left on a glass substrate when a solvent was evaporated on the glass. The solvent contaminant in the left-hand image was "sticky." The glass appears yellow while the residue spots appear blue because the phase shift of the cantilever's motion was retarded further-- with respect to the phase shift on the glass-- when it touched those spots. On the other hand, the contaminant in the right-hand image was "bouncy." The glass appears blue while the residue appears

yellow because the phase shift of the cantilever's motion was advanced when it touched this material.
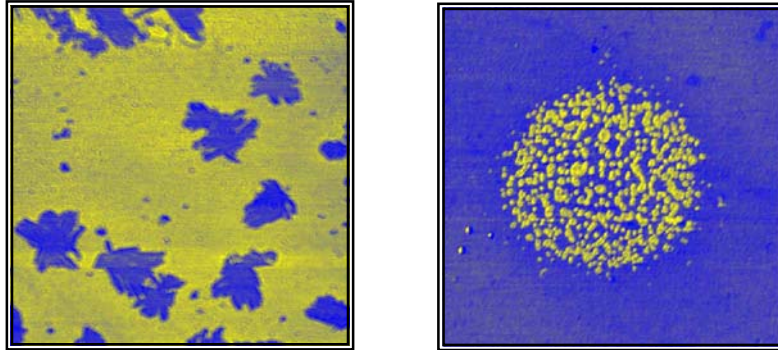
12-3 Phase images of solvent contamination deposited on glass slides by evaporation. Both scan sizes 4 μm.

❖Note: The z-axis units for *Phase* images are "au" (arbitrary units) or "kau" (1000 x arbitrary units). The phase shift is uncalibrated in this instrument.

12.2 SETTING THE PHASE DETECTOR

❖*Note: Older SPM systems with the Type 1 stage electronics do not have adjustable phase detection circuitry.   When the software detects Type 1 stage electronics the Phase option in the Sweep Type panel is disabled, and this adjustment cannot be made.*

To setup the system for phase imaging follow these steps:

1. Adjust the cantilever vibration amplitude and frequency at the **Wave Configuration** window for wavemode imaging (Ref. Section 4.6)

2. After locking on the selected operating frequency select the *Phase* option in the *Sweep Type* panel. The graph display will switch to a sweep of the phase detector output as a function of the phase of the reference oscillator, as shown in Figure 12-4.

XOR Detector
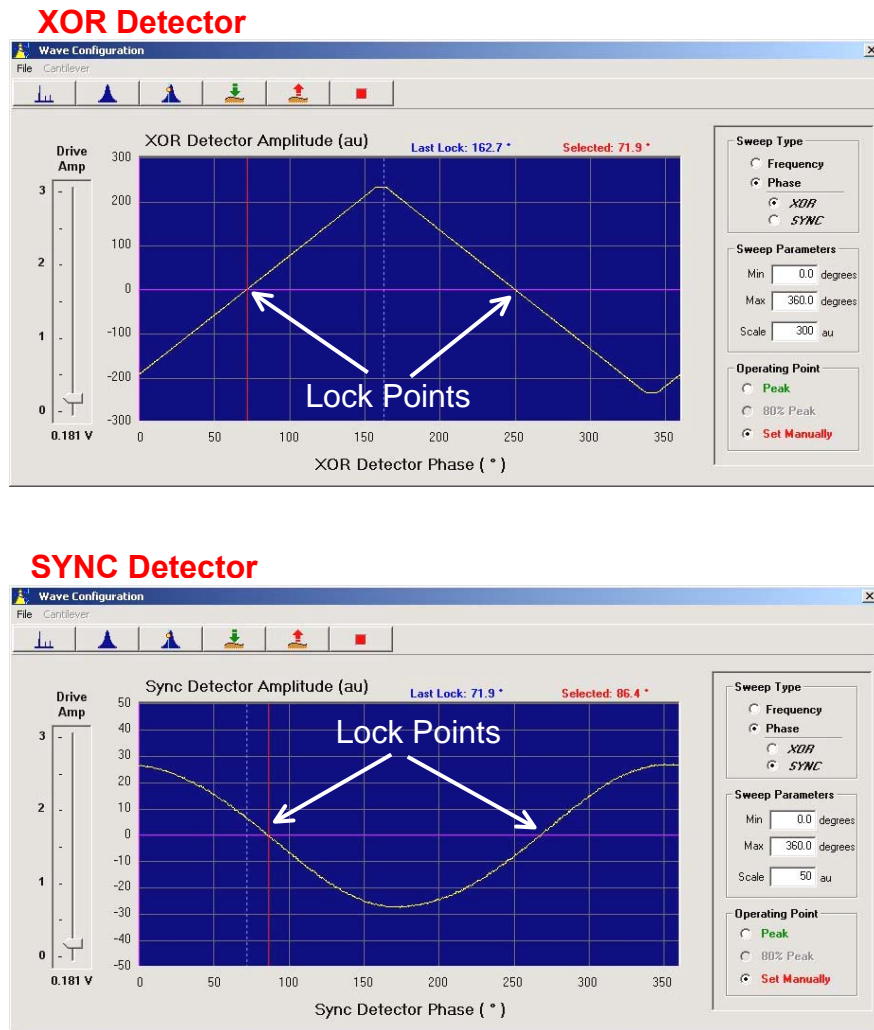
SYNC Detector

Figure 12-4 Top: output of XOR phase detector. Bottom: output of SYNC phase detector. The phase imaging lock points normally selected are indicated for each detector.

3. At this point a selection is made between the two phase detectors in the system: XOR and SYNC. In almost all instances it will be best to select the XOR detector because it provides the better noise performance. The detector options are described below.

- **SYNC** The signal output of the SYNC detector is, as the name suggests, the output of a synchronous or "lock-in" style detector. The input signal to the synchronous detector is the photodetector's Top-Bottom signal, which tracks the vibration movement of the cantilever. The reference signal for the synchronous detector is produced by a separate oscillator in the system which operates at

the same frequency as the cantilever drive signal, but at a relative phase which is adjustable. The amplitude of the SYNC signal is proportional to the amplitude of vibration of the cantilever; moving the *Drive Amp* slider up and down will alter the signal level. This means that the signal-to-noise ratio for the SYNC detector is also amplitude dependent.

- **XOR** The XOR detector is an Exclusive-Or logic gate with the photodetector's Top-Bottom signal and the reference oscillator signal as inputs. The amplitude of the XOR detector is independent of the amplitude of the cantilever's movement, and its signal-to-noise ratio is fairly constant.

4. To give the phase detector equal dynamic range for both positive and negative phase shifts the operating phase generally selected is one of the two points where the detector output crosses zero. There are two points where this happens, one around 90º and a second around 270º. The slope of the phase detector output is different for these two points, and this affects the color contrast of the *Phase* image produced. Usually the point with the rising slope is selected, so that positive phase shifts in the image correspond to brighter colors and negative phase shifts correspond to darker colors.

   Select the operating phase by clicking on the detector graph at the desired point. The red *Set Manually* marker line will be moved to the selected phase. Finally, press the *Lock* toolbar button to lock the phase detector at this phase.

Adjusting the Phase Detector while Scanning

When the selected scanning mode requires a vibrating cantilever (*Wavemode*, *Phase*, *BiPhase*, *ME C-Amp*, etc.) the *Wavmode* tab panel in the **Realtime** window will be enabled. Three parameters can be adjusted from this panel: 1) the amplitude of the cantilever's vibration, 2) the frequency of the cantilever's vibration, and 3) the phase of the phase-detector's reference oscillator.

Tweaking the cantilever amplitude and frequency parameters by small amounts can, in some circumstances, greatly improve the phase contrast in an image. Note, however, that if the frequency or amplitude are moved too far from the initial values selected at the **Wave Configuration** screen the Z feedback loop may become unstable. This is because changing the amplitude or frequency at the **Realtime** window also has the side effect of altering the damping factor.

The phase parameter can be changed freely from 0-360º.   The corresponding change in the phase image depends upon which phase detector is being used.

- **XOR** Changing the detector phase only shifts the DC level of the image signal. The image color changes but the image contrast remains the same. The sensitivity of the detector does not change until the phase point has been shifted so far that it is near one of the transition points seen in the top graph of Figure 12-4, where the signal slope switches from positive to negative.

- **SYNC** When the phase image contrast falls near the middle of the color palette the detector operation is near the zero crossing points of the sine wave in Figure 12-4. The sensitivity of the detector is largest, and has the greatest linear range at the zero crossing points.

13   *Magnetic Force Microscopy*

Magnetic Force Microscopy (MFM) requires a special cantilever with a magnetized tip. While the cantilever is vibrated near its resonance frequency it is rastered just out of contact with the sample surface in order to detect the fields near the surface through changes in the cantilever vibration amplitude or phase. Typical MFM applications include imaging the magnetic bit profile of data stored in magnetic media, and imaging the fields near Bloch wall boundaries and other domain boundaries in magnetic solids.

Unlike the topographic modes of Q-Scope operation, where bright and dark features in an image can simply be interpreted as high and low features in the surface, interpreting MFM images requires an understanding of the physical interaction between the magnetic probe and the magnetic field near the surface, and the mechanism by which the image contrast is generated. Users interested in an introduction to MFM imaging theory may wish to read Manual Supplement 9, *An Introduction to MFM Theory*.

In this chapter, the operating procedure for making MFM measurements is given in Section 13.1, followed by guidelines for optimizing the resolution of MFM images in the Section 13.2.

❖Note: Thorough familiarity with *WaveMode* operation of the instrument is essential before attempting to operate the microscope in MFM mode.

13.1 MFM IMAGING PROCEDURE

1. Install a magnetic cantilever into the probe holder. If your scan head has the standard Q-Scope probe holder, small magnets behind the probe holder body will pull the metal cross against the holder to keep it in place. The magnetic field from these magnets is weak enough to allow MFM imaging of high coercivity materials (> 100 Oe).

   If your scan head has the non-magnetic probe holder follow these installation steps:

   a) Move the tilt lever to the horizontal position and lightly lift the probe holder spring by pushing the insertion tool under it, as shown in Figure 9-1. Make sure the insertion tool is at either the left or right edge of the slot to allow room for the metal cross.

      ❖Note: Be careful. Over-extending the spring will permanently deform it.

b) Next, holding the metal cross by one of its tabs with tweezers, insert the bottom end of the cross under the spring as shown in Figure 9-2. Gently remove the insertion tool.

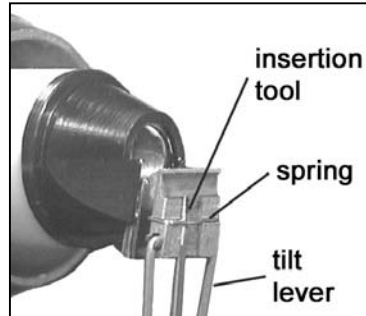c) Center the probe in the holder by sliding it laterally with the tweezers.
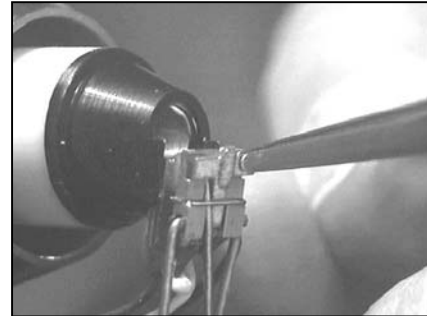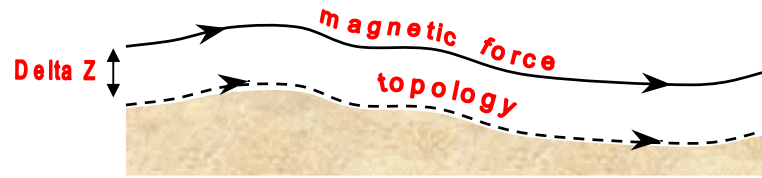

Figure 13-1

Figure 13-2

2. In the **SPM Configuration** window select one of the four *ME* imaging modes listed in the table below. A description of each mode is given below.

ME Mode	Recorded Signal	Probe Motion
T-Amp	Vibration Amplitude	The surface terrain is followed at a constant distance.
T-Phase	Phase shift	
C-Amp	Vibration Amplitude	The Z extension of the piezo tube is fixed; terrain is not followed.
C-Phase	Phase Shift	

- The Q-Scope can record either the amplitude (*-Amp*) of the cantilever vibration or the phase (*-Phase*) shift of the cantilever vibration as the probe is rastered across the surface. The phase signal generally provides the best signal-to-noise ratio, so in almost all instances you should choose either the *T-Phase* or the *C-Phase* mode.

- The probe may follow the surface topography as the MFM data are recorded (T-) or the probe may move at a constant vertical height (C-) as the data are recorded. The distinction between these options is:

  a. In the "follow the terrain" method (*T-*) the probe passes over each scan line twice. In the first pass the topology of the surface is recorded with *WaveMode* feedback, then in the second pass the feedback is disabled and magnetic force data (cantilever amplitude/phase) are recorded as the probe is scanned at a constant vertical distance above the surface.

The (T-) option has the advantage of allowing the probe to closely follow a rough surface profile. It has the disadvantages of making it more likely that the surface topology will introduce extraneous image contrast in the magnetic image, and because for each line in the image the surface is scanned twice, it is twice as slow as the (C-) method.

b. In the "constant extension" (*C*-) method the probe passes over each scan line only once. At the beginning of each scan line the feedback is disabled and the probe lifted above the surface and scanned with a fixed extension of the piezo tube.   On the retrace of each scan line normal feedback is enabled so that the location of the surface is re-established before beginning the next MFM line.

The (C-) option has the disadvantage of only working well on surfaces which are smooth, and without excessive upward tilt along the x-axis of the image.   There is the risk of the probe bumping into the surface if it is not lifted high enough. It has the advantages of being twice as fast as the (T-) option, and also having the better signal-to-noise figure.

3. When an MFM mode has been selected in the **SPM Configuration** window the *Delta Z* controls will be enabled. *Delta Z* sets the distance which the probe is raised above the surface in the magnetic data gathering sweep across the surface. *Delta Z* must be large enough to raise the vibrating cantilever out of contact with the surface, but not too large, because the resolution of an MFM image decreases as the probe is moved further away. A typical initial setting to try is 400 nm.

❖Note: The maximum setting the *DeltaZ* control will accept is 2000 nm. However, in all circumstances the actual maximum lift distance is limited by the capabilities of the scan head. For example, if the scan head has a total vertical range of 3 μm, and the probe is imaging the topology near the center of the available vertical range, then the probe can be raised only 1.5 μm above the surface.   When *DeltaZ* is set to 2000 nm in these circumstances the actual lift distance will be truncated to 1500 nm by the system. To obtain the full 2000 nm of *DeltaZ* it would be necessary to manually lower the probe further down so that it images the topology at the lower-end of the vertical range.

Wave
Configuration

4. Open the **Wave Configuration** window. Locate the cantilever resonance and magnify the sweep to a 10 kHz range about the resonance with the *Zoomed Sweep* control. (Ref. Section 4.6) Adjust the amplitude slide control set the resonance peak at about 15% of full scale.   This is a typical initial amplitude for EFM imaging.

❖Note: Vibrating the cantilever at even smaller resonance amplitudes will allow the probe to be brought closer to the surface, thus increasing the image resolution. Decrease the amplitude with care, however. If the amplitude is too low there will be insufficient signal for the system to establish stable feedback.

5. When the mode of operation is either *TAmp* or *CAmp*, lock the frequency of the bimorph oscillator at the 80% point (select the *80% Peak* radio button). If the mode of operation is either *TPhase* or *CPhase* lock the frequency of the bimorph oscillator to the peak frequency (select the *Peak* radio button).

6. When imaging with either the *TPhase* or *CPhase* mode it will be necessary to set the operating point for the phase detector.   All of the guidelines given in Section 12.2 on how to set the operating point apply to MFM as well.

7. Open the **Engage** window. In the **Engage** window, adjust the *Setpoint Offset* control to make the damping factor approximately 50%.

8. The probe can now be lowered to the surface and imaged in the usual way. The scan speeds used should be slow, ≤ 2 Hz.

Example: MFM Images of a Magnetic Disk Sample

The interaction between the magnetic tip and the magnetic field at a surface is generally weak, and low scan rates are required to obtain good MFM images. The following *CAmp* and *CPhase* images were obtained from a magnetic disk test sample similar to the one provided with your instrument. The **SPM Configuration** window settings and orientation of the sample are also given below.
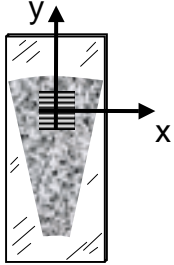
Magnetic test sample orientation under the scanner.

Scan Size	40 μm	Integral Gain	250	Image Mode	ME C-xxx
Scan Rate	2 Hz	Proportional Gain	150	XY Disable	no
Setpoint	50% damping	Derivative Gain	0	Center X	0 μm
Scan Direction	0 °	Scan Resolution	300	Center Y	0 μm
Delta Z	200 nm	Bias Voltage	0 V	XY Signal Mode	Standard
				Z Signal Mode	Standard
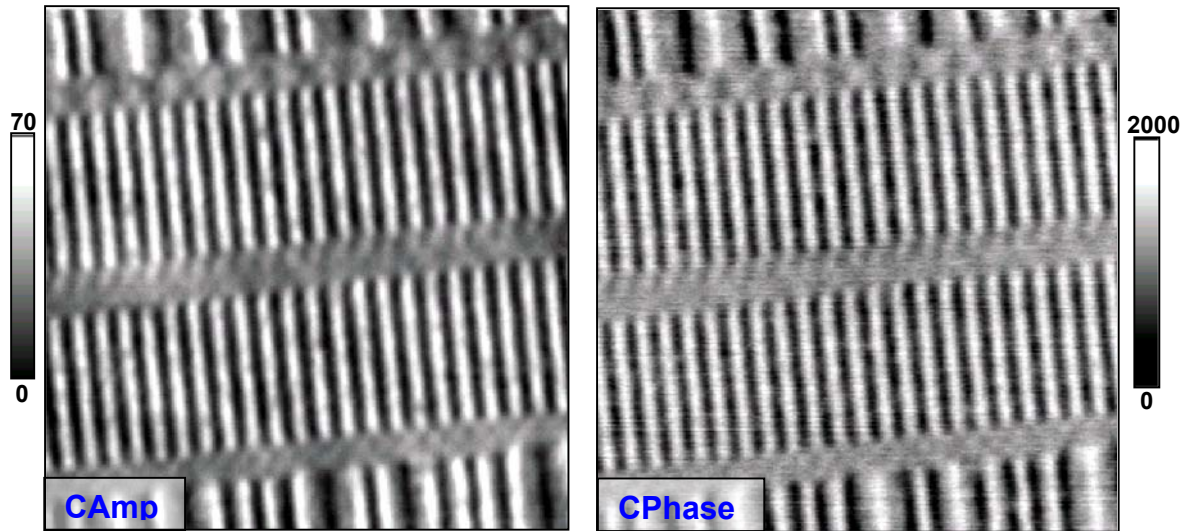
Figure 13-4 Examples of MFM scan results for the CAmp and CPhase scanning modes.

Bright/dark areas in the *CAmp* image correspond to higher/lower cantilever vibration amplitudes, respectively. Bright/dark areas in the *CPhase* image correspond to forward/backward phase shifts of the cantilever oscillation, respectively. Note that the contrast generated by the phase signal is the *reverse* of the contrast from the amplitude signal.

13.2 OPTIMIZING MFM IMAGES

13.2.1 Nondestructive MFM Imaging

When imaging a magnetic sample for the first time, keep in mind that a strong sample field may gradually alter the magnetic properties of the tip, or a soft magnetic sample may have its magnetic structure altered by the field of the tip. In either case the image obtained is inaccurate, and these situations should be avoided. As a rule of thumb, the conditions for nondestructive MFM imaging are that the sample field strength at the probe should be much smaller than the coercivity of the probe material, and the probe's field at the surface should be much smaller than the coercivity of the sample. One method for testing if the imaging process is destructive is to scan the same surface features repeatedly and check for gradual changes in the image.

The direction of the polarization of the cantilever can intentionally be realigned by placing it in a very strong magnetic field, such as the field from a small rare-earth magnet. The MFM probe manufacturers do not guarantee that every magnetic probe is properly polarized; therefore is advisable to magnetize every new cantilever before using it. Also, if a probe fails to give a magnetic image on a known reference sample after all other adjustments have been attempted, it may be that the probe needs to be re-polarized.

Another common way magnetic resolution is lost is by having a portion of the probe tip break off. This is may occur when imaging a hard surface, or a surface with steep features. Tip breakage may also occur if feedback is lost for any reason while the probe is in feedback range. The topological resolution of the probe always decreases when the probe breaks, so simply performing a *WaveMode* scan on a surface with known fine features (such as the calibration grating provided with the instrument) will quickly reveal if this is contributing to any magnetic imaging problems.

13.2.2 Frequency/Phase Optimization

In some instances the best imaging results are obtained at a frequency slightly higher or lower frequencies than the frequency selection made at the **Wave Configuration** window. The *Wavemode* tab panel in the **Realtime** scan window can be used to tweak the bimorph frequency as the surface is scanned to search for the optimum setting.

Keep in mind that if the frequency is shifted too far from the resonance peak the feedback loop will become inoperative, and the tip will be pressed into the surface, potentially damaging it. The scanning software recognizes when feedback has been lost and terminates the scan with an accompanying error message. Always

change the frequency control setting with care. It is usually best to restrict manual frequency shifts to a range of about ±100 Hz.

When scanning in either *CPhase* or *TPhase* modes the phase detector operating point can also be changed. Any value from 0-360º is valid. The phase detector operating point should only be adjusted if there is some clipping in the phase detector signal. Adjusting the phase detector does not influence the quality of the MFM image in any other way.
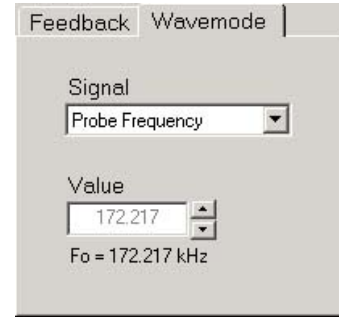

Figure 13-5 Realtime window adjustment controls for the vibration frequency, amplitude, and phase detector.

13.2.3 Adjusting the Probe-Surface Distance

Decreasing the distance between the sample and the magnetic probe increases the lateral resolution of an MFM image. The data below give an indication of how rapidly the resolution varies with tip-surface distance while scanning 2 μm magnetic tracks on a Zip drive (*CAmp* mode). The surface was tilted along the x raster direction by 1.3º. *Delta Z* was adjusted to place the probe 800 nm above the surface at the left edge of the image and barely in contact with the surface on the right edge. Contact occurs at the two black spots on the right edge of the MFM image, shown at the top. A cross-section of the MFM image is shown at the bottom.

There are several interrelated factors which determine the closest distance between the vibrating probe and the surface. These include the bimorph drive voltage, the bimorph frequency, the vertical offset *Delta Z,* and the feedback damping percentage. The connection between these factors is illustrated in Figure 13-7. Waves (1) through (5) in this diagram indicate the amplitude of vibration of the cantilever tip in different locations with respect to the surface. In normal instrument operation the free cantilever vibration amplitude is adjusted via the bimorph amplitude and

Figure 13-6 Change in lateral resolution with probe-surface distance.

frequency controls when the probe is several micrometers from the surface (1). Then when the probe is lowered to the surface and the vertical feedback control is active (2) the *Setpoint Offset* control determines the reduced amplitude of vibration with the probe touching the surface. The reduction percentage is indicated by the *Damping Factor* in the **Engage** window. Typically the setpoint is adjusted to make the damping factor about 50%. For example, if the free amplitude of cantilever vibration is 200 nm (peak), and the damping factor is 55%, then the damped cantilever amplitude will be about 45%(200 nm) = 90 nm while tapping the surface. This also means the average cantilever position is maintained at 90 nm above the surface by the feedback circuit. Preceding each scan line of magnetic data the z position of the probe is raised an amount *Delta Z* above this average height (3), which should lift the probe clear of the surface. The new vibration amplitude will not be quite 200 nm due to air damping effects (Ref. Section 4.7.2). Assume it is now about 190 nm. Then if, for example, *Delta Z* is chosen to be 300 nm, the actual distance of closest approach between the vibrating probe and the surface will be about 90 nm + 300 nm - 190 nm = 200 nm. As the probe is scanned over magnetic domains in the surface (4,5) the amplitude will rise and fall from the 190 nm baseline amplitude.
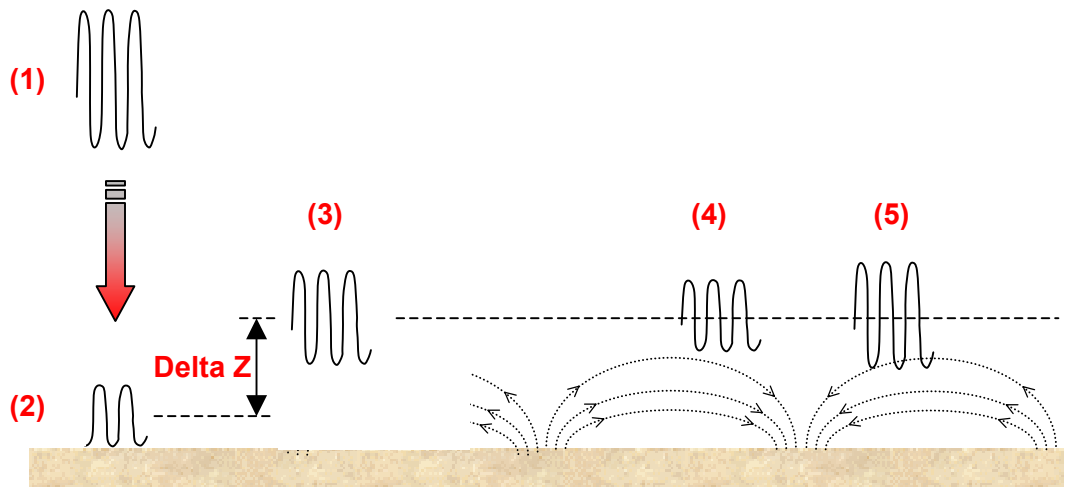
Figure 13-7 Amplitude of tip vibration in different locations with respect to the surface.

The best lateral resolution of the instrument is achieved when the average distance between the vibrating cantilever and the surface is as small as possible. The general optimization procedure is to adjust the bimorph amplitude to a low practicable level-- with enough signal to establish WaveMode feedback-- then image the surface with a high initial value of *Delta Z* and gradually lower its value until surface contact is observed in the image. This lowest setting for *Delta Z*, Delta Z_{min}, essentially corresponds to zero probe-sample separation. When the surface is scanned at higher values of *Delta Z* the nominal probe-sample separation is Delta Z - Delta Z_{min}.

If the region of interest in a sample is tilted, or has bumps in its profile, the *TAmp* and *TPhase* imaging modes allow the probe to be brought closer to the surface. The three images below of video tape data illustrate this. The surface topography in the left image reveals a positive left-right slope and several large dust particles on the surface. In the *CPhase* MFM mode, the smallest value of *Delta Z* which can be used to image this surface without tip-surface contact is 225 nm. In *TPhase* mode, *Delta Z* could be lowered to 125 nm without contact. The successful *TPhase* scan is shown in the right image. The center image shows what happens when the same value for *Delta Z* is used in the *CPhase* mode. There is considerable surface contact at the high points.
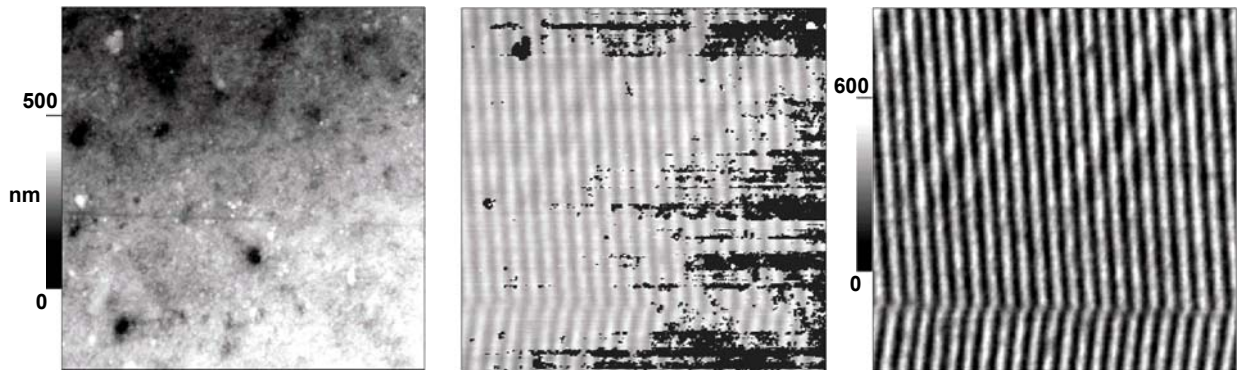
Figure 13-8 Surface topology (left) and MFM images (center, right) of video tape.

13.2.4 Separating Magnetic Information from Background Noise

When the magnetic data are measured the detection system operates in an open loop configuration to sense extremely small magnetic forces, making the measurement susceptible to small sources of noise. Systematic image noise can be attributed to imperfections in the laser optics, imperfect manual alignment of the laser beam, and mode hopping of the cantilever. Nonsystematic noise can be attributed to both random and periodic electronic noise and thermal noise. In the next few pages examples of the effects of several of these noise sources will be given, along with tactics for reducing their unwanted contributions to an MFM image.

Systematic Optical Noise

Image 13-9(A) is a *CAmp* scan of a 3.5" floppy disk surface taken with *Delta Z* = 400 nm. The magnetic data appear as the vertical stripes in the image. Superposed on the vertical stripes are dark and bright patches, which *a priori* could be part of the magnetic structure, but in fact are due to imperfections in the laser optics used to measure the deflection of the cantilever. This can be verified by increasing *Delta Z* to 2000 nm and rescanning the surface, as shown in B. At

this greater altitude, evidence of the true magnetic data might barely be discernable in the image, as expected, because the magnetic fields are weaker, but the bright and dark patches clearly remain with the same amplitude. The false nature of these patches can be tested further by imaging a completely different region of the disk and verifying that a very similar patch pattern is produced.
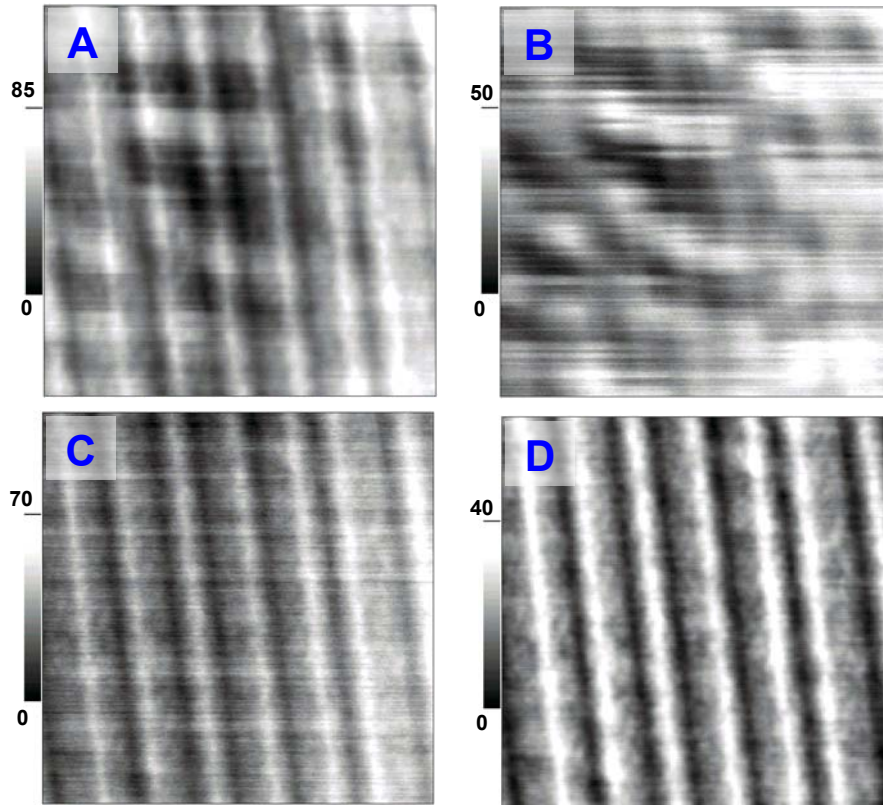
Figure 13-9 Identifying optical noise.

It is important to note that a *WaveMode* topology image of this same section of the surface, taken with exactly the same laser adjustments, will appear fine. The imperfections shown here are the result of an extremely small false laser signal. It can appear in other forms, such as diagonal waves across the image, or a broad concave or convex background in the image. In worst-case situations it is possible for the systematic optical noise to completely obscure the magnetic signal.

Once it is identified, the solution to this problem is to raise the probe clear of the surface, change the tilt of the cantilever probe slightly, and realign the laser optics in the usual fashion. A better alignment will eventually be found where the systematic laser noise is tolerable, as shown in image C. In this case there is a small tilt in the MFM image and a small amount of streaking produced by random line-by-line noise. The image can be cleaned up by using the line-by-line and parabolic tilt removal feature of the software. The final clean image of the disk data is shown in D.

Optical noise artifacts can largely be avoided by scanning in an MFM *Phase* mode instead of an *Amp* mode, since the phase shift signal is little affected by variations in the laser optics.

Cantilever Mode Hopping

The nominal best frequency for *TAmp* and *CAmp* imaging is the frequency corresponding to 80% peak amplitude; the nominal best frequency for *TPhase* and *CPhase* imaging is the frequency corresponding to the peak amplitude. Between these two frequencies, with some cantilevers, there is a narrow frequency range over which the cantilever will make a transition between two different vibration modes. The *Camp* and *CPhase* images in Figure 13-12 show the effects of the transition as the bimorph frequency is gradually increased from $\sim f_{80\%}$ at the top of the image to $\sim f_{peak}$ at the bottom.
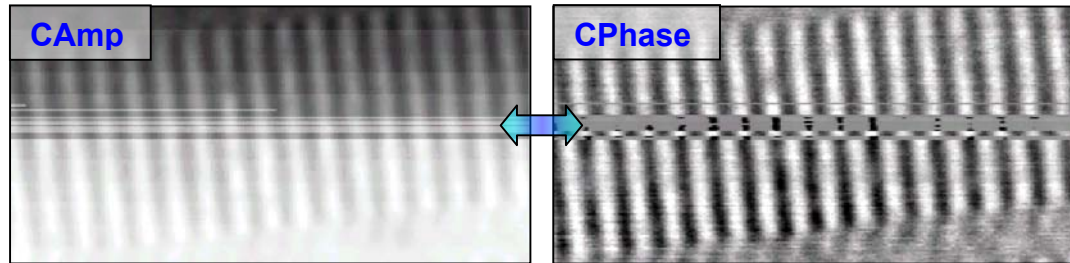
Figure 13-12 Cantilever mode hopping.

Notice the 180° phase reversal in the *CPhase* scan. If the bimorph oscillation frequency is inadvertently set to within the transition zone, or it happens to slowly drift into the transition zone over time, intermittent streaks will appear in the MFM image. The solution to this problem is to readjust the oscillation frequency. When streaking occurs in a *CAmp* or *TAmp* image the frequency needs to be lower. When streaking occurs in a *CPhase* or *TPhase* image the frequency needs to be higher.

Vibrational, Acoustical, Thermal, and Electrical Noise

Vibration noise and acoustic noise generally do not degrade an MFM image unless they are severe. In a typical MFM scan, where the closest distance between the tip and surface might be 50 nm, the distance between the cantilever and the surface would have to randomly jump by at least ~10 nm in order to occasionally produce tip-surface contact. When there is no tip-surface contact the rate of change in the magnetic signal with vertical distance is too gradual for a few nanometers of vibration to appear in the image.

Thermal noise can be a problem if the instrument is located in a room with drafts and temperature fluctuations from the on-and-off cycling of an air conditioner or heater. For example, image A in Figure 13-11 of a Zip drive surface was taken with the Q-Scope uncovered in a room with a cycling heater and people moving nearby. The image was taken in *CPhase* mode with 256x256 resolution. *Delta Z* was set to the high value of 900 nm in order to simulate a weak magnetic sample. The roller coaster drop in the image brightness from top to bottom was caused by thermal changes in the microscope over the five minute scan time. Shifts in the resonance frequency of the cantilever are mostly at fault here.

Thermal noise problems caused by air currents are usually easily solved by continuously operating the Q-Scope under a plastic cover or other form of enclosure, and allowing an initial warm-up time for the system.

In image B, the thermal noise has been removed from A using the horizontal line-by-line background subtraction function in the software. This image appears grainy due to the remaining electronic noise of the instrument. There are two ways to reduce the effects of the electronic noise: 1) increase the signal averaging by scanning more slowly or scanning at a higher pixel resolution, or 2) filter the image either with the FFT routines or a matrix low-pass filter. The final image C is the result of increasing the scan resolution from 256x256 to 512x512 and applying a low-pass filter to the image
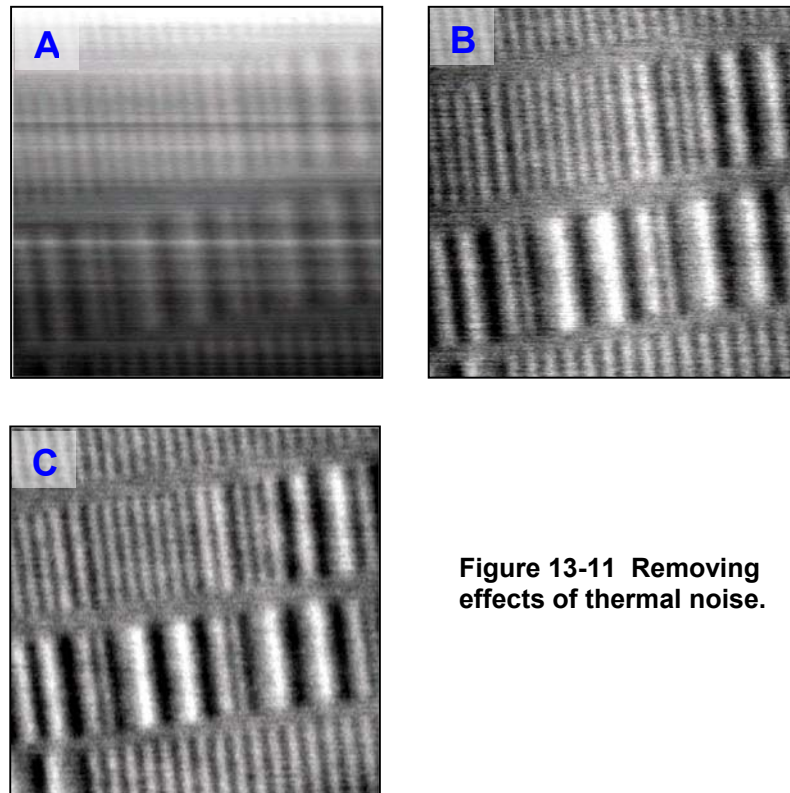

Figure 13-11 Removing effects of thermal noise.

14 Electric Force Microscopy

14.1 INTRODUCTION

The term "electric force microscopy" (EFM) is used in different ways in the scientific literature. Here, EFM is defined to be the direct analog of the MFM imaging technique discussed in Chapter 13– i.e., the probe is vibrated with a small amplitude above the sample to interact with the stray electric field above the surface, and what is detected by the probe is essentially an electrostatic force gradient. The goal of EFM is to infer from a set of force gradient measurements information about the surface potential and surface charge distribution in materials such piezoelectrics, ferroelectrics, and dielectrics, or man-made structures such as semiconductor circuitry.

As a starting point, the following simple model will be used to describe the technique. The EFM probe is generally a regular silicon cantilever with a 50 nm front coating of metal so that the lever and point can be electrically connected to a voltage source and held at a controlled potential. The model surface is taken to be a perfectly flat metal which has surface patches of varying potential, as illustrated in Figure 14-1. A concrete example of this might be a polished plate of heterogeneous metal, where the work function differences in the metal grains provides the varying surface potentials. An external bias voltage V_{bias} is applied between the sample bulk and the cantilever. The voltage difference between the cantilever and the surface V_{cs} can be thought of as the external bias voltage V_{bias} minus a local internal voltage difference V_s between the bulk and the area directly beneath the probe: $V_{cs} = V_{bias} - V_s$.
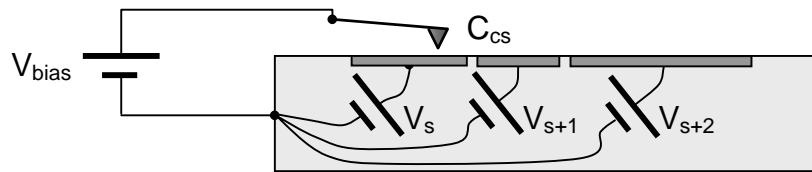

Figure 14-1   A simple model for understanding EFM.

The gap between the surface and the probe forms a capacitance C_{cs} which stores an amount of electric potential energy U of

$$U = \frac{1}{2}C_{cs}(V_{bias} - V_s)^2$$

Associated with this electric potential energy is an electrostatic force of attraction. As in the MFM technique, in an EFM scan the cantilever is vibrated at a small amplitude near its resonance frequency. For small vibration amplitudes the gradient in the electrostatic force on the cantilever along the vertical direction, F_o', can be approximated by

$$F_o{}' = \frac{1}{2}\left[\frac{d^2C_{cs}}{dz^2}\right]_{z=zo}(V_{bias} - V_s)^2$$

If you are unfamiliar with calculus the derivative term might be bothersome, but it is really only important to understand that F_o' depends on both the probe-surface capacitance (i.e., the geometry of the parts) and the square of the probe-surface voltage difference. The force gradient F_o' effects the way the cantilever vibrates, much as if it acts like a second spring attached to the vibrating cantilever to change the way it moves. By measuring by the amplitude, phase, or frequency changes as the probe is rastered, a map of the variations in F_o' is created.

In the simplest case, where the sample surface is flat and the probe is moved at a constant height above the surface, the capacitance derivative term d^2C/dz^2 will be a constant. In this case the EFM image contrast can be interpreted as being proportional to $(V_{bias} - V_s)^2$. From this simple point of view, imaging the surface with different bias voltages can help to extract the surface potential information from the EFM data. The example numbers presented in Table 14-1 illustrate the following points:

- If the bias voltage is set to zero and the adjacent surface potentials in Figure 14-1 are of roughly equal magnitude but opposite sign (Configuration 1) then there is no difference in the EFM signal (i.e., F_o') over the two regions.   But note that as the probe passes between the two regions the average voltage experienced by the probe will go through zero. Therefore along the boundary lines between the regions it may be possible to see EFM image contrast in the form of a dip in the signal amplitude.

- When there is a difference in the magnitude of the potential between adjacent regions (Configuration 2) there will be EFM signal contrast between the two regions.

- Imaging the surface twice, with equal and opposite bias voltages may make it possible to determine the polarity of the potential in adjacent regions (compare Configurations 3 and 4).

Config	V_{bias}	V_s	V_{s+1}	$[F_o']_s - [F_o']_{s+1}$
1	0	+1	-1	1-1 = 0
2	0	+1	+2	1-4 = -3
3	+5	+1	+2	16-9 = +5
4	-5	+1	+2	36-49 = -13

Table 14-1   Model calculations of the relative strength of the EFM signal when the probe is moved over adjacent patches on the surface with different voltages. To simplify the results, in the calculations for F_o' the $\frac{1}{2}[d^2C/dz^2]$ term has been set to 1.

Image Interpretation Problems

The EFM imaging technique is difficult. Setting aside the limitations of the hardware, the following problems are commonly encountered:

1. It is necessary to consider the fact that the cantilever point generally experiences forces from the fields of many different patches of potential, not just one individual patch as suggested by the model in Figure 14-1. The contributions of the different patches to the total force will depend on the value of V_s for each patch and the capacitance between the patch and the probe point, as indicated in Figure 14-2. The size of the patches, the size of the probe point, and the distance between the probe point and the surface all influence how much of the net electrostatic force is due to the patch immediately beneath the probe and how much is due to the rest of the neighborhood.

    The cantilever arm itself generally experiences electrostatic forces from such a large number of patches that the average interaction of its capacitance with the entire surface remains constant during the scan.
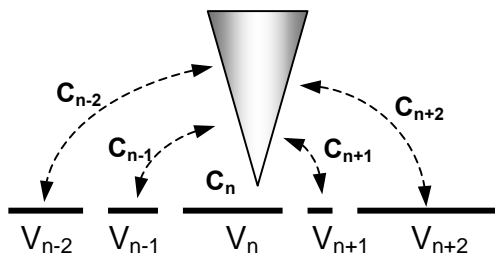

Figure 14-2   The cantilever experiences forces from many surface areas with different surface-probe capacitances.

2. Another problem that will be encountered is that the surface topology contours leach into the EFM image because the capacitance will not be constant for a surface which is rough, even when the probe is nominally held at a fixed height above the surface topography. The capacitance derivative term d^2C/dz^2 will *not* remain constant during the scan and this will introduce structure into the EFM image which is unrelated to the surface potential.

   In some cases the capacitive effects can be differentiated from surface potential effect by imaging the surface twice, once at a small positive bias voltage and then again at a small negative bias voltage. Regions where there is image contrast reversal when the bias polarity is changed are probably at a different surface potential (Ref. Table 14-1).

3. The simple model presented above is for a conducting sample surface. The EFM imaging technique can also be applied to insulating samples, but the interpretation of the results is complicated by the fact that the surface may acquire trapped charges, and the dielectric properties of the surface become an added parameter to consider.

14.2 PROCEDURE

❖Note: Thorough familiarity with *WaveMode* operation is essential before attempting to operate the microscope in EFM mode.

Hardware Requirements

EFM requires a Wavemode cantilever coated on the front surface with a conductive film, and the cantilever must be attached to the stainless steel pre-mount with conductive glue. A resonance frequency near 70 kHz provides the best sensitivity. EFM cantilevers can be purchased directly from Ambios.

The scanner must have a bias voltage lead running from the stage electronics to the probe holder. This hardware is optional. Check the electrical connections near the probe holder of your scanner to see if there is a small diameter, grey coaxial lead present. The black wire lead soldered to the gold colored probe holder must be connected to this coax for EFM imaging. This lead provides the bias voltage to the probe holder.

There is a 10 MΩ resistor in series with the bias voltage, located either inside the housing of the 15 pin scanner cable connector (pin 13), or at the very end of the coaxial lead right next to the probe holder. This resistor limits the current between the cantilever tip and the surface in the event that the tip touches a

conducting surface with a bias voltage applied. This helps to prevent damage to the thin metallic coating on the probe tip.   The 10 MΩ resistor may be changed by the user.

EFM Scanning

1. Insert an EFM cantilever into the probe holder.

2. In the **SPM Configuration** window select one of the four *ME* imaging modes listed in the table below. A description of each mode is given below.

ME Mode	Recorded Signal	Probe Motion
TAmp	vibration amplitude	the surface terrain is followed at a constant distance
TPhase	phase shift	
CAmp	vibration amplitude	the Z extension of the piezo tube is fixed
CPhase	phase shift	

- The Q-Scope can record either the amplitude (*-Amp*) of the cantilever vibration or the phase (*-Phase*) shift of the cantilever vibration as the probe is rastered across the surface. The phase signal generally provides the best signal-to-noise ratio, so in almost all instances you should choose either the *T-Phase* or the *C-Phase* mode.

- The probe may follow the surface topography as the EFM data are recorded (T-) or the probe may move at a constant vertical height (C-) as the data are recorded. The distinction between these options is:

    a. In the "follow the terrain" method (*T-*) the probe passes over each scan line twice. In the first pass the topology of the surface is recorded with *WaveMode* feedback and the tip bias voltage set to zero. Then in the second pass the feedback is disabled, the tip bias voltage is set to the value selected at the **SPM Configuration** window, and electric force data (cantilever amplitude/phase) are recorded as the probe is scanned at a constant vertical distance above the surface.

The (T-) option has the advantage of allowing the probe to closely follow a rough surface profile. It has the disadvantages of making it more likely that the surface topology will introduce extraneous image contrast in the magnetic image, and because for each line in the image the surface is scanned twice, it is twice as slow as the (C-) method.

b. In the "constant extension" (*C*-) method the probe passes over each scan line only once. At the beginning of each scan line the feedback is disabled, the probe is lifted above the surface, the bias voltage is set to the **SPM Configuration** value, and then the probe is scanned with a fixed extension of the piezo tube. On the retrace of each scan line the bias voltage is set to zero and normal feedback is enabled so that the location of the surface is re-established before beginning the next EFM line.

The (C-) option has the disadvantage of only working well on surfaces which are smooth, and without excessive upward tilt along the x-axis of the image. There is the risk of the probe bumping into the surface if it is not lifted high enough. It has the advantages of being twice as fast as the (T-) option, and also having a better signal-to-noise figure.

❖Note: The maximum setting the *DeltaZ* control will accept is 2000 nm. However, in all circumstances the actual maximum lift distance is limited by the capabilities of the scan head. For example, if the scan head has a total vertical range of 3 μm, and the probe is imaging the topology near the center of the available vertical range, then the probe can be raised only 1.5 μm above the surface.   When *DeltaZ* is set to 2000 nm in these circumstances the actual lift distance will be truncated to 1500 nm by the system. To obtain the full 2000 nm of *DeltaZ* it would be necessary to manually lower the probe further down so that it images the topology at the lower-end of the vertical range.

3. Open the **Wave Configuration** window. Locate the cantilever resonance and magnify the sweep to a 10 kHz range about the resonance with the *Zoomed Sweep* control (Ref. Section 4.6.2). Adjust the amplitude slide control set the resonance peak at about 15% of full scale. This is a typical initial amplitude for EFM imaging.

❖Note: Vibrating the cantilever at even smaller resonance amplitudes will allow the probe to be brought closer to the surface, thus increasing the image resolution. Decrease the amplitude with care, however. If the amplitude is too low there will be insufficient signal for the system to establish stable feedback.

4. When the mode of operation is either *TAmp* or *CAmp*, lock the frequency of the bimorph oscillator at the 80% point (select the *80% Peak* radio button). If the mode of operation is either *TPhase* or *CPhase* lock the frequency of the bimorph oscillator to the peak frequency (select the *Peak* radio button).

5. When imaging with either the *TPhase* or *CPhase* mode it will be necessary to set the operating point for the phase detector.   The instructions given in Section 12.2 concerning how to set the operating point apply to EFM as well.

6. Open the **Engage** window. In the **Engage** window, adjust the *Setpoint* control to make the damping factor approximately 50%.

7. The probe can now be lowered to the surface and imaged in the usual way. The scan speeds used should be slow, ≤ 2 Hz.

14.3 EFM TEST

A simple way to test the EFM operation of your instrument is to use the sample simulator shown in Figure 14-3. This consists of a gold coated glass disk connected to a function generator capable of producing a stable low frequency triangular waveform with a variable amplitude and variable DC offset. The gold disk is placed under the Q-Scope scanner, and the ground lead of the function generator is connected either to the translation stage or the scanner case.
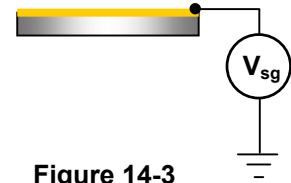
Figure 14-3

The idea is to engage the EFM cantilever with the gold surface following the procedure described in Section 14.2, but instead of having the probe actually scan over the sample surface, the scanner XY motion is disabled so that the EFM data are measured at one point on the gold surface. As the scan proceeds a slowly varying triangle voltage is applied to the gold film to simulate the probe crossing over regions of the surface with varying potential. The frequency of the function generator is adjusted so that it is synchronous with scan speed of the SPM. This

makes the high and low regions in the EFM image align in the scan image, to create what looks like continuous groves in the surface.

Recalling from Section 14.1 that the EFM signal varies as the square of the voltage difference between the probe and the surface, if the triangle waveform shown in Figure 14-4 (A) is applied to the gold film then the output of the phase detector will vary parabolically as shown in Figure 14.4 (B) (we assume the scan type is set to C-Phase).

This is true in the ideal case, but in reality it is likely that there will be a built-in DC voltage difference between the probe and the gold surface due to the work-function difference between the two metals— the gold film and the metal coating on the cantilever. (More simply put, there will always be a voltage difference between any two dissimilar metals). The effect of this DC offset voltage is equivalent to shifting the triangle waveform in (A) up or down. If this shift is small compared to the amplitude of the triangle wave then the ideal waveform in (B) will change to something similar to (C). If the shift is larger than the amplitude of the triangle wave then the detector output will look similar to (D).

The work function voltage offset can be compensated for by adding an equivalent DC voltage to the waveform produced by the function generator. As the scan proceeds, observe the waveform in the section view panel of the **Realtime** window and slowly vary the offset voltage control. You should be able to observe the shape of the section line trace go through the transformations shown in Figure 14-4 (B) , (C) and (D).

Figure 14-4   The triangle voltage shown in (A) is applied to the gold film. If there is no DC voltage difference between the gold film and the probe then the parabolic waveform shown in (B) will be detected in the EFM scan. If there is a DC voltage difference in addition to the triangle AC voltage then the detected signals will be altered as in (C) or (D), depending on the size of the DC difference.

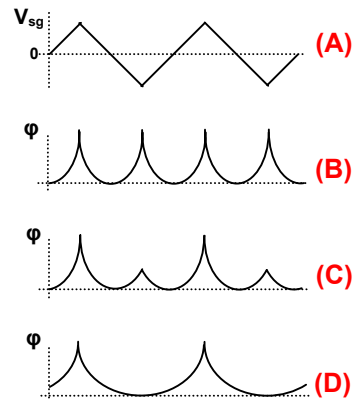Figure 14-5 shows section-lines taken through a simulated EFM scan image as described above. The scan rate was 0.5 Hz and the scan type was C-Phase. In the upper graph the voltage generator was set to 3 volts peak, with a DC offset of 1.5 volts. In the lower image the amplitude of the triangle wave was reduced to 0.8 volts peak.
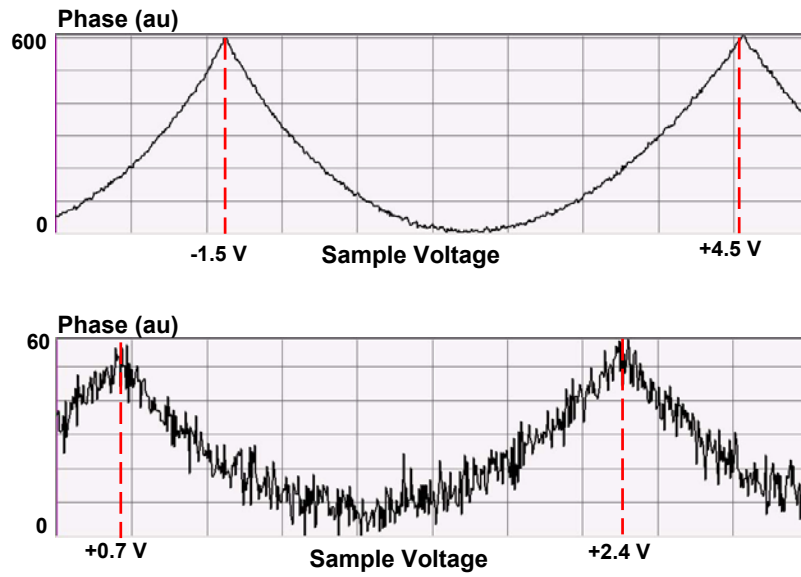
Figure 14-5 Cross-sections of sample scans performed with the EFM sample simulator.

Appendix A   Troubleshooting

Diagonal lines in image.

Mechanical vibration, acoustic noise, or air currents could be the cause.

- Remove any equipment with a fan, such as the EIU or computer, from the table.
- Use a vibration isolation system, such as foam rubber or an air table.
- Make sure the microscope stage is placed on a sturdy table or workbench.
- Build a cover to shield the microscope stage against acoustic noise and/or air currents.

Poor resolution in the image.

The probe tip could be damaged or dull, the feedback loop may be responding too slowly, or the Setpoint is too great.

- Replace the probe.
- Re-optimize the Z feedback loop.
- Disengage the tip, realign the laser optics, and re-engage the probe with the normal *Setpoint* value for the selected mode of operation.

Low cantilever resonance amplitude.

The Q of the cantilever is low due to damage. The acoustic coupling between the probe holder and the cross may be poor.

- While observing the resonance in the **Wave Configuration** screen slowly move the tilt lever up or down. When the coupling between the probe holder and the cross improves the resonance peak will jump up. It will be necessary to realign the laser beam onto the back of the cantilever after moving the tilt lever.

- Slide the cantilever in the probe holder slot slightly to the right or the left and then realign the laser optics. Sometimes the cantilever will resonate much better when the cross is not at the center of the probe holder.

- Make sure the slot in the probe holder is clean. If necessary, clean the slot with alcohol and a cotton swab. Do not use acetone or other strong solvents.

AutoEngage does not work.

Caveat... AutoEngage will not work with every cantilever placed in the probe holder, and there are situations in which the *Standard Engage* method must be used with a particular cantilever.

AutoEngage failure modes:

o *Error Message-- "Invalid AutoEngage cantilever parameter settings. Check selection."*
Every cantilever type has a unique vibration resonance frequency and signature amplitude change. For this reason the user must specify the type of cantilever installed in the probe holder before initiating the Auto Engage process. The drop-down list next to the Auto check box lists the standard cantilever types available from Ambios. Make the appropriate selection before pressing the AutoEngage button.

o *Error Message-- "Insufficient signal amplitude for AutoEngage. Use standard Engage method."*
The system has searched for a resonance in the +/-30kHz range of the nominal resonance frequency, and either has not found a resonance, or the resonance found has an amplitude which is too small. Solutions:

- For intermittent contact mode cantilevers, verify that the actual resonance set at the Wave Configuration window falls within the +/-30kHz search range as defined in the Advanced Scan Parameters window. It may be necessary to change the nominal resonance frequency setting.
- Reseat the cantilever in the probe holder to get a better resonance. Do this by sliding the cantilever laterally, or moving the tilt lever up and down. Cleaning the probe holder slot with alcohol may help.
- Change the cantilever.
- Use the standard engage method.

o *Error Message-- "Insufficient signal reliability for AutoEngage. Use standard Engage method."*
The system has searched for a resonance, found one, but the system finds that the amplitude does not remain steady in time. The only solution is to change the cantilever, or switch to the standard engage method.

o *The scan head moves down quickly at first, but switches to the 'slow' mode with the probe far from the surface.*

This happens when the vibration amplitude falls below the damping tolerance point before the probe is near the surface. The tolerance settings can be viewed and changed at the **Advanced Scan Parameters** window. The damping tolerances are expressed in terms of a fractional change in amplitude. For example, if the tolerance setting is 0.06, and the amplitude of vibration is 100 nm, the 'fast' part of the *AutoEngage* process will end when the vibration amplitude falls below 94 nm. Solutions:

- Room vibrations and air currents can cause false amplitude signals. The stage should be covered (e.g. inside the AVIC).
- The tolerance level may be increased slightly. Do so with caution, however, because if the tolerance is too high the cantilever may touch the surface during AutoEngage and be damaged.
- Change the cantilever.
- Use the standard engage method.

o *At the end of the 'fast' movement of the head the error message "Approach started with the signal already past the set point value." appears.*
This message appears at the outset of the 'slow' phase of the engage process because the system finds that the probe is already touching the surface. Solutions:

- Lower the damping tolerance at the **Advanced Scan Parameters** window.
- Check if it is possible that the probe has landed on a dust particle.

Alternating light and dark bands at the edges.

The feedback loop is responding too quickly. The surface is electrostatically charging and discharging.

- Re-optimize the Z feedback loop. (Reduce *Integral* and/or *Proportional* gains.)
- Discharge the surface by grounding it, or increasing the air humidity, or use an ion source.

The scanner does not have the expected Z range.

The sample may have too much tilt or the sample features may be too high and/or deep and exceed the maximum Z Range for the scanner you are using. Probe

motion which exceeds the scanner Z range will appear either as flat valleys or flat peaks in the image.

- Level the sample.
- Scan a smaller area of the sample.

System will not go into feedback or becomes extremely unstable.

The surface of the sample may be reflecting laser light into the detector system, the gain parameters may be too high, the laser optics may be misaligned, or the Setpoint may be incorrectly set.

- Withdraw the scanner, move to a different surface location, and restart the approach. If this doesn't work, try the following:
- Contact cantilevers-- raise the laser dot further above the center of the target pattern in the **Beam Align** window. Intermittent-contact cantilevers-- increase the damping percentage.
- Reduce the *Proportional* and *Integral* gains.
- Once the system is in feedback and a scan is underway, optimize the PID gains while the probe is moving.

Feedback control cannot be maintained.

The probe or probe holder may be defective or dirty. The laser and/or photodetector may be out of alignment. The mechanical path from the sample to the stage may be loose. The Z feedback loop settings may be incorrect.

- Replace the probe. Cracked segments in the cantilever may not be visible but will prevent the system from going into feedback.
- Clean the probe holder.
- Realign the laser optics.
- Check the mechanical path from the sample to the stage. The sample may not be rigidly held by the sample holder; the sample may be bowed and flex like a drum; the probe may not be firmly fixed in the probe holder; the attachment of the scanner to the dovetail plate may be loose.
- Re-optimize the Z feedback loop.

Control of the feedback loop cannot be maintained during scanning.

The cantilever may be cracked or otherwise damaged. The sample features may be too high or deep for the scanner's Z Range. The sample may have too much tilt.

- Replace the probe.

- Scan a smaller area of the sample.
- Level the sample.
- Contact cantilevers-- raise the laser dot further above the center of the target pattern in the **Beam Align** window. Intermittent-contact cantilevers-- increase the damping percentage.

The image shows excessive drift.

Thermal equilibrium may not have yet been established, or there may be strong air currents flowing by the scanning head.

- Allow sufficient time for thermal equilibrium to be established.
- Turn off any room air conditioner or heater. Place the dust cover or other enclosure around the microscope stage.

Streaks appear in the image.

The probe tip may have picked up a particle of dirt.

- Replace the probe.
- Continue scanning different areas of the surface. The dirt may eventually detach from the tip.
- The sample itself may be dirty. Clean the sample.

The laser spot cannot be located in the camera view.

- Check if the laser spot appears on a sheet of white paper placed on the sample stage under the scanner. Try locating the laser spot on the sheet of paper by centering the X laser position knob and moving the Y position knob across its full range. If the laser spot still cannot be found then the system is grossly misaligned. Call Ambios Technical Support for guidance in bringing the system back into alignment.

Little or no beam intensity.

The cantilever may be damaged. The coating on the back of the cantilever may have corroded.   The laser control knobs on the scanning head may have been moved to extreme positions.

- Replace the probe.
- Realign the laser beam on the cantilever to locate a more reflective spot.
- Adjust the probe tilt lever.
- Check that the alignment mirror position knob is rotated fully clockwise.

- Rotate the X laser position knob slightly in both directions while looking at the laser spot on the frosted glass window. By watching the spot intensity you should be able to see the laser slide on and off the cantilever as the X knob is turned. The laser is centered on the cantilever when the spot in the glass window is at maximum brightness.

Beam intensity dropped to zero with the probe away from the sample.

You may have accidentally flipped the alignment mirror knob on the front of the scanner to the counter-clockwise position, blocking the laser beam.

- Check the position of the mirror adjust knob. It should be rotated fully clockwise.

Screeching noise occurs along with dramatic oscillations.

Engagement has occurred with the probe tip on a steep or otherwise irregular feature of the sample. One or more of the PID gains is much too high.

- Move the probe tip to a flatter area of the sample.
- Reduce all PID gain settings.

Scanner Z voltage drifts radically during feedback.

The sample is statically charging. Stray laser light is reflecting off of a mirror-like sample into the laser optic. The probe has landed on a dust particle on the surface. The probe cantilever is cracked. The z feedback signal is too low.

- Realign the laser spot on the back of the cantilever.
- Discharge the surface by increasing the humidity.
- Move to a different area of the sample.
- Replace the probe.
- Readjust the laser optics and the Setpoint to get a larger feedback signal.

Samples known to have sharp edges give images with rounded edges.

The scanning speed may be too fast to allow good definition of edge features, and/or the Z feedback gain parameters may be too low.

- Reduce the scan speed to 1 Hz or less.

- Increase the *Proportional* and *Integral* gain settings until just below the point where the system becomes unstable.
- Switch to the *Broadband* or *BB Wavemode* imaging mode.

Unpredictable or strange program behavior.

The computer may have crashed, or the Windows operating system has memory usage failures. There may be a power supply failure in the electronics.

- Shut down the program and reboot the computer.
- Check the power supply LED indicators on the back panel of the EIU.

Appendix B   SPM.INI File Definitions

The spm.ini file contains software flags, calibration constants, and various instrument settings for the microscope. Some of the entries are under software control; other can only be changed by opening the file with a text editor and manually typing the value.   The entries are not case sensitive, but they must be under the correct section labels, e.g. [SPM System].

Keyword/Section	Description	Default Value	Program Controlled
[SPM System]			
Model	[Integer] SPM model: Nomad=1,Q-250=3, Q-400= 4, USPM = 5, etc.		Yes
Stage	[0,1,2] Motorized translation stage: 0=none, 1= Q250 Optical MiniStage, 2 = Q250 HardStop MiniStage, 3= Q400 rotary stage.		Yes
LithographyInstalled	[True/False] Flag indicating if the Lithography option has been added to the system.		Yes
MetrologyInstalled	[True/False] Flag indicating if the system has the Metrology hardware.		Yes
CDanalyisisIntalled	[True/False] Flag indicating if the CD analysis software should be made available to operator.		Yes
Owner	[Text] The name of the institution owning the SPM.		Yes
SerialNr	Coded number for your version of the software.		No
[Stepper Motors]			
Xaxis	[0-4] The stepper driver number that is connected to the X-axis stepper-motor.	4	No
YAxis	[0-4] The stepper driver number that is connected to the Y-axis stepper-motor.	3	No
Zaxis	[0-4] The stepper driver number that is connected to the Z-axis stepper-motor.	2	No
Motory$n$FastStep	[n=0-4, value=integer] High speed (maximum) slew rate in PPS. If the setting is too high the stepper motor will stall.	2000	No
Motor$n$SlowStep	[n=0-4, value=integer] Slow speed slew rate. Motor is guaranteed to go from dead stop to this speed, or reverse directions without missing any steps.	140	No
Motor$n$InitialStep	[n=0-4, value=integer] Starting step rate for high speed slew rate, or the initial step rate at the start of the motor ramp up.	250	No
Motor$n$RampUp	[n=0-4, value=integer] Amount of time to ramp up to high speed measured in milliseconds.	2000	No
Motor$n$RampDown	[n=0-4, value=integer] Amount of time to ramp down to a dead stop from high speed.	800	No

Keyword/Section	Description	Default Value	Program Controlled
Motory*n*Calibration	[n=0-4, value=real] Linear Motion: Millimeters of movement per step of the motor. Rotary Motion: Degrees of movement per step of the motor.	X,Y 0.000396875 Z 0.000529166	No
[Graphics]			
Graphics Editor	The hard drive file location of the program used to work with bitmap images created by the ScanAtomic software.		Yes
UseDIB	Flag used by C subroutine dll_zcolor2 located in the render32.dll. (may not be active)	0	No
[General]			
Light1	[0-32767] The startup setting of the internal illumination when the on-axis camera is turned on. It records the last setting when the user turns the camera off.	17000	Yes
Light1Step	[0-32767] The speed with which the illumination is changed.	17000	No
Light1Minimum	[0-32767] The minimum setting for the illumination.	-7000	No
idStageElectronics	[0,1,2] Valid entries: original stage board…0, separate stage/wave boards…1, new stage board…2.	Hardware Detected	No
[Video]			
VideoType	[0,1,4] The WinTV video card model.		Yes
[Advance Scan]			
PreScanTime	[integer] Number of seconds to scan the first line of a scan to remove any final hysteresis. Can be increased to eliminate distortion at top of image.	5	Yes
InterScanTime	[integer] Number of seconds to scan the first line of a subsequent scan to remove any slow scan direction hysteresis, and to allow the computer to finish the prior scan before going on with the next.	5	Yes
HVHigh	[integer] The 'Hills and Valleys, High Cutoff' advance scan parameters setting.	11000	Yes
HVLow	[integer] The 'Hills and Valleys, Low Cutoff' advance scan parameters setting.	-11000	Yes
SumTolerance	[integer] The allowed change in the laser sum signal during a tip approach, beyond which the DSP will consider that the laser is no longer on the photo-diode and aborts the approach.	800	Yes
BroadbandErrorFactor	[real] Broadband calibration factor: microns of cantilever movement per volt change in photodetector T-B signal		Yes
FeedbackInterlock	[True/False] Not used.		
ConnectADC3toExtSig	[[True/False] Set to True the software should switch the ADC3 input to one of the back panel BNC connectors in the RCP option.	False	Yes
OverscanTime	[integer] Microseconds extra time added to each sweep to allow for the delay of the scan waveforms caused by the Bessel filtering.	1000	No

Keyword/Section	Description	Default Value	Program Controlled
AutoEngageCantilever*n*	[n=0-9] The various cantilevers which can be used with the AutoEngage feature. Column entries: Type, Resonance, Tolerance.		Yes
nA_CurrentSensor Range	[real] The calibration constant for any current sensor attached to the system. Value gives maximum current reading of the amplifier, in nA.	100	Yes
nA_CurrentSensor Offset	[real] Adjust the zero level of the current sensor reading.	0	Yes
vBiasVoltageOffset	[real] Adjust the zero level of the bias voltage output.	0	Yes
auEIUSetpointOffset	[real] Adjusts the zero level of the setpoint DAC.	0	Yes
[Head *n*]	**[n=0-18] Each scanner type is assigned an integer identifier.**		
CeramicZExpansion	[Real Number] Full range travel of the scanner along the z-axis, in microns.		Yes
SCC()	Standard Mode Calibration Constants Row1: Angle, rate, size, CeramicXexpansion, ra0, ra1, ra2, ra3 Row 2: Angle, rate, size, CeramicYexpansion, da0, da1, da2, da3		No
CC()	Metrology Mode Calibration Constants		No