The Burly Control User Manual

Scanning Tunneling Microscope Software

Michael Duckwitz

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1 Quick Start Guide

1.1 Overview

A Scanning Tunneling Microscope (STM) is used to resolve the surfaces of conducting samples with atomic precision. Several process come together to make this possible:

- quantum mechanical tunneling
- precise mechanical control using piezoelectrics
- negative feedback
- vibration control
- data collection, manipulation, and presentation

This manual mainly deals with the last item. The Burleigh Instructional STM^{TM} was originally designed to work with a 486 machine. Because this old system is not expected to function forever and because retrieving and printing surface images is very involved, it was decided to create a modern data acquisition system to work with the Burleigh STM.

The modern data acquisition system consists of a National Instruments PCI acquisition card (the PCI-6111, see Figure 1) and software written using LabVIEW. Criteria for selecting the card included the number of digital to analog and analog to digital converters (DAC's and ADC's), input and output voltage ranges, and maximum output rate of the DAC's.

1.2 Abreviated Procedures

Collecting data using the Instructional STM is done using the following steps. For more detailed procedures, see Section 2.

1. prepare a conducting sample (e.g. a gold grating)
2. prepare a tip from tungsten or platinum iridium wire
3. mount sample and tip into vibration isolated STM head
4. set STM panel controls (servo loop response, bias voltage, etc.)

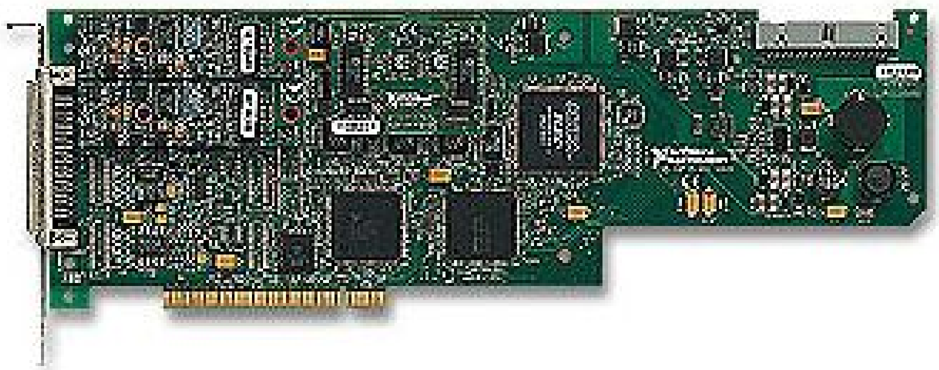

Figure 1: National Instruments PCI-6111 data acquisition card.

5. load the Burly Control software
6. configure the Burly Control software
7. begin tunneling using the STM panel Tip Approach Controls
8. start the sweep
9. retract tip from sample
10. define and apply a data filter if desired
11. save images

2 How to Scan a Surface

Several steps need to be completed in order to obtain a surface image. There is a section that corresponds with each one of these steps.

1. prepare a conducting sample (e.g. a gold grating)
2. prepare a tip from tungsten or platinum iridium wire
3. mount sample and tip into vibration isolated STM head
4. set STM panel controls (servo loop response, bias voltage, etc.)
5. load the Burly Control software
6. configure the Burly Control software
7. begin tunneling using the STM panel Tip Approach Controls
8. start the sweep
9. retract tip from sample
10. calibrate scales and return to step 8 (if required)
11. define and apply a data filter if desired
12. save images

This paper will be concerned mainly with using the software, i.e. steps 5, 6, 8, 11, and 12. Section 3 of the Instructional Scanning Tunneling Microscope Workbook provided by Burleigh gives much more detailed information about the other steps than this manual.

2.1 Preparing a Sample

When preparing the sample, take special care with those from the Burleigh sample kit. Parts, services, and samples are no longer provided for this equipment (hence the need for writing the in-house software). Also, make sure that there is good conduction between the surface and the sample mount. If there isn't, the tip will crash into the sample every time. Both the tip and sample are damaged when this occurs.

Figure 2: Special diagonal cutters for making tips.

2.2 Preparing a Tip

Use the tungsten wire first and only the platinum iridium when the tungsten is found to be insufficient.[1] After cutting the wire at an angle using the special diagonal cutters, see Figure 2, do not let anything touch it. An ideal tip will have a single atom on the end. Touching the tip can make it blunt at the atomic level. When placing the tip into the tip mount, bend the wire a small amount to hold it in place.

Special diagonal cutters are required because the wire is very hard. Damage to the tool may result when using regular cutters.

2.3 Mounting the Tip and Sample

Because the tip and sample are held in place using magnets, use care when mounting and unmounting them. It is easy to scratch the surface or to destroy the tip by bumping them into each other. The surface mount has a set screw and a handle, but pliers will have to be used with the tip. Using non-magnetic needle nose pliers can help.

2.4 Front Panel Controls

Refer to Figure 3. Under `Tunneling Controls` in the upper left corner of the front panel there are two dials that set the bias voltage and the reference

[1] The platinum iridium wire costs around $100/inch.

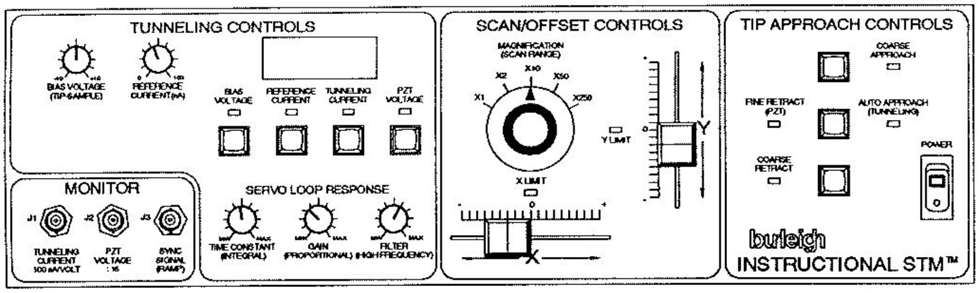

Figure 3: Instructional STM front panel.

current. The bias voltage is the voltage between the tip and the sample. When the tip approaches the sample, the bias voltage creates a current between the two through quantum tunneling. When this current reaches the reference current, the tip stops approaching the surface and the STM is ready to take data.

To the right of these two dials is an LCD display and four buttons. These allow the user to see the bias voltage, reference current, actual tunneling current, and the piezoelectric transducer (PZT) voltage one at a time.

Below the four buttons are three dials that control the `Servo Loop Response`: time constant, gain, and filter. The time constant determines how fast the tip will react (move up and down) as the surface is being scanned. Gain determines by how much the tip reacts and the filter eliminates high frequencies to discourage oscillations. Read Section 3.5 of the Instructional Scanning Tunneling Microscope Workbook for typical values.

The `Scan/Offset Controls` in the middle of the front panel affect the scanning of the tip. The `Magnification` knob decreases the distance swept by the factor selected. Two slides are provided that allow the user to change the location of the sweep on the surface of the sample.

Understanding how to use the `Tip Approach Controls` on the right side of the panel is very important. Incorrect use can lead to damaging the tip by allowing it to crash into the surface.

There are three tip control buttons. The two white ones provide coarse control and the red one provides fine control. The coarse control buttons cause a finely threaded screw to rotate and move a lever to which the tip is attached. Fine movement is done using the PZT. Take care when using the coarse adjustments that the tip doesn't crash into the surface or move beyond its limits. If the tip assembly is retracted too far, the screw can get jammed.

The `Auto Approach` button is used in conjunction with the `Coarse Retract` button. To begin tunneling using the auto approach function, tap the `Coarse Retract` button and then the red `Auto Approach` button. While the system is approaching the surface, the `Auto Approach` light will flash. When the tip is close enough to the surface to allow a tunneling current equal to the reference current, the `Auto Approach` light is steady and the auto approach stops. The microscope is now tunneling and ready to take data.

Taping the red button while the microscope is tunneling activates the fine retract. This retracts the tip from the surface beyond tunneling distance using the PZT. To return to the tunneling state, tap the red button again.

2.5 Burly Control Main Window

When the the Burly Control software has loaded, you should see a window similar to Figure 4. There are three plots on three different tabs labeled `3D Plot`, `Surface Data`, and `Deviation of Data`. The surface plot is a 2-dimensional, intensity plot. At each (x, y) grid point, data is taken repeatedly[2]. The deviation plot is the standard deviation of this data.

2.6 Configuring the Burly Control

Before performing a sweep of the surface, configure the software by clicking on the `Configure` button at the lower left-hand side of the main Burly Control window. A new window will open and will look like Figure 5. There are five parts of the configuration window: `Data Points`, `Scan Ranges`, data mode, `Dwell Time`, and `Electronics Settings`.

Data Points

A square grid with sides of length specified by the user defines the number of data points. For example, if the user specifies 256, there will be a total of $256 \times 256 = 65,536$ points. Once the system is calibrated, change only the `Zoom Multiplier` button when using a different zoom level. The Burly Control takes care of the plot scales from the value of the `Zoom Multiplier` as discussed below.

[2] The number of points depend on the dwell time – see the discussion about dwell time on page 10

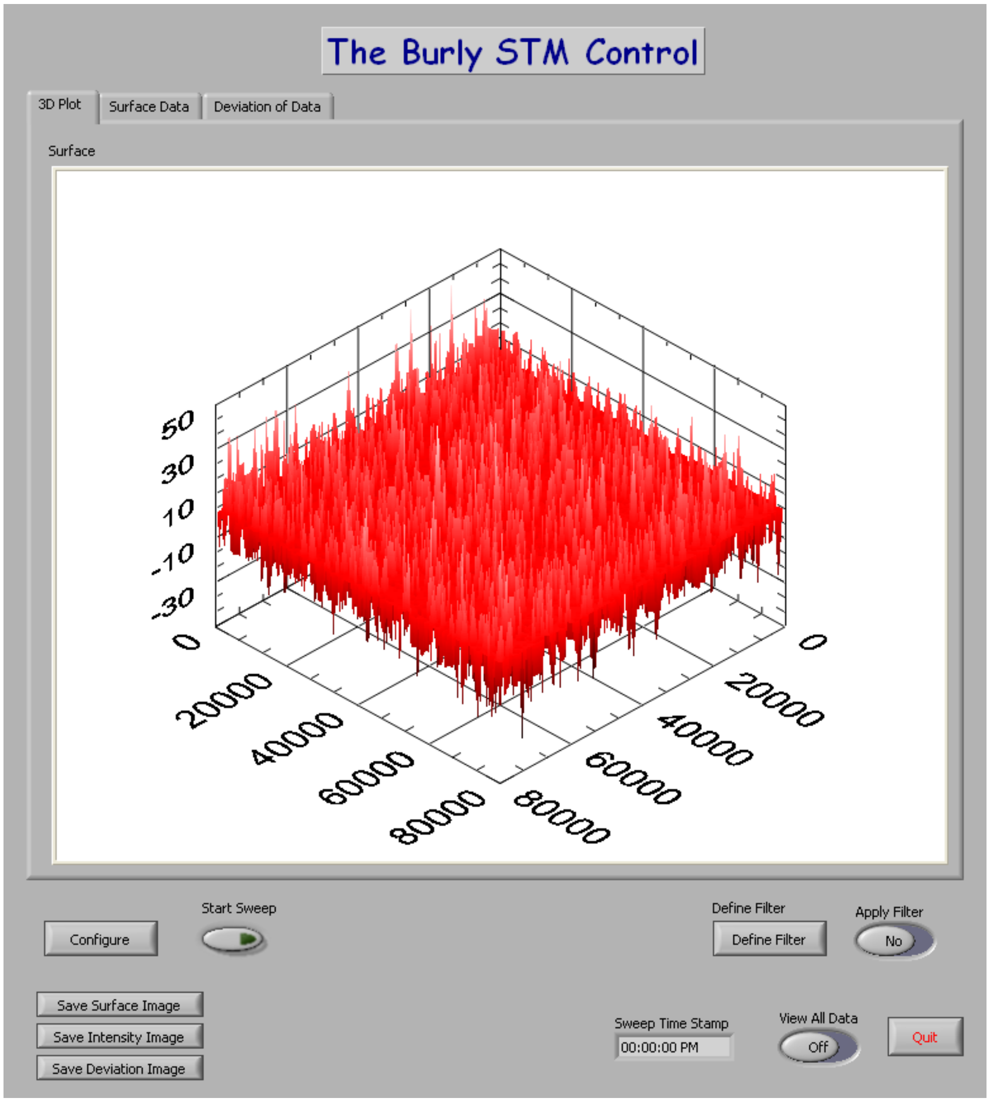

Figure 4: The Burly Control main window.

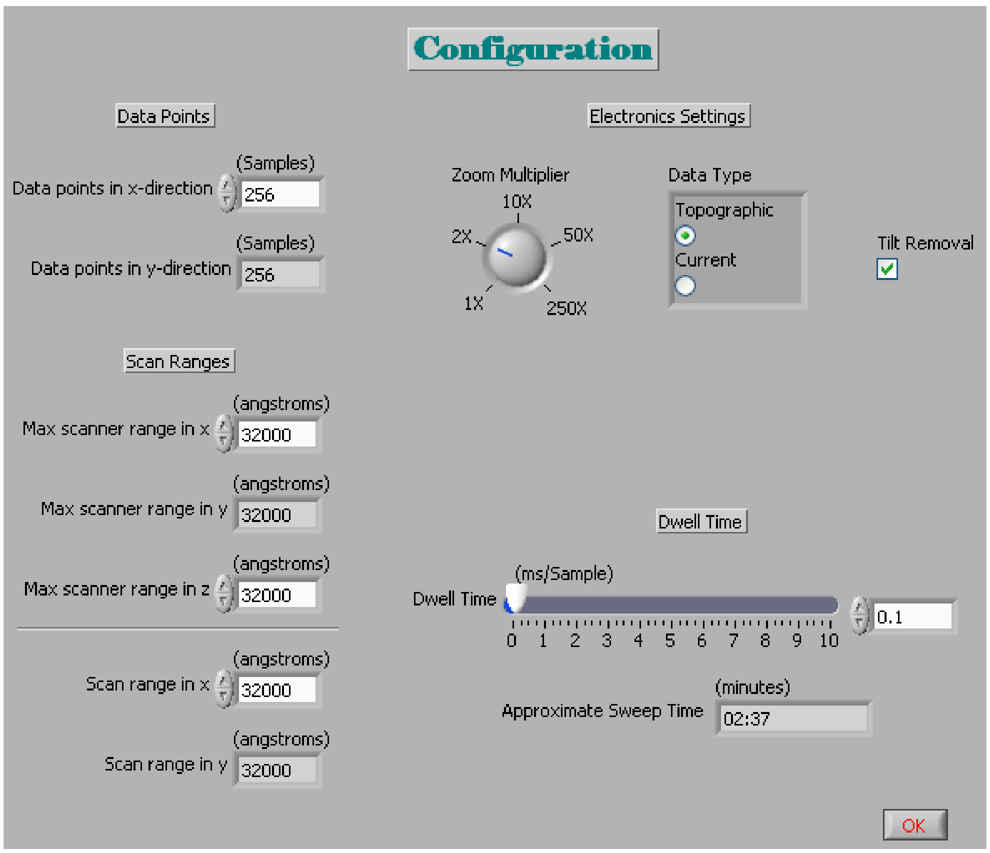

Figure 5: The Burly Control configuration window.

Scan Ranges

Maximum scanner ranges set the scale for the plots, but do not affect how the data is taken. However, the scan ranges do affect how the data is taken. If the scan ranges are equal to the maximum scan ranges, then the tip will be swept through its entire range. If the scan range is set to, say, half the value of the maximum, then the tip will be swept through only half of its entire range.

To obtain the correct scale, the user must scan a surface with a known periodicity.[3] For example, a gold grating with periodicity of $4,000\text{Å}$ can be scanned at zoom level $2\times$ to easily calibrate the system and set the max scanner range.

Data Mode

There are two modes in which the Scanning Tunneling Microscope can run: topographic and current. When topographic mode is selected in the software, the data recorded is the height of the microscope tip. In current mode, the data recorded is the tunneling current.

The behavior of the microscope in the two modes , controlled by the `Servo Loop Response`,[4] is very different and it is important to understand how. In topographic mode, the tip must move up and down following the contours of the surface while scanning. Therefore, the response time of the tip (the *time constant*) must be small and the response level (the *gain*) must be large.

In current mode, the current level indicates the height of the surface and so the tip must stay at the same level. As the scans occurs, the surface gets closer and farther from the tip, changing the amount of tunneling current that flows between the two. To keep the tip at the same height during the scan, the time constant must be large and the gain of the loop must be small.

The `Tilt Removal` check-box indicates whether the best fit plane should be removed from the data. This option allows the details on the surface to be seen more clearly when the surface is not level. For more information about how tilt removal is done, see the Plane Removal chapter in the full, non-student version of this document.

[3] Be sure to account for the zoom level when calibrating the scale.

[4] Refer to Section 2.4 on page 5 for a discussion on the servo loop response knobs.

Dwell Time

Dwell time is the time spent at each data point on the square grid over the surface. Each data point actually consists of a bunch of data taken at regular intervals. Therefore, doubling the dwell time doubles the pieces of data taken and doubles the amount of time per scan. In fact, the data in the `3D Plot` found on the main window[5] is actually the average of all the data taken at each point.

Below the `Dwell Time` slide bar is the `Approximate Sweep Time` display. This number is affected by both the dwell time and the number of data points. Data is taken every 10μs.

Electronics Settings

The `Zoom Multiplier` setting in the software affects how the data is presented. The plot ranges are divided by the value of the `Zoom Multiplier`. For example, if both the scale range and the maximum scale range for the x-axis are 4000Å and the `Zoom Multiplier` is set to 2×, the plot range will be 2000Å. Therefore, the scan ranges should not be changed when different zoom levels are selected.

`Bias Voltage` and `Tunneling Current` settings are provided for reference only and affect neither how the data is taken nor presented.

2.7 Quantum Tunneling

Once a tip and a sample have been prepared and the software has been configured, the system can be used to scan the surface. Bring the tip within tunneling distance by briefly tapping the `Course Retract` button and then pushing the `Auto Approach` button. The LED to the right of the `Auto Approach` button should start blinking. When the LED stays steady without blinking, the system should be tunneling. Check that the tunneling current is in the ball park of the reference current by using the `Tunneling Controls` buttons.[6]

[5]Refer to Figure 4 on page 7.

[6]See Section 2.4 on page 5 for a discussion of the controls.

Figure 6: The Burly Control sweep progress bar.

2.8 Scanning a Surface

To start scanning the surface, click the `Start Sweep` button in the lower left corner of the Burly Control main window. A progress bar will appear showing the approximate time remaining, see Figure 6. The sweep cannot be stopped once it has begun. Use the `Approximate Sweep Time` in the Burly Control configuration window to estimate the duration of the process.

2.9 Retracting the Tip

After the sweep has finished, it is a good idea to retract the tip from the surface to reduce the possibility of crashing the tip. One may use either the fine or the course retract. If the `Fine Retract` button is used, the PZT itself retracts the needle and therefore the system can be returned to the tunneling state quickly by tapping the red `Fine Retract` button again.

2.10 Calibration

As shown in Figure 4 on page 7, the surface is shown with a scale (in Å). In order to calibrate the scale, a sample with a known structure must be scanned. It is convenient to use a grating with a known period, like the 4000 Å gold grating in the lab.

There are two ways to calibrate the scale: 1) measure the period directly on the 3D or intensity plot itself or 2) use the Fast Fourier Transform option in the software to measure the period automatically and give a suggestion for the maximum scale value. In either case, the value of the `Max scanner range in x` in the Configuration Window will have to be changed (see Figure 5 on page 8).

2.10.1 The Direct Method

The first method is simpler to understand, but requires a calculation and is less precise. After finishing a sweep of a sample with a known period, estimate the period shown in either the 3D or the intensity plot. The best way to do this is to measure the distance spanned by as many periods as possible and divide that by the number of periods. Why is this superior to measuring only a single period?

When updating the `Max scanner range in x` using the first method, be sure the account for the `Scanner range in x` and the `Zoom Multiplier`. Both of these values affect the scale shown in the graphs, but the `Zoom Multiplier` does not change the actual distance swept by STM.

2.10.2 The Fourier Transform Method

The second method involves using a Fourier transform and picking out the dominant frequency component – which is done by the software. To use this method, select the `Surface Data` tab on the Burly Control Main Window, position the two cursors on the intensity graph to define a cross section across the grating, and click on the `Fourier Transform` button shown in Figure 7. A window similar to Figure 8 will appear. The lower graph shows the height of the surface along the line between the cursors. The upper graph is the Fast Fourier Transform (FFT) of that height data.

Figure 8 is actually simulated data:

$$\sin\left(\frac{2\pi}{4000}x\right) + \text{noise} \tag{1}$$

Notice that the frequency component of the 4000 Å period can be seen in the upper plot. Becuase of the noise and an imperfect choice of the cursor positions, the measured frequency is about 0.0002523 1/Å, not exactly 1/4000 as expected. This corresponds to a period of 3964 Å and the software suggests changing the `Max sanner range` from 32,000 to about 32,300 Å.

When choosing where to place the cursors, choose a cross section that cuts perpendicular to the grating. Also, a better FFT will be obtained if the cursors are placed at the same position on the wave, that is to say, at the same phase. For example, place both cursors on wave peaks or both between the peaks. Why is this best (more advanced question)?

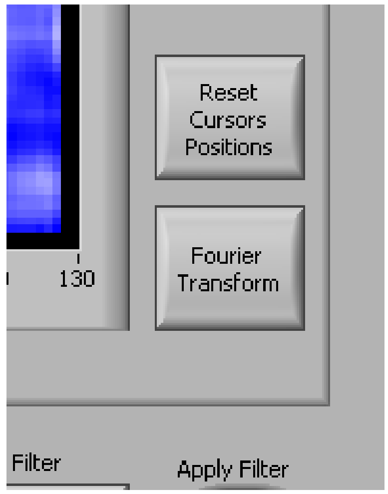

Figure 7: The `Fourier Transform` button on the intensity graph in the Main Window.

This is all done automatically by the software, but it is important to understand to some degree what is happening in order to know when an invalid result occurs. Normally, Fourier transforms are done in the time domain, but the mathematics is still valid when using space or any other variable.

$$F(k) = \int_{-\infty}^{+\infty} f(x) e^{-i2\pi kx}\, dx \tag{2}$$

where k is a spacial frequency in units of, say, 1/Å.

A grating should look fairly sinusoidal: $h_0 \sin(2\pi k_0 x)$, where $1/k_0$ is the grating period and h_0 is the height of the grating.[7] What does a sine wave look like in the frequency domain? A frequency domain plot shows the amplitude of the signal at each frequency. Because a sine wave has only one frequency, it is a delta function at that frequency.[8]

The FFT is an efficient algorithm that computes the discrete Fourier transform. If sampling is sufficiently high (i.e. there are many data points between the cursors), this is a good numerical approximation of the Fourier transform in Equation 2.

[7] Spacial frequency is denoted with k to distinguish it from frequency in time, f.
[8] Technically, $\sin(2\pi k_0 x) \rightarrow h_0[\delta(k - k_0) - \delta(k + k_0)]/2$.

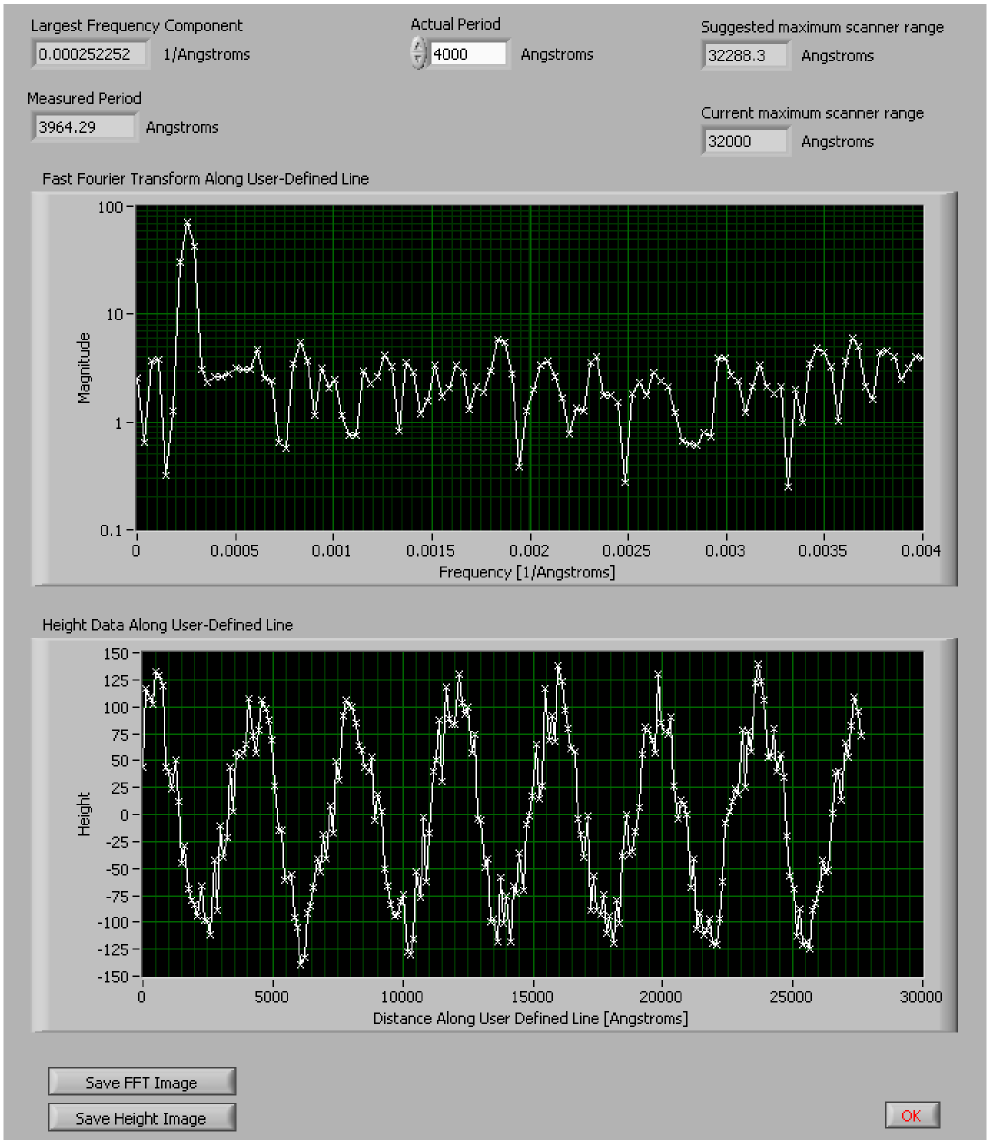

Figure 8: The Fourier transform window showing the FFT (upper graph) and the height data (lower graph) along the line defined by the cursors on the intensity graph.

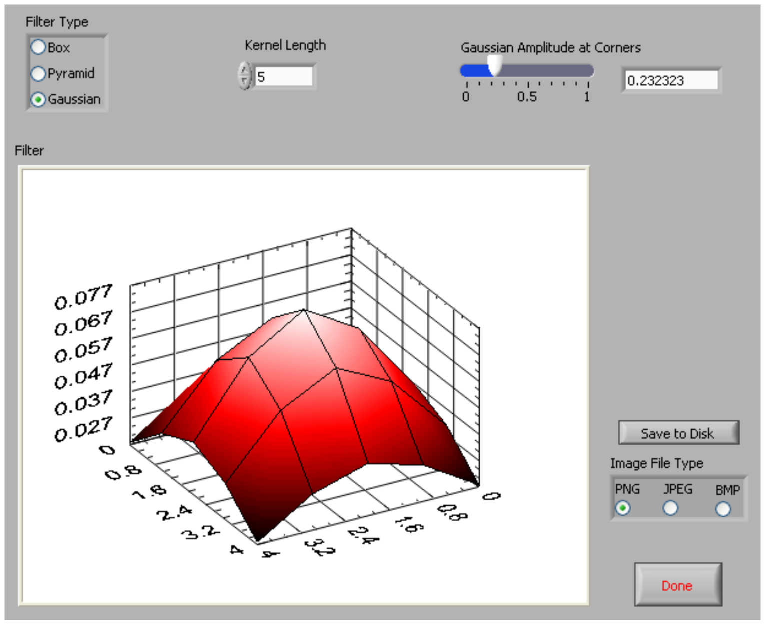

Figure 9: The Burly Control filter definition window.

2.11 Filtering the Data

Filtering data refers to selectively passing some frequency components and rejecting others. Many signals can be written as a (possibly infinite) sum of sinusoidal signals, each of a different frequency and amplitude. A low-pass filter, for example, will significantly decrease the amplitude of sinusoids with high frequencies and leave amplitudes of sinusoids of low frequencies relatively unchanged.

To filter the data, define the type and extent of the filter by clicking on the `Define Filter` button in the lower right corner of the Burly Control main window, see Figure 4. In the upper left corner of the filter definition window, Figure 9, one of three types of filters may be chosen: box, pyramid, or gaussian. The filter kernel, the function used to filter the data, is defined on a square grid of length specified by the user.

Filtering is done using a method known as convolution.[9] Basically, low-pass filtering consists of taking the weighted average of neighboring data

[9]Visit `http://www.jhu.edu/~signals/discreteconv2/index.html` to gain an intuition about (1-dimensional) convolution through interactive examples.

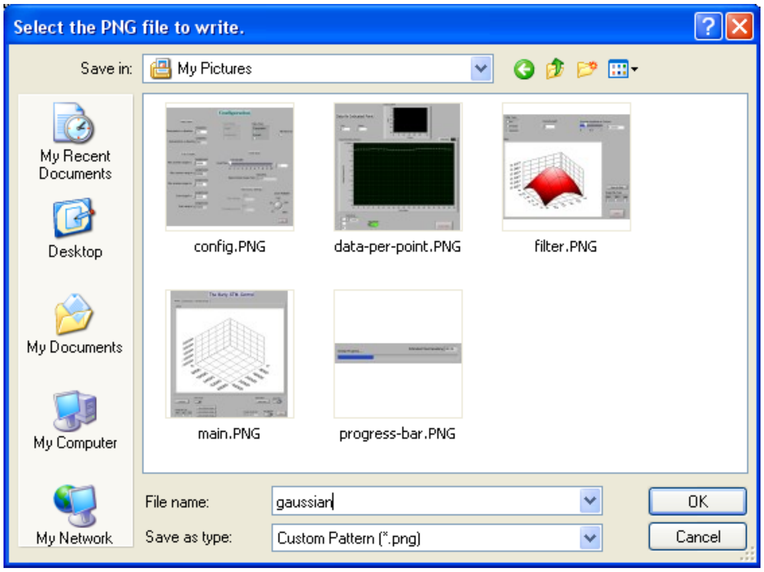

Figure 10: Save image dialog.

points. The filter kernel gives the weight of each point and the kernel size determines how many neighbors are included in the average. For example, if one chooses a 5×5 box for the kernel, each data point will be the unweighted average of the data point and 24 of its neighbors.

2.12 Saving Images to Disk

An image of the filter kernel can be saved to be included with a lab report. Click the button corresponding to the images you would like to save, select the type of image in the dialog that appears (PNG, JPEG, or BMP), and click OK. Choose the location and name of the file to save using the default Windows file saving dialog that pops up as in Figure 10.

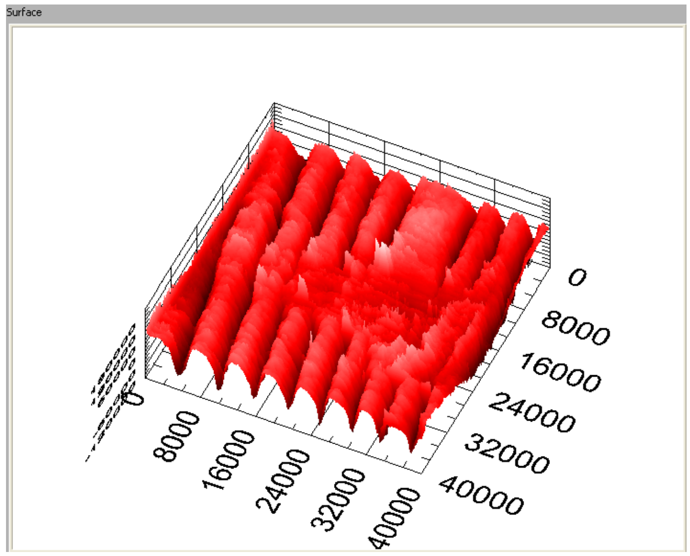

Figure 11: 3D gold surface with the best-fit plane removed.

3 Gold Grating Example

Using the Scanning Tunneling Microscope and the new Burly Control software, the surface of a gold grating with period of 4000Å was scanned. As usual for topographic scans, the time constant was almost at its minimum, the gain was almost at its maximum, and the filter was all the way to its maximum. Scan parameters included:

- 0.1 ms dwell time
- 256×256 data points
- $2\times$ zoom factor
- tilt removal on
- bias voltage of 1.31 V
- reference current of 15.3 nA.

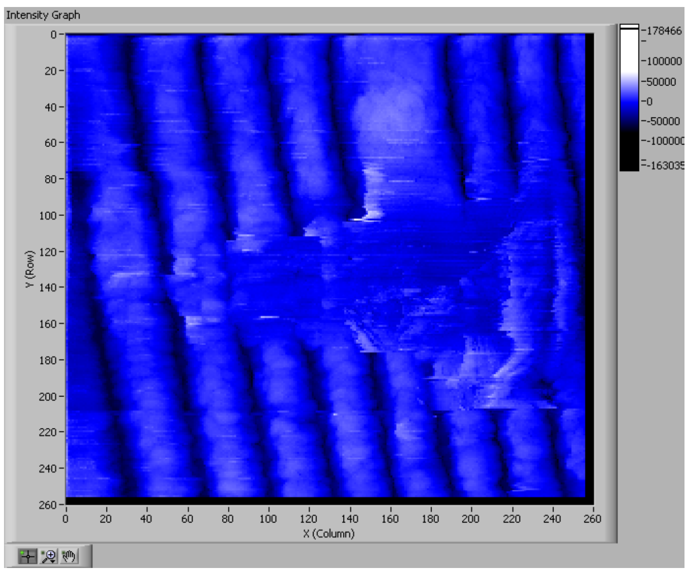

Figure 12: Gold surface intensity plot with the best-fit plane removed.