

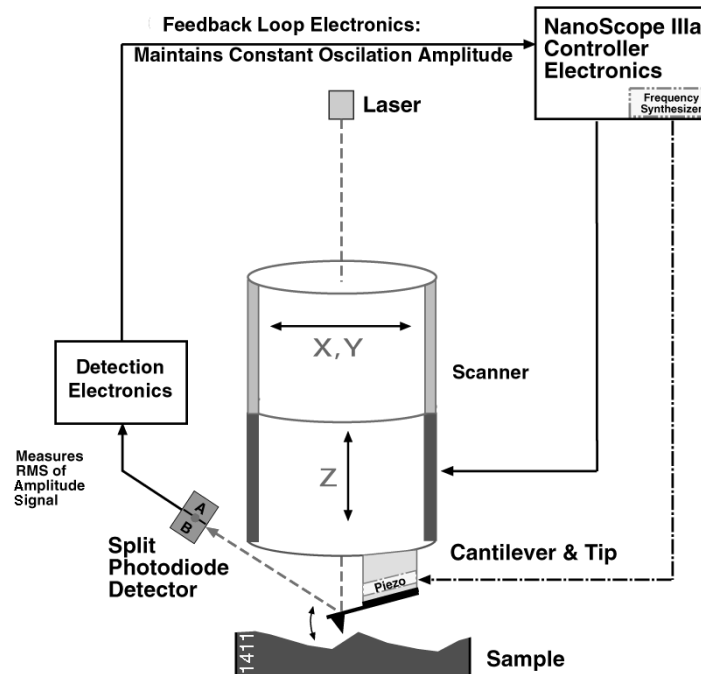
Atomic Force Microscope (Veeco-3100)

User Instruction

Revised from Veeco SPM Training Notebook
004-130-100 (cleanroom)

TappingMode AFM

Feedback Loop Electronics



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

The cantilever is oscillated at or slightly below its resonance frequency with an amplitude ranging typically from 20nm to 100nm. The tip lightly “taps” on the sample surface during scanning, contacting the surface at the bottom of its swing.

The feedback loop maintains a constant oscillation amplitude by maintaining a constant RMS of the oscillation signal acquired by the split photodiode detector.

The vertical position of the scanner at each (x,y) data point in order to maintain a constant “setpoint” amplitude is stored by the computer to form the topographic image of the sample surface. By maintaining a constant oscillation amplitude, a constant tip-sample interaction is maintained during imaging.

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

When imaging in air, the typical amplitude of the oscillation allows the tip to contact the surface through the adsorbed fluid layer without getting stuck.

TappingMode AFM

Advantages:

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

Disadvantages:

- Slightly slower scan speed than contact mode AFM.

Abbreviated Instructions for the MultiMode AFM

Mode of Operation

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

Mount Probe

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

Select Scanner

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

Mount Sample

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

Place Optical Head on Scanner

1. Raise all three coarse-adjust screws on the scanner so that there is enough clearance between the tip and sample when the optical head is placed on the scanner. If using a JV or EV scanner, you only need to raise the motor screws.
2. Place the optical head on the scanner, still checking that the tip doesn’t touch the sample. Attach the springs to the optical head.
3. Plug in the connector from the optical head to the base.
4. Bring the tip close to the sample keeping the head level by lowering all three coarse-adjust screws.

Align Laser and Tip-Sample Approach (2 Methods)

1. Magnifier Method for Aligning Laser and Tip-Sample:
 - a. Focus on the side-view of the cantilever with the magnifier. If you are having trouble finding the cantilever, try searching for the red light of the laser and focus on that. Use the “paper method” described below for positioning the laser spot on the cantilever:
 - b. Move laser until it is at the front edge of the cantilever substrate. Move laser just off the front edge and move laterally along the edge looking for the reflection of the laser spot from the cantilever onto the paper. Center the laser on the cantilever at its end.
 - c. Keeping the optical head level, focus on the laser reflection of the cantilever and sample to bring the cantilever close to the sample. Use screws at the base of the optical head (front and left) to position the cantilever over the area of interest on the sample.
2. Optical Viewing Microscope Method for Aligning Laser and Tip-Sample
 - a. Place the microscope on the optical microscope positioning stage.
 - b. Turn on the monitor and the light source.
 - c. Focus on the cantilever (zoom out, if using optical microscope equipped with zoom).

Use the base screws on the stage of the optical microscope to center the cantilever in the field of view. Lower the focus of the optical microscope to the sample surface. You will still see an out of focus “shadow” of the cantilever in the field of view. Keep the optical head level while lowering the cantilever until it is almost in the same plane of focus -keep the shadow of the cantilever in the field of view at all times. It is helpful to go up and check the focus on the cantilever from time to time to see how close it is to the sample surface.

d. Once the cantilever is close to the sample surface, adjust the laser so that it is positioned over the cantilever. Use the two screws at the top of the optical head to move the red laser spot onto the cantilever. You may need to change the field of view of the optical microscope initially to find the laser spot.

e. Next use the “paper method” (as described under Magnifier Method) to fine position the laser spot on the cantilever. Use the two screws at the base of the optical head (front and left) to position the cantilever over the area of interest on the sample. As the stepper motor moves during engagement, the cantilever will shift towards the back of the microscope (unless you are using a Vertical Engage Scanner). This means that you should place the cantilever in front of (below on the monitor) the area where you want to engage.

Adjust Photodiode Signal

Note where the laser reflection enters the photodiode cavity. If necessary, adjust the mirror (lever on back of optical head) to center the laser reflection into the photodiode cavity. Leave the mirror at an angle such that the **SUM** signal (circular meter in bottom LCD) is maximized.

- Tapping: Adjust the **Vertical Difference** value (bottom LCD) to zero using the screw on the top left side of the optical head.
- Contact: Set the **Contact AFM Output Signal** value (Vertical Difference, top LCD) to -2.0V using the screw on the top left side of the optical head. Adjust **Horizontal Difference** value (bottom LCD) to zero using the screw on the back, left side of the optical head.

Cantilever Tune (TappingMode Only)

Select **View > Cantilever Tune** (or select the **Cantilever Tune** icon). For Auto Tune Controls, make sure **Start Frequency** is at 100 kHz and **End Frequency** is at 500 kHz. **Target Amplitude** should be 2-3 volts. Click on **Auto Tune**. A “Tuning...” sign should appear and then disappear once Auto Tune is done. When finished, quit the Cantilever Tune menu.

Set Initial Scan Parameters

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

- Tapping: In the **Feedback Controls** panel, set **Integral Gain** to 0.4, **Proportional Gain** to 0.6, and **Scan Rate** to 2 Hz.
- Contact: In the **Feedback Controls** panel, set the **Setpoint** is to 0 volts, the **Integral Gain** to 2.0, the **Proportional Gain** to 3.0, and the **Scan Rate** to 2 Hz.

Engage

Select **Motor > Engage** (or select the **Engage** icon).

Adjust Scan Parameters

Tapping

a. Select **View > Scope Mode** (or click on the **Scope Mode** icon). Check to see if the Trace and Retrace lines are tracking each other well (i.e. look similar). If they are tracking, the lines should look the same, but they will not necessarily overlap each other, either horizontally or vertically.

b. If they are tracking well, then your tip is scanning on the sample surface. You may want to try keeping a minimum force between the tip and sample by clicking on **Setpoint** and **Realtime** using the right arrow key to increase the Setpoint value gradually, until the tip lifts off the surface and the Trace and Retrace lines no longer track each other. Then decrease the Setpoint with the left arrow key until the Trace and Retrace follow each other again. To make sure that the tip will continue to track the surface, it is best to decrease the Setpoint one or two arrow clicks more with the left arrow key. Then select

View > Image Mode (or click on the **Image Mode** icon) to view the image. 

c. If they are not tracking well, adjust the **Scan Rate**, **Gains** and/or **Setpoint** to improve the tracking. If Trace and Retrace look completely different, you may need to decrease the Setpoint one or two clicks with the left arrow key until they start having common features in both scan directions. Then, reduce **Scan Rate** to the lowest speed with which you feel comfortable. For scan sizes of 1-3 μm try scanning at 2Hz; for 5-10 μm , try 1Hz; and for large scans, try 1.0-0.5Hz. Next, try increasing the **Integral Gain** using the right arrow key. As you increase the Integral Gain, increase the **Proportional Gain** as well (Proportional Gain can usually be 30-100% more than Integral Gain). The tracking should improve as the gains increase, although you will reach a value beyond which the noise will increase as the feedback loop starts to oscillate. If this happens, reduce the gains until the noise goes away. If Trace and Retrace still do not track satisfactorily, the last thing to try is to reduce the **Setpoint**. Once the tip is tracking the surface, select

View > Image Mode (or click on the **Image Mode** icon) to view the image. 

Set Desired Scan Size, Scan Angle, and Offsets

Once the scan parameters are optimized, scan size and other features may be adjusted for capturing images for analysis. When changing the scan size value, keep in mind that the scan rate will need to be lowered for larger scan sizes.

Realtime Operation

The Realtime parameters are located in the control panels which are available in the Panels pull down menu. The main control panels for topographic imaging are “Scan controls,” “Feedback Controls,” “Other Controls,” and “Channel 1.”

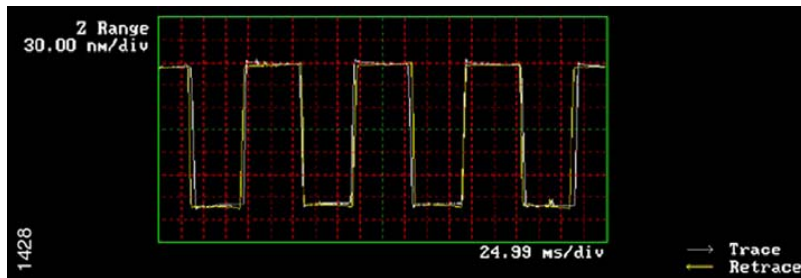
There are three primary feedback parameters that need adjusting every time you engage the microscope to capture an image in TappingMode AFM or Contact Mode AFM: **Setpoint**, **Integral Gain**, and **Scan Rate**.

To demonstrate how these parameters affect the image, examples of TappingMode operation on the 10 μm x 10 μm pitch calibration grating will be shown. These examples were acquired by viewing the **Scope Mode** (in the **View** menu), which displays a two-dimensional view (X vs. Z) of the Trace (left-to-right) and Retrace (right-to-left) scan lines being acquired in Realtime.

Scope Mode may be used to diagnose how well the tip is tracking the surface. If the feedback parameters are adjusted optimally, the trace and retrace scan lines should look very similar, but may not look completely identical.

An optimized scope trace of a 40 μm TappingMode scan across the pits of the grating is shown below.

Scope Trace with Optimized Realtime Parameters



Setpoint

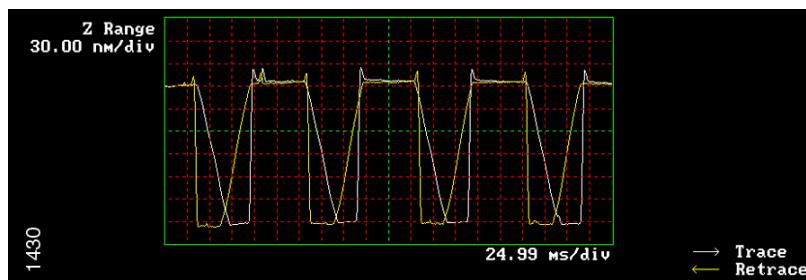
The Setpoint parameter tells the feedback loop what amplitude (TappingMode) or deflection (Contact Mode) to maintain during scanning.

Set this parameter so that the smallest amount of force is applied during scanning while still maintaining a stable engagement on the surface.

If the setpoint is too close to the free air amplitude (TappingMode) or free air deflection (Contact Mode) of the cantilever, the tip will not trace the topography properly.

This problem will be more pronounced on downward slopes with respect to the scan direction. An example of this is shown below.

Scope Trace Demonstrating the Effect of the Setpoint Being Adjusted Too Close to the Free Air Amplitude During TappingMode AFM



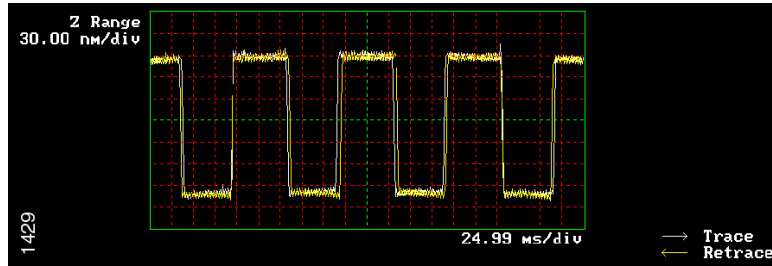
Notice that the tip tracks the surface up the sidewall properly but not down the sidewall with respect to the scan direction. This occurs on opposite sides of features for the Trace and Retrace scan directions. This problem can be remedied by decreasing the Setpoint in TappingMode, or increasing the Setpoint in Contact Mode.

Integral Gain

The Integral Gain controls the amount of the integrated error signal used in the feedback calculation. The higher this parameter is set, the better the tip will track the sample topography.

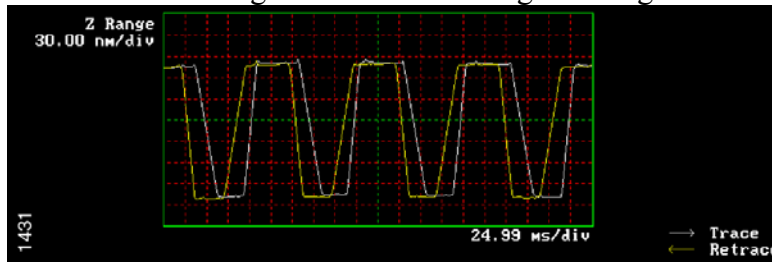
However, if the integral gain is set too high, noise due to feedback oscillation will be introduced into the scan, as shown below.

Scope Trace Demonstrating the High Frequency Noise that Occurs when the Integral Gain is Set Too High



Setting the integral gain too low may result in the tip not tracking the surface properly, as shown below.

Scope Trace Demonstrating the Effect of Setting the Integral Gain Too Low



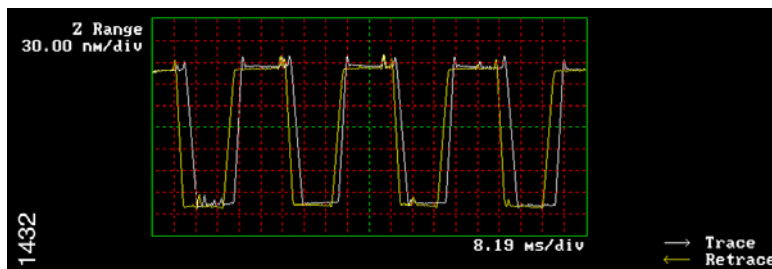
Set the Integral Gain as high as possible by increasing the gain until noise is seen, then reduce the gain just lower than the value where the noise disappears.

Scan Rate

The Scan Rate is the number of trace and retrace scan lines performed per second (Hz).

- For example, with a scan rate set to 1Hz, the tip will scan forward and back (trace and retrace) in 1 second. Set this value so that the feedback loop has time to respond to changes in the sample topography. Setting the scan rate too high will result in poor tracking of the surface, as shown below.

Scope Trace Demonstrating the Effect of Setting the Scan Rate Too High



The actual *tip speed* or of the tip depends on two parameters: **Scan Rate** and **Scan Size**. Since the Scan Rate units are lines per second (Hz), increasing the Scan Size without changing the Scan Rate actually increases the scan velocity of the tip.

- For example, if the Scan Rate is 1Hz and the Scan Size is 1 μ m, the scan velocity is 2 μ m/sec (since it performs the trace and retrace scans in 1 sec). By increasing the Scan Size to 100 μ m, the scan velocity increases to 200 μ m/sec if the Scan Rate remains 1Hz.

The Scan Rate setting will greatly depend on the scan size and the height of the features being imaged. In general, the taller the features and/or the larger the scan size, the slower the scan rate. Typical Scan Rate settings are 0.5 to 2.0Hz for TappingMode and 1 to 4Hz for Contact Mode.

Other Important Parameters

Scan Size: Adjusts the size of the X,Y scan area

X Offset, Y Offset: Translates the scan area in X and Y directions without changing scan size

Note: The **Zoom** and **Offset** commands found on the display monitor may also be used to change the scan size and X and Y offsets.

Scan Angle: Controls the angle of the fast scan direction of the scanner with respect to the X axis

Samples/line: Determines the number of data points or pixels in X and Y (128, 256, or 512)

Slow Scan Axis: Enables and Disables movement of the scanner in the direction of the slow scan axis. (Y direction at 0° Scan Angle)

Proportional Gain: Controls the amount of proportional error signal used in feedback calculation
Typically set 30 to 100% higher than the Integral Gain

Data Type: Selects the signal viewed on the display monitor - this parameter is set to Height for topographical measurements

Line Direction: Selects the direction of the fast scan during data collection: Trace (left to right) or Retrace (right to left).

Microscope Mode: Sets mode of operation to Tapping, Contact, or Force Mod

Data Scale: Controls the vertical scale of the full height of the display and color bar. This parameter does not effect the Realtime operation of the microscope, only the expansion and contraction of the color scale.

Z-limit: Allows the 16 bits of the digital-to-analog converters to be applied to a smaller vertical range. This has the effect of increasing the vertical sampling resolution and should be used for imaging very smooth surfaces (<5nm RMS) or performing atomic resolution.

- For example, a Dimension or J MultiMode scanner may have a full vertical movement of 6µm over 440V. By reducing the Z-limit to 55V, the full vertical movement of the scanner is reduced to 0.75µm over the same 16 bits. Therefore, the vertical sampling size becomes smaller, which increases the Z resolution.

Note: Do not reduce the Z-limit if there is a chance that a feature will exceed the reduced vertical range

- **Offset:** Does not remove the tilt from the scan lines, but does calculate and remove the Z offset from each scan line individually. This setting is useful if you need to view the tilt in the sample in Realtime

- **None:** Does not remove the tilt or the Z offset from the image. This setting is not generally recommended.

Offline Planefit: Controls whether the images are saved with or without tilt correction. There are two primary choices:

- **Full:** Applies a first order planefit (explained in Offline Analysis) to the image in X and Y and removes the Z offset before the image is saved.

- **Offset:** Saves the image without removing the tilt with a first order planefit, but does remove the Z offset.

- **None:** Saves the image without removing the tilt or the Z offset.

The Full setting is commonly used for everyday imaging. However, the Offset setting can be useful when a first order plane fit would negatively affect the measurement of interest. This can be demonstrated in the example below. If the measurement of interest is the height of the step, then setting the Offline Plane fit to Full will result in the tilting of the data. However, if the Offline Plane fit is set to Offset, then a plane fit is not applied and the step orientation is not altered. If the Full setting were applied, a first order plane fit could be applied in the Offline software to reorient the features without negatively affecting the measurement.

Once images are captured during Realtime operation, they are viewed and measured with the Offline commands. Here we will touch on a few of the basic operations and functions.

- Each captured image is immediately stored in the Capture directory in Offline.
- Access to different disk drives is available at the top of the file directory panel. The !:\ drive is the Capture directory, the A:\ drive is a floppy drive, the C:\, D:\ and E:\ are usually the computer hard drives. If the system has additional drives, they are set through Z:\.
- The data management commands are found in the **File** pull down menu. This menu contains the **Move**, **Copy**, **Delete**, **Rename**, and **Create Directory** commands for transferring data between directories.
- The **Browse** command, also under the **File** menu, places up to twenty-four images on the screen with a variety of commands available at the top of the **Browse** screen. There is also a **File** menu within the **Browse** commands which provides the ability to specify in any order which images to **Move**, **Copy**, **Delete**, or **Rename**. Browse also provides the ability to view two images side-by-side by using **Dual**, or to view up to six images side-by-side using **Multi**.

Image Analysis

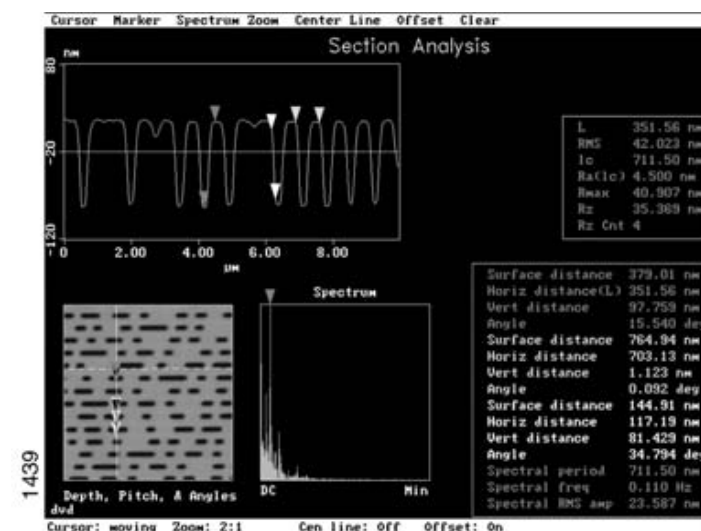
A wide variety of analysis functions are available in the **Analyze** menu in the Offline for measuring captured SPM images.

Each of the analysis routines is useful and described in detail in the Command Reference Manual. Some of the most commonly used analysis routines are briefly described below.

Section

Depth, height, width, and angular measurements can be easily made with Section. For an example, see the following figure.

Cross-Sectional Measurement on a DVD Replica Disk



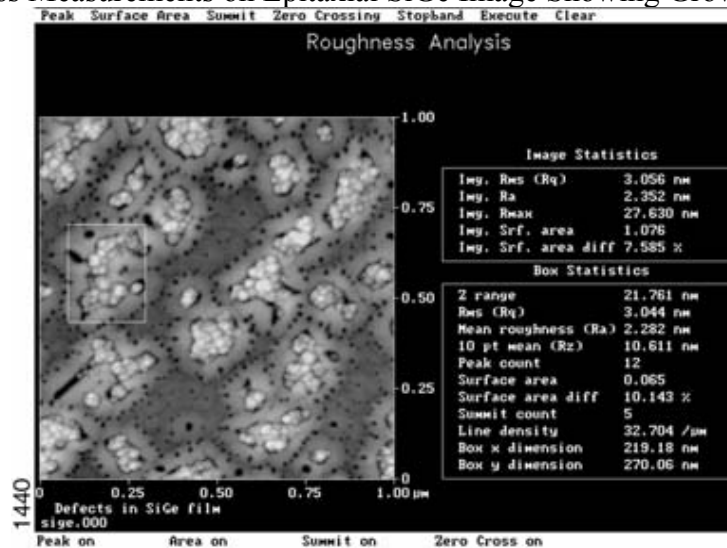
A cross-sectional line can be drawn across any part of the image, and the vertical profile along that line is displayed. The Cursor menu located at the top of the Display monitor provides the ability to draw a fixed, moving, or averaged cross section.

Up to three pairs of cursors may be placed on the line section at any point to make horizontal, vertical, and angular measurements. These measurements are reported in the box at the lower right of the screen. Cursors may be added or deleted with the Marker menu located at the top of the Display monitor. The measurements are displayed in the same colors as the corresponding markers. The power spectrum (fast Fourier transform (FFT)) along the cross section is displayed in the lower center window. The cursor may be used to determine the predominate periodicities along the cross section by placing it at peaks in the spectrum. The roughness measurements of the portion of the cross section between the two colored cursors are displayed in the window in the upper right.

Roughness

Roughness measurements can be performed over an entire image or a selected portion of the image with **Roughness**.

Roughness Measurements on Epitaxial SiGe Image Showing Growth Defects



There are a wide variety of measurements made in Roughness. The roughness parameters which are displayed are chosen under the Screen Layout menu.

The measurements made on the entire image are displayed under “Image Statistics.” Roughness measurements of a specific area may be determined by using the cursor to draw a box on the image.

After selecting “Execute,” the measurements within the selected area are displayed under “Box Statistics.”

The most common measurements are the following:

1. **RMS (Rq)**: The Root Mean Square (RMS) Roughness is the standard deviation of the Z values within a given area.
 - **Zave** is the average Z value within the given area, Z_i is the current Z value, and N is the number of points within a given area.
 - **Ra**: The Mean Roughness (Ra) represents the arithmetic average of the deviations from the center plane.
 - **Zcp** is the Z value of the center plane, and Z_i is the current Z value, and N is the number of points within a given area.

Note: The above equations for RMS and Ra are presented for ease in understanding.

2. **Rmax**: The difference in height between the highest and lowest points on the surface relative to the Mean Plane
3. **Surface Area**: The three-dimensional area of a given region. This value is the sum of the area of all of the triangles formed by three adjacent data points.
4. **Surface Area diff**: The percentage increase of the three dimensional surface area over the two dimensional surface area.

Bearing

Bearing ratio determination and depth histogram measurements are possible with Bearing.

Bearing provides a method to analyze how much of the surface lies below or above a given height.

The “bearing ratio” of the surface is the percentage of the surface at a specific depth with respect to the entire area analyzed. (See manual for further description)

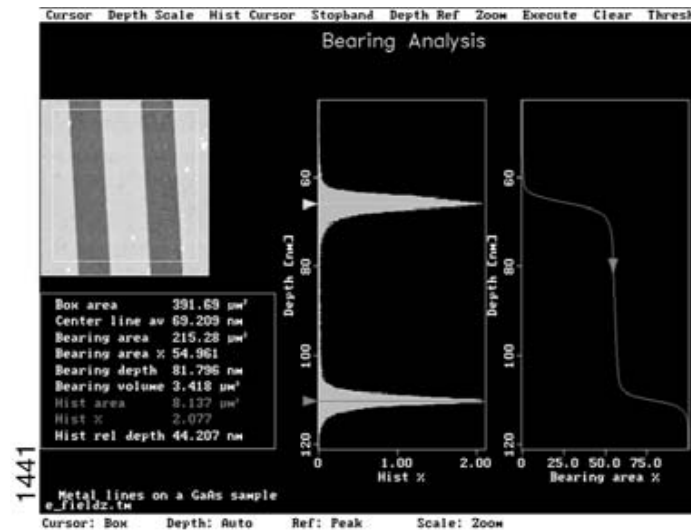
The depth histogram plots depth versus percentage of occurrence of data at different depths.

By enabling the Histogram Cursor (top menu, display screen), two cursors are available on the histogram to make relative depth measurements.

Area depth measurements can be made by placing the two cursors at peaks representing different feature heights. The area depth measurement can be made by determining the relative depth between the two cursors.

- Planefit and/or Flatten may need to be performed before making this measurement. This will produce sharper peaks in the depth histogram. The **Depth** feature may be used to make automated depth histogram measurements over many images. (See manual for details)

Area Depth Measurement of GaAs Lines using the Bearing Histogram



Filters

There are a wide range of modification functions found in the Modify menu that may be applied to an image once it has been captured. These functions are explained in detail in the Command Reference Manual.

It should be kept in mind that by using any modification functions, the data is being changed which may or may not affect the measurements of interest. In general, it is good practice to modify the image as little as possible, and to understand how the applied function will affect the image and measurements.

Flatten may be used to remove image artifacts due to vertical (Z) scanner drift, image bow, skips, and anything else that may have resulted in a vertical offset between scan lines.

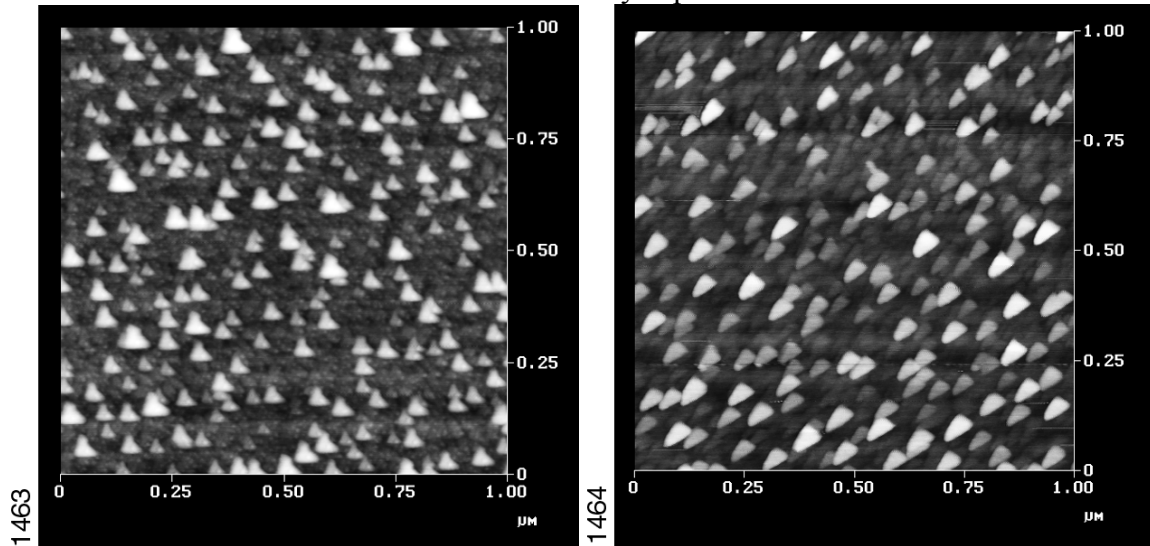
Flattening modifies the image on a **line-by-line** basis. It consists of removing the vertical offset between scan lines in the fast scan direction (X at 0° scan angle) by calculating a least-squares fit polynomial for a scan line, and subtracting the polynomial fit from the original scan line.

- This has the affect of making the average Z value of each scan line equal to 0V out of the +/- 220V z-range. Flattening can be performed by applying a 0th, 1st, 2nd, or 3rd order polynomial fit to each scan line.

Typical Image Artifacts

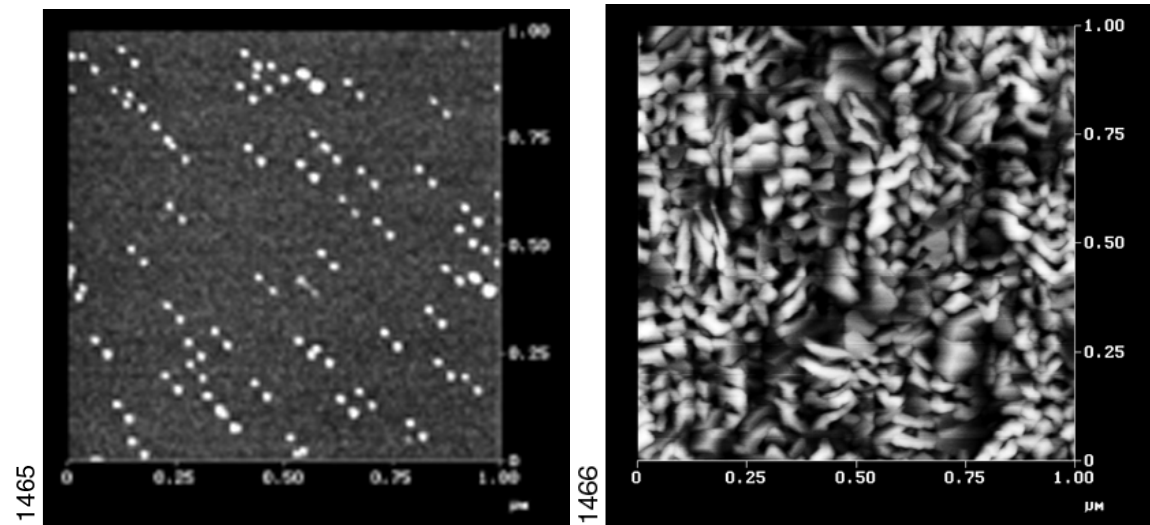
If the tip becomes worn or if debris attaches itself to the end of the tip, the features in the image may all have the same shape. What is really being imaged is the worn shape of the tip or the shape of the debris, not the morphology of the surface features.

Dull or Dirty Tip



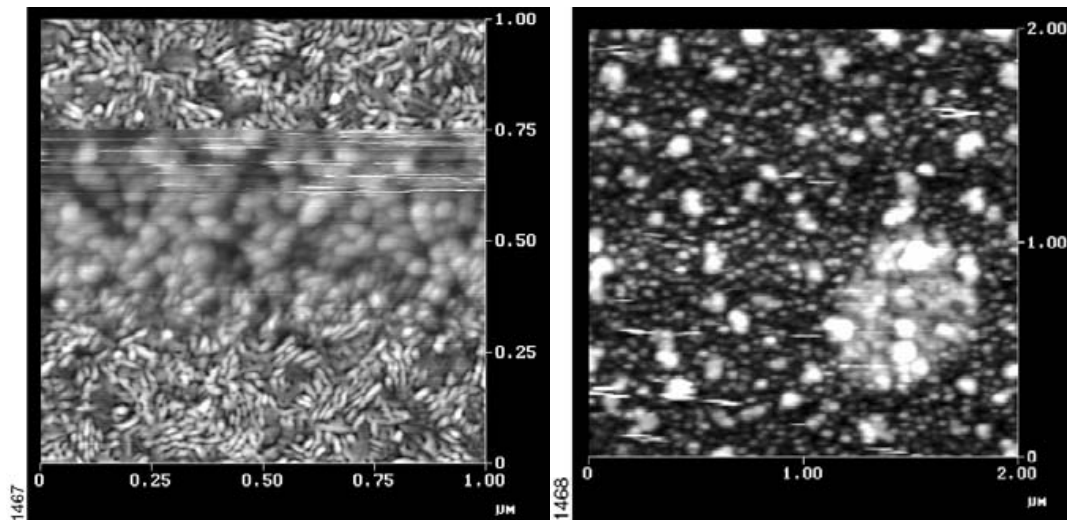
Double or multiple tip images are formed with a tip with two or more end points which contact the sample while imaging. The above images are examples.

Double or Multiple Tips



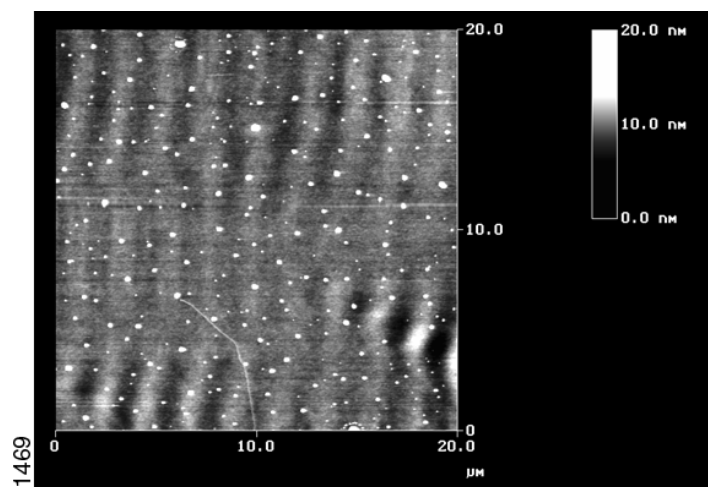
Loose debris on the sample surface can cause loss of image resolution and can produce streaking in the image. The image on the left is an example of the loss of resolution due to the build up of contamination on the tip when scanning from bottom-to-top. It can be seen how the small elongated features become represented as larger, rounded features until the debris detaches from the tip near the top of the scan. The image on the right is an example of skips and streaking caused by loose debris on the sample surface. Often, loose debris can be swept out of the image area after a few scans, making it possible to acquire a relatively clean image. Skips can also be removed from a captured image with the Erase Scan Lines function.

Contamination from Sample Surface

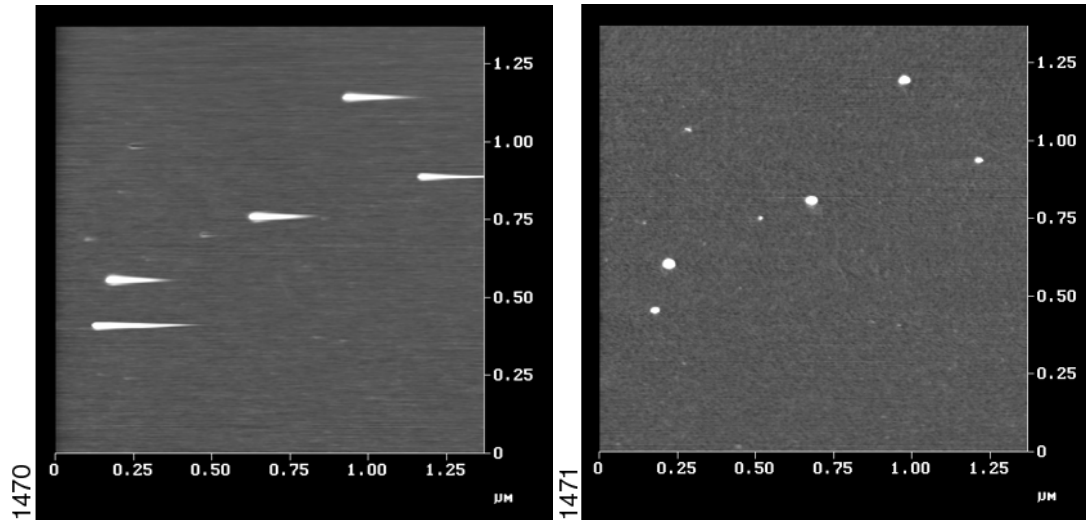


Interference between the incident and reflected light from the sample surface can produce a sinusoidal pattern on the image with a period typically ranging between 1.5-2.5µm. This artifact is most often seen in contact mode on highly reflective surfaces in force calibration plots and occasionally in TappingMode images. This artifact can usually be reduced or eliminated by adjusting the laser alignment so that more light reflects off the back of the cantilever and less light reflects off the sample surface, or by using a cantilever with a more reflective coating (MESP, TESPA).

Optical Interference

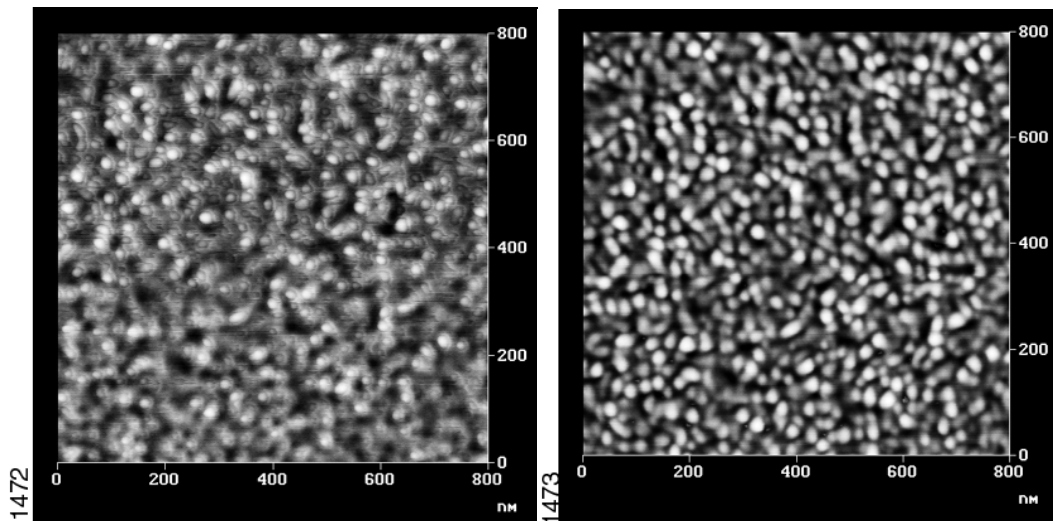


When the feedback parameters are not adjusted properly, the tip will not trace down the back side of the features in TappingMode. An example of this can be seen in the image on the left which was scanned from left-to-right (trace) producing “tails” on the colloidal gold spheres. The image on the right is the same area imaged with a lower setpoint voltage, increased gains, and slower scan rate.



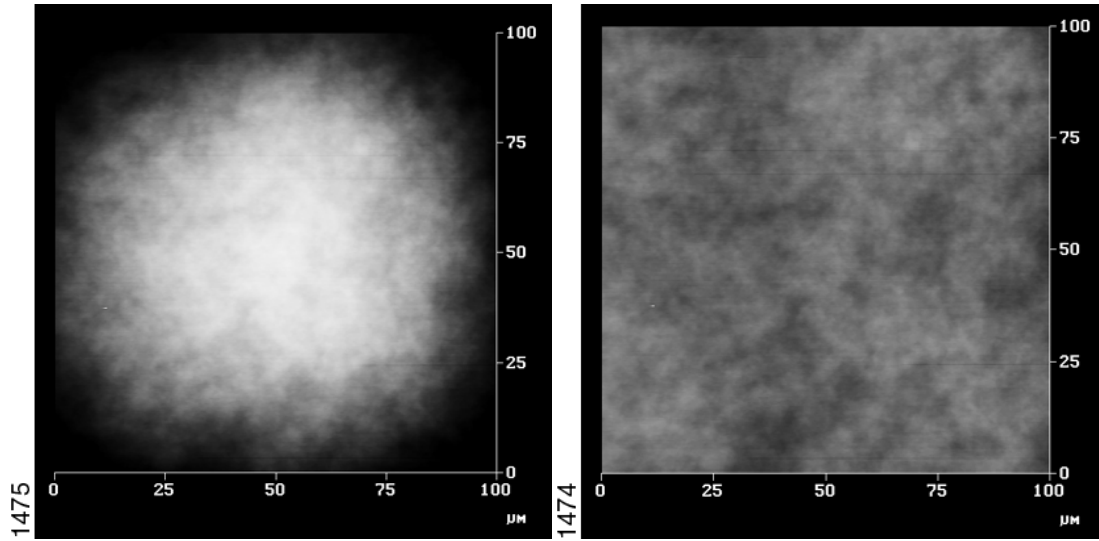
In TappingMode, when operating on the high frequency side of the resonance peak, rings may appear around raised features which may make them appear as if they are “surrounded by water.” An example of this can be seen in the image of the Ti grains on the left. Decreasing the Drive Frequency during imaging can eliminate this artifact, as shown in the image on the right (when reducing the Drive Frequency, the Setpoint voltage may need to be reduced as well).

Rings During High Frequency Operation



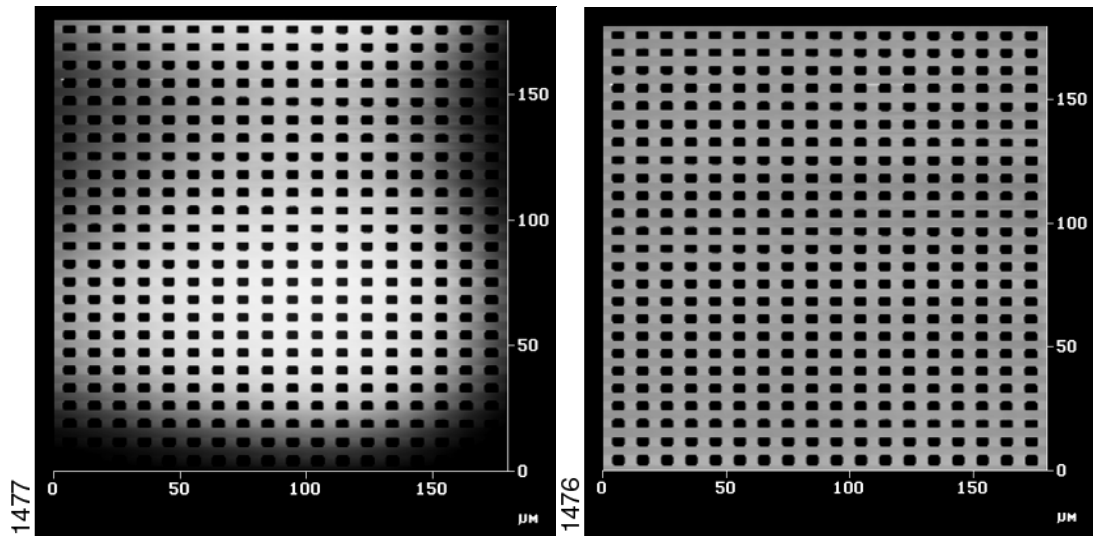
The arch shaped bow in the scanner becomes visible at large scan sizes (left). The bow in this image can be removed by performing a 2nd order Plane fit in X and Y (right). (Data Scale = 30nm)

2nd Order Bow



At large scan sizes, the bow in the scanner may take on an S-shaped appearance (left). This may be removed by performing a 3rd order plane fit in X and Y (right). (Data Scale = 324nm).

3rd Order Bow



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