ZETA 20 3D OPTICAL PROFILER: SYSTEM DESCRIPTION AND STANDARD OPERATING PROCEDURE

Version: 1.1

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1. Introduction

The Zeta-20 Optical Microscope is a fully integrated microscope based system that provides 3D imaging and metrology capability in a small, robust and cost effective package. Based on proprietary technology, the Zeta-20 enables imaging of surfaces with very low reflectivity and very high roughness.

1.1 Principle of Operation

Conventional microscopes have a very limited depth of focus. Test surfaces and features are clearly visible only when they are within the focal depth. The Zeta system scans a sample over a user specified vertical (or Z) range. At each Z position, it records the XY location and the precise Z height of the pixels using the Zeta Optics Module. This information is used to create a true color 3D image and a 2D composite image. The resulting image has an extended depth of focus so the entire surface is seen clearly. The Zeta 3D software can be used to ascertain dimensional and roughness information. An optional film thickness module allows calculation of transparent layer thicknesses on the surface. Figure 1 shows a comparison between a conventional microscope image and Zeta images. The microscope image is in focus for only part of the image, while the Zeta 2D image is in focus for the entire image.
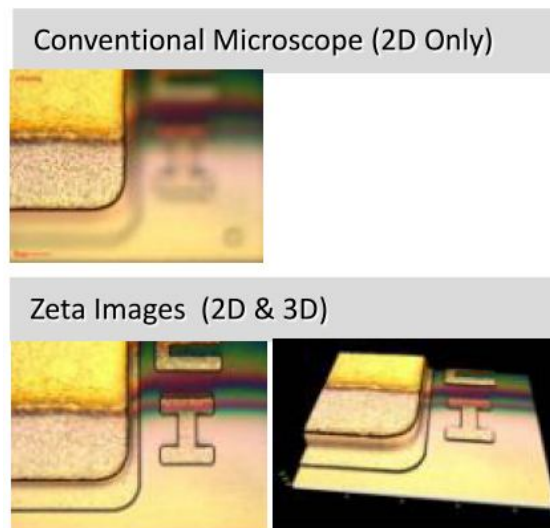
Figure 1. Comparison between a conventional microscope and Zeta 3D images

1.2 System Description

Various components of the Zeta 3D Optical microscope are shown in figure 2 and are as follows:

1. **CCD Camera** - To capture sample images and focus map data.
2. **Zeta Optics Module** – Contains a focus map signal generator, a high intensity white light LED source to preserve sample color and optics to optimize illumination.
3. **Precision Z-drive mechanism**- For sub-micron level resolution.
4. **Zeta Control Box**- Contains the controller for Z-drive and optics module electronics.
5. **Substrate Holder**- To place the sample with X-Y and angular adjustment.
6. **Computer System** – Contains Zeta 3D imaging and analysis software.

Figure 2. Schematic view of the Zeta 20 3D system

Imaging can be performed with different magnifications based on the resolution and Field Of View (FOV) requirements. The details of the various objectives are given in table 1. The highlighted objects are the ones that are installed in the system.

Table 1. Specifications for the various objectives

	NA	Working distance (mm)	Z resolution (µm)	XY resolution (µm)	Optical resolution (µm)	FOV with 0.35X coupler 1/3" camera	2/3" camera	FOV with 0.5X coupler 1/3" camera	2/3" camera
2.5X	0.08	10.7	22	3.60	4.20	5364 × 4024	9394 × 7044	3788 × 2840	6614 × 4960
5X	0.15	20.0	5.9	1.80	2.20	2682 × 2012	4697 × 3522	1894 × 1420	3307 × 2480
10X	0.30	11.0	1.5	0.90	1.10	1335 × 1000	2327 × 1745	944 × 708	1644 × 1233
20X	0.45	3.1	0.5	0.45	0.75	668 × 500	1169 × 877	468 × 351	822 × 616
50X	0.8	1.0	0.1	0.18	0.42	267 × 200	466 × 349	189 × 142	328 × 246
100X	0.9	1.0	0.01	0.09	0.37	133 × 100	234 × 175	93 × 70	164 × 123
150X	0.9	1.0	0.01	0.06	0.37	88 × 66	156 × 116	62 × 46	109 × 82

2. System Startup and Software Details

Before start up, ensure that no samples are placed on the platform and the turret is turned to place the lowest magnification objective (20x in this case). The fixing of turret is confirmed by a click sound that confirms locking of the specific objective.

2.1 Powering and Logging In

The sequence for powering up the system is as follows:

1. Power up the computer. The Windows password is set at the factory to "Zeta." Wait for around 30 seconds after powering the computer.
2. Power up the Zeta-20 by pressing the round button on the front of the base. It glows blue when the system is powered up.
3. Double click on the "Zeta 3D" icon on the screen to start the Zeta 3D software.
4. Log in to the Zeta 3D software in the popup window shown in figure 3. The user name and password are set to "a" at the factory but you may have other user accounts on your system.
5. After logging into the software, a window with the various options as shown in figure 4 will be displayed.

Figure 3. Zeta 20 3D software login screen

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While shutting down the system after measurements, always turn off the computer system first and then the Zeta 20 3D microscope.

2.2 Software Organization

The Zeta 3D has many features which can be accessed through the various tabs on the top left of the software screen. A snapshot of the different tabs and windows panels is shown in figure 5. The top level of organization is a tab. Functions within a tab are shown in a ribbon of commands. The user can choose to hide or display the ribbon by double-clicking on the tab name. Each tab ribbon contains several groups of functions and each group contains active items such as buttons, checkboxes, or fields for data display or data entry. The main part of the screen contains one or more windows which contain the measurement results. Figure 6 shows the analysis window with the different components.

Every window has a colored label at the top. The first window, which is located at the far left side, is usually the live video window and is labeled 'Live Video'. There are three other types of windows:

- 3D images,
- 2D composite images, and
- Analysis windows.

The maximum number of different windows for each scan is three (one for each of the three types) and all related windows have the same window label. There is no limit (besides computer memory) to the number of windows which can be open at the same time, but it is recommended to keep only around 4-5 windows open at a time. If the 3D image has been saved, the window name is the file name with the extension of .zmg.
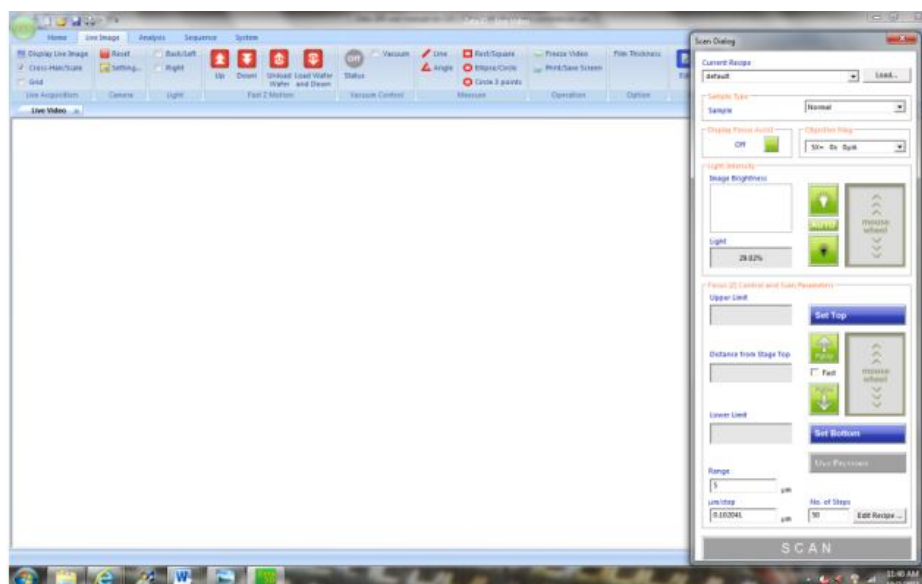
Figure 4. Screen Shot of initial software screen
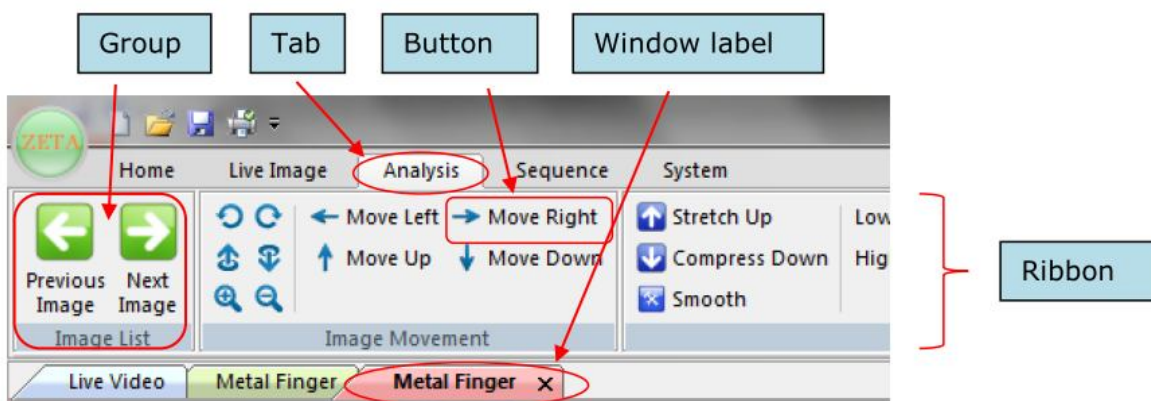

Figure 5. Software screens with the various tabs and window panels.
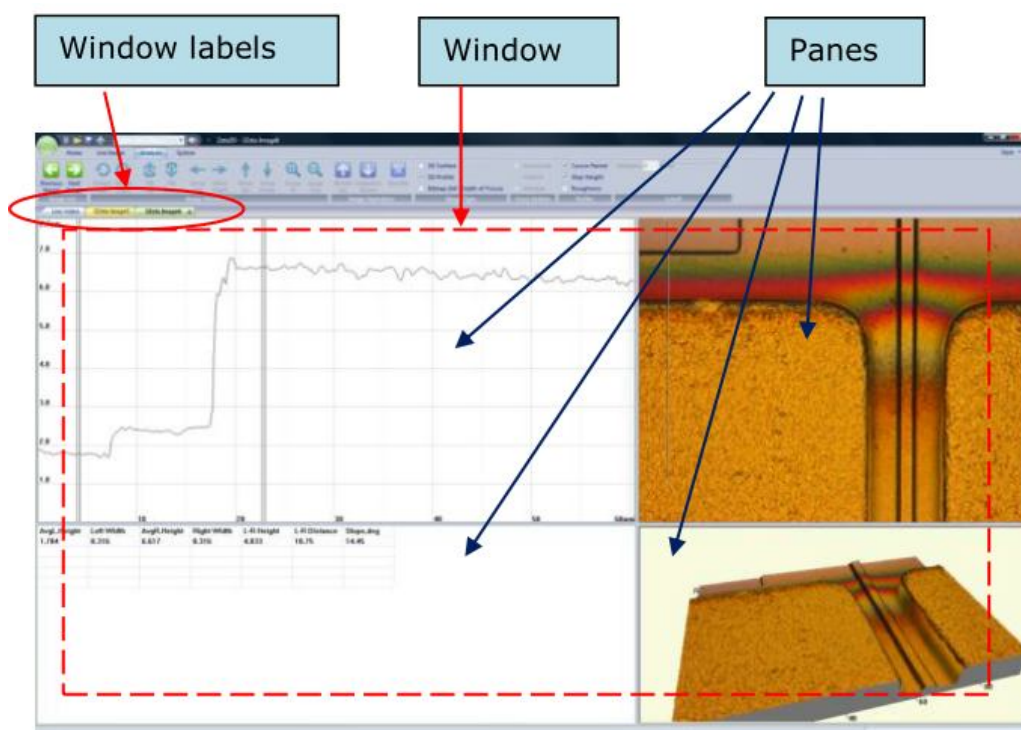
Figure 6. Different Panes in Analysis Window

If you perform a new scan or open a saved image file, a new 3D image window with a new name appears to the right of the existing windows. Analysis windows for the new image have the new image name. As indicated in figure 6, each window is divided into different panes, where pane has a specific purpose. The user can drag the pane boundaries to adjust the pane sizes to change the appearance of a screen capture. However, the size adjustment cannot be saved. The software makes extensive use of situational menus. If you click the right mouse button, a menu appears which contains items that are appropriate for the object under the cursor.

2.3 Image Analysis Options

The Zeta 20 3D microscope uses and stores the measurement and analysis results in various formats outlined below:

- Image Files (*.zmg) - An image file contains the raw data from a measurement scan. It can be viewed and analyzed in two-dimensional (2D) and three-dimensional (3D) ways. This is the only file type that can be fully reanalyzed later.

- Display Files (*.bmp, *.jpg,*.png) - 2D and 3D sample views are very useful for reports. A bitmap (*.bmp) file is an uncompressed format with one pixel per measurement pixel, which provides the highest quality picture. A JPEG (*.jpg) file is a lossy compressed format which produces the smallest file size with a reasonable quality picture. A PNG (*.png) file is a lossless compressed format which is set to have a transparent background. This is useful for capturing 3D objects without the screen background.
- TIFF files (*.tiff) - This is a type of 2D display file which is saved with calibration information to preserve accurate lateral dimensions.
- Results files (*.txt and *.csv) - In order to import the numbers into a spreadsheet or word processing program, other file types are required. Text files (*.txt) contain simple text that includes headings, punctuation marks, and spaces. Text files have an appearance similar to the results on the screen and can be printed. Comma separated value files (*.csv) contain numbers separated by commas to make it easy to import the values into Microsoft Excel.

2.3.1 Opening and Saving Image Data Files

Image files with .zmg and .tiff extension can be reopened and analyzed by the software, while the other images cannot be opened with the Zeta software. To open an existing image data file, click on the File Open option and select the specific file to be opened. Choose the specific option as shown in figure 7 below. These options control the appearance of the screen when the file is opened, but do not change the underlying raw data. "Zeta Image File" displays a 3D image window, "Zeta Image Profile File" displays a default step height analysis window, and "Zeta Image (bitmap) from 3D Surface file" displays a 2D image window. In addition, whenever the Zeta software is running, you can double click on any *.zmg file name within Windows Explorer. The image will open in 3D view mode.
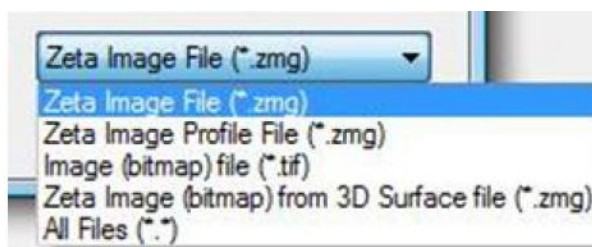

Figure 7. Options for opening image files

3D and 2D image data can be saved either by clicking on the 'File save' option from the top left corner of the software or by right clicking the image to open a menu. 3D data can be saved as *.zmg files, while the 2D data file can be saved in *.tif or *.jpg format. A screen shot of the current window can also be

taken via the Print icon on the Quick Access toolbar. The file can be stored in jpeg, bitmap or png format.

The analysis data appears in the Analysis Report pane in a spreadsheet format. The data can be exported to another program such as a word processor or spreadsheet program by right-clicking within the report pane and selecting the 'Save to File' option. The choices are "Tab-separated text file (*.txt)" and "Comma-separated text file (*.csv)." The data points behind most graphs may be exported in comma separated values (CSV) format as well.

2.4 Making Recipes

Recipes are files that contain settings for performing the scans. The details for the specific case can be saved in a form of recipe, which can be loaded again at a later stage. Recipes can be loaded via the 'Load' button in the Recipe group of Live Image Tab as shown in figure 8 or via the 'Load' button in the Scan Dialog Window (discussed in next chapter). Recipes may be located at the top level of the browse window or in folders below this level. Recipes in any other folders will not be recognized. Similarly current recipes can be edited and saved using the same icons. Recipe files must have an extension of *.rcp. Do not change the file extension.
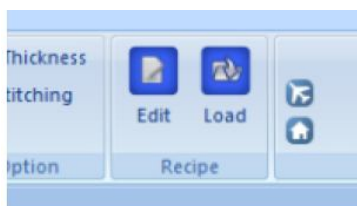
Figure 8. Tab for loading a Recipe

3. Making Measurements with Zeta 20

In this section, the main features and settings for measurements will be discussed. The detailed step-wise measurement sequence will be covered in the Standard Operating Procedure (SOP) ahead.

3.1 Sample focusing for a scan

Since the auto-turret option is not installed, rotate the turret to place the lowest magnification objective (20X in this case) into the vertical position for measurement. After initialization, select the lowest power magnification in the Scan Dialog window. This has to be done every time before a measurement run.   Once the sample is under focus, the sample type should be selected from the Scan Dialog Box. The various options for the sample type are:

- Normal- Suitable for most samples
- High- For very reflective surfaces such as metal films
- Low- For low reflectivity surfaces such as anti-reflective coatings

For flat or very smooth samples, the 'Display Focus Assist' option in the Scan Dialog window can be turned on. This will project a grid of dots (called Z-dots) on the sample surface. When the sample is in focus, the dots will be clearly visible else blurred when not in focus. An example of the grid pattern is shown in figure 9. The focus control can be used to move the optical head up and down, and choose a position that puts the desired surface in focus (makes the dots visible and in focus on the surface of interest). The light intensity can also be varied to ensure the sample surface is well illuminated.
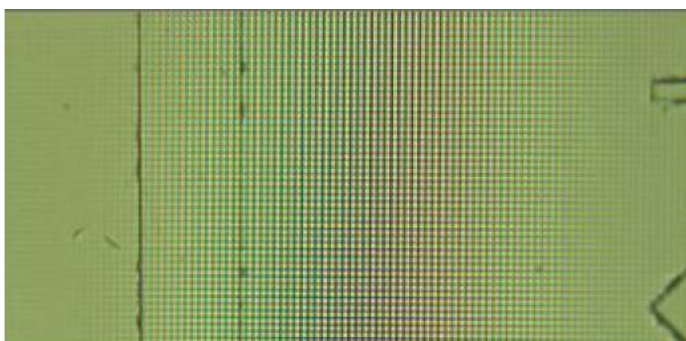
Figure 9. Z-dots produced by Focus-Assist option

3.2 Working with Live Image

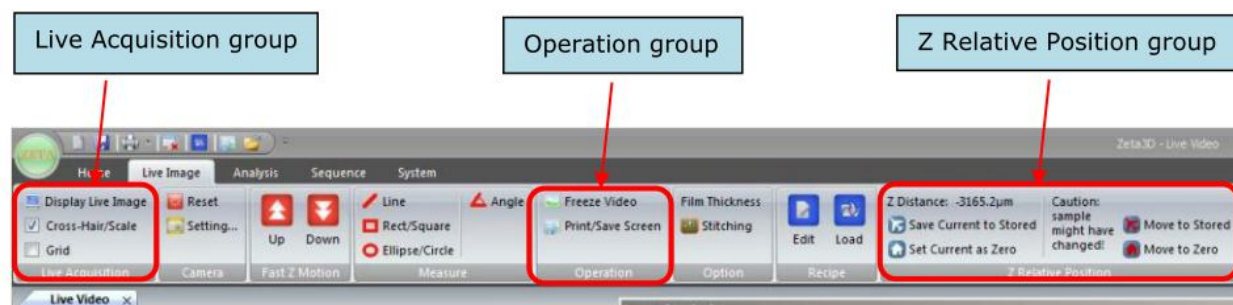The Live Image tab consists of various functions as shown in figure 10.

Figure 10. Function Groups in the Live Image Tab

The features of the various groups are as follows:

- Live Acquisition Group: This section allows the user to vary the scale displayed in the image. The default display is 'Cross-Hair/Scale'. This option places a cross-hair in the center of the field of view (FOV) and a label in the lower left corner of the image that includes the FOV, the objective in use, and a distance scale. Fig. 11 shows an example of the scale. The 'Grid' scale option draws squares on the image and places a scale bar on the top left corner as shown in figure 12.

- Operation Group: The Operation group provides a way to save the image as a screen shot. Click on Freeze Video to take a snapshot of the live image; a new window opens. Click on 'Print/Save Screen' to create a screen shot file. The frozen image is a 2D snapshot of the microscope image.

- Z Relative Position Group: This option allows user to save the focus position on the sample. This is useful when one needs to move back and forth between features of different heights. Click on 'Save Current to Stored' to save a Z position. Click on 'Set Current as Zero' to set the Z position to zero to serve as a reference plane. Click on 'Move to Stored' or 'Move to Zero' to move the head to either of these positions. Be very careful when using these commands. If you change the sample, do not use previously stored positions as the surface height may have changed.
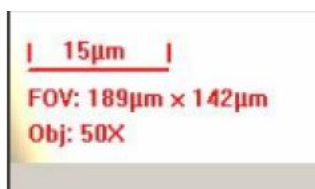

Figure 11. Scale for Cross-Hair/Scale Option

Figure 12. Scale with Grid Option

3.3 Setting the Scan Range

In a typical scan, the optical head moves over a range of positions that puts all surfaces in focus at some point. Therefore the lowest head position (scan bottom) should have a focal plane below the lowest surface, and the highest head position (scan top) should have a focal plane above the highest surface. During the scan, digital images are captured as the head moves. User can set the scan range manually or you can use Auto Focus. The 'Auto Focus' option can be selected from the Edit Recipe tab in the Scan Dialog box.

The steps for setting the scan range using Manual Focus are as follows:

1. Focus on the highest surface of the sample using the mouse wheel for fine focus position control.
2. Move the optical head a small amount higher than the highest surface; the image will look a little bit fuzzy.
3. Click Set Top to set the top of the scan range. The Upper Limit field displays the Z position.
4. Focus on the lowest surface of the sample.
5. Move the optical head a small amount lower than the lowest surface.
6. Click Set Bottom to set the bottom of the scan range. The Lower Limit field displays the Z position and the Range field displays the scan range.
7. Set the number of steps (in the field labeled No. of Steps). A value of 100 is a good starting point, but the maximum value is limited only by the computer memory. Increasing the number of steps reduces the Z resolution but increases the measurement time.

The Z resolution is displayed in the field labeled µm/step and is calculated as the range divided by the number of steps. If the value is below the minimum of 0.013 µm, you will be prompted to change the range or the number of steps to correct it. If you edit the Range field, the bottom scan position stays fixed and the top position is changed to fit the new range. If you edit the resolution field, the closest available value is selected and the number of steps is recalculated.

To set the scan range using Auto Focus:

1. Locate the highest and lowest surfaces of the sample using the mouse wheel for fine focus position control.
2. Move the optical head approximately half way between the highest and lowest surfaces.
3. Click 'Set Nominal Focus'.
4. Set the number of steps, range, or resolution values. The default behavior is to center the Z range at the final auto focus position, so the range should be large enough to accommodate the known feature sizes.
5. If necessary, change the way the Z range is set relative to the auto focus position by editing the value of Auto Focus % in the recipe. This is the percentage of the Z range that is scanned above the final auto focus position.

3.4 Working with 3D Images

The 3D image contains the raw image data and can be used to calculate a number of parameters ranging from step height to roughness. Manipulating the image in different ways can give insights into the surface features. The 3D image can be viewed by selecting by ticking the 'ZView 3D' option or by selecting the 3D image view from the main window. Various options for moving, rotating, etc the 3D can be obtained from the Analysis tab or by right clicking the 3D image.

3.4.1 Filtering and Color options for 3D images

A surface can be described as a combination of waviness, roughness, and discrete features. Waviness is the base surface or the underlying shape, which is a property occurring over a long length scale (wavelength). Roughness is the surface height variation on a short length scale. Discrete features are items that do not cover the entire surface, such as trenches or steps; these are short wavelength features. The Zeta 3D software offers several options for modifying the appearance of a scanned surface by filtering the raw data. They are found in the Image Operation group of the Analysis tab, as shown in figure 13. The most useful filter is the Gaussian filter which is accessible on the toolbar. The Gaussian filter eliminates short or long wavelength effects and displays the surface as if that data didn't exist. Moving the Low Pass slider to the right eliminates short wavelength data, such as fine scale roughness. Moving the High Pass slider to the left eliminates long wavelength data, such as waviness. Experimenting with the filters and observing their effects on both the 3D and 2D images is the best way to understand them. It is often useful to filter a surface before performing step height or roughness measurements. For example, removing some surface roughness is often helpful when you are measuring a step height, and removing waviness may be helpful when you want to measure roughness.
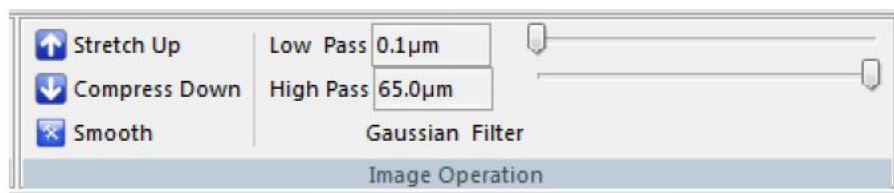
Figure 13. 3D Image Filtering Options

Zeta 3D images are presented in True Color. However, for some surfaces there is not enough color variation to adequately delineate all of the features. This can happen for very flat surfaces or very monochromatic surfaces. Therefore an option to display 3D images in false color is available by using color lookup tables (LUTs). These are text files with an extension of *.lut located in the software's system folder. A lookup table assigns red, green, and blue values to each of 256 height levels.

To change the color of a 3D image, following steps are to be taken:

1. Uncheck the box labeled True Color in the 3D View group, located at the far right of the toolbar on the Analysis tab. The most recently selected LUT file will be used.
2. To select a lookup table, right click on the 3D image and select Load Color Look-Up-Table (LUT) file.
3. Choose one of the available LUT files.

Fig. 14 illustrates the effect of changing the color lookup table. The surface is textured, but over a relatively small range of heights. It also has a coating that makes it very uniform in color. The image on the left is in True Color, while the image on the right is the same surface displayed with a lookup table in which blue represents the lowest height and red the highest. It is much easier to visualize the surface variations with this color scheme. When false color is employed, you can select Display Color Bar from the right-click menu to display a key that shows the correspondence between height and color. Another option to analyze a 3D image is to a histogram which will show the count of the various height points. The histogram can be viewed by right-clicking and selecting the 'Display Histogram' option.
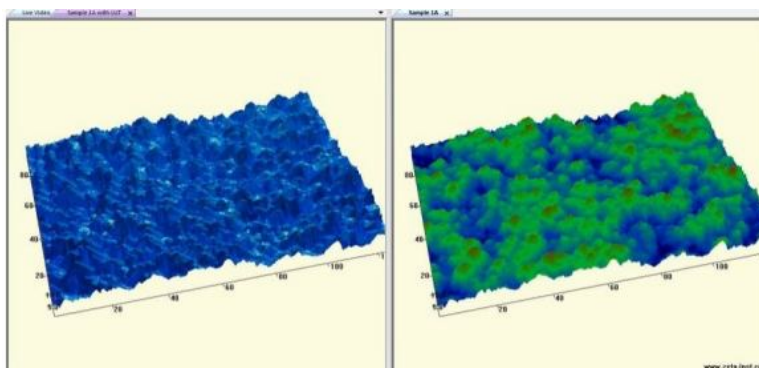
Figure 14. Surface displayed with two color options

3.5 Important Measurements and Features

The Zeta 20 microscope along with taking 3D images, also allows for measurements of feature height, surface roughness, etc.

3.5.1 Step Height Analysis

After completion of a 3D scan, the analysis window allows for step height measurements on the sample surface. Figure 15 shows the window with the feature height measurement for a selected cross-section on the sample area. Step height is the difference in average height between two locations on the sample surface defined by vertical cursors in the 2D Line Profile pane. The average height for a location is the average of all values within the pair of cursors, while the step height is the average right side height minus the average left side height; it can be positive or negative depending on which side is higher. The cross-section across the sample can be modified with various options that are available by right clicking on the '2D Composite View' window. Cross sections can be horizontal, vertical or oblique and its length can be changed by dragging the cross-section line. Also the area over which the cross-section measurements are performed can be averaged over an area by specifying the cross-section width. There are also additional features like adding user comments and memorizing the user settings which can be used for future analysis.
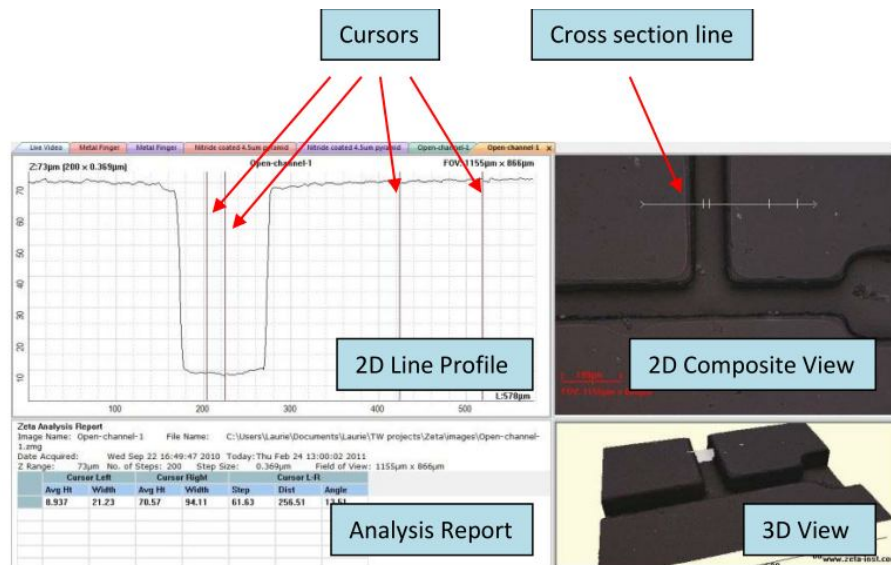
Figure 15. Step Height Analysis Window

Boundaries of the step height measurement can be changed by modifying the cursor widths or the distance between the two sets of cursors. The analysis values change in real time as the cursors moves. In addition to step height, the analysis window displays the average height of each location, the width of each cursor region, the distance between the two locations, and the angle between them. The default Y axis range of the profile is based on the range of heights in the 2D image. To modify the range, select Set Y-Axis Limits in the right-click menu.

3.5.2 Step Height measurement on multiple cross-sections

To do surface analysis across many cross-sections, additional cross-sections can be added to the 2D window by selecting the 'Add Cross-Section' option. By using this command more cross-sections can be added to the image. Correspondingly, same number of profile graphs and data will be added to the profile and analysis window as illustrated in figure 16. The length and orientation of each cross-section can be modified independently. To highlight one set of data, use the cursor to click on the cross section line in the 2D Composite View. This becomes the active profile and its number changes to 1 (other lines are renumbered at the same time). The corresponding data set moves to the top of the Analysis Report pane. The cross sections and data lines are also colored to help show which data sets correspond to which cross section lines. However, the colors are not unique and will repeat as you add more cross section lines. The same set of four cursors is used for analysis on all cross sections. If there are three or more cross sections, the Analysis Report also includes statistics for each column of data.

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Figure 16. Multiple cross-section analysis for a sample.

Height measurements on multiple locations can be made using additional cursors known as 'Markers' which can be selected by right clicking on the analysis window. A maximum of three markers can be added to the window and each can be moved independently across the cross-sections. As indicated in figure 17, data for the corresponding markers will also be automatically added to the analysis window. If there is more than one profile, the X-axis positions of the markers are used to define the calculation points for all profiles. However, the markers will show the correct Y-axis position for only one profile at a time. To move the markers to a different profile, click on a cross section in the 2D Composite View to make it the active profile. The markers move to the new active profile and the analysis for the active profile moves to the top line of the results table. The actual results do not change because they already used the markers' X-axis positions to find the correct heights for all profiles.

Figure 17. Illustrations of profile markers across multiple cross-sections

3.5.3 Leveling of the Sample Surface

When samples are not very flat, a cross section of the surface may show a strong tilt. It is easier to measure step height if the user can level the surface. The two types of leveling that can be performed are: 1) Profile Leveling and 2) Surface Leveling.

3.5.3.1 Profile Leveling

'Profile Leveling' is performed in the profile window using the vertical cursors and cannot be done using markers. Profile leveling does not change the image data. This means that if you draw another cross section on the 2D image, the resulting profile will not be leveled. The steps for Profile Leveling are as follows:

- Move the two sets of vertical cursors in the 2D Line Profile pane so that their center points define two positions that you would like to put on a level surface with each other. If there is more than one profile in the graph, the same cursor positions are used for leveling all profiles.
- Right click on the profile window and select 'Leveling' which shows various options as illustrated in figure 18.
- If the surface between the two sets of cursors is fairly linear without any steps, choose 'Least Squares Line Fitting' in the 'Line Definition Method' frame. This option uses all of the data points between the far left and far right cursors to fit a line. This line becomes the zero height line.
- If the surface contains anomalies such as bumps or pits that do not represent the underlying surface, choose 'Center Points of Cursors'. This option uses only two points to fit the zero height line: the data points at the center of each pair of cursors.
- In the 'Levelling Method' frame, choose Subtract or Rotate. The Subtract option affects only the Y axis (height) values. The Rotate option is more physically accurate, and it affects both the Y axis and X axis values. In most cases, the results are very similar between the two options. Subtract is faster and is the default choice.
- Click Apply. Analysis data automatically updates.
- To reset the profile, click on the cross section in the 2D Composite View pane.
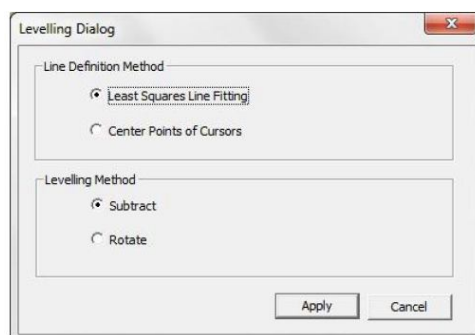
Figure 18. Leveling Dialog Box

An example of profile leveling is shown in Fig. 19. Before leveling, the base surface is strongly tilted. Leveling was done using the Center Points of Cursors and Rotate options. After leveling, the base surface is set to zero height so the Y-axis is adjusted accordingly. The Y-axis range is also smaller so the step is the focus of the profile graph. The results change automatically. Before leveling, the Z positions (labeled as Avg Ht values) of the data points at the cursor positions are 8 to 26 microns above the scan start position. After leveling, the Z positions are close to zero, and so are the step height between the cursors and the angle between them. The width and distance values changed because the cursors were moved after leveling.
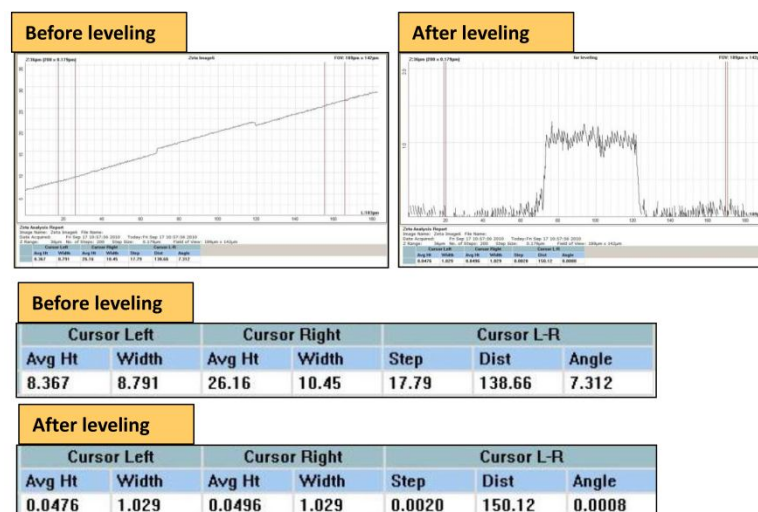

Before leveling

Cursor Left		Cursor Right		Cursor L-R		
Avg Ht	Width	Avg Ht	Width	Step	Dist	Angle
8.367	8.791	26.16	10.45	17.79	138.66	7.312

After leveling

Cursor Left		Cursor Right		Cursor L-R		
Avg Ht	Width	Avg Ht	Width	Step	Dist	Angle
0.0476	1.029	0.0496	1.029	0.0020	150.12	0.0008

Figure 19. Impact of Profile leveling on a tilted sample

3.5.3.2 Surface Leveling

For some operations, leveling the base surface of the raw image is necessary. This includes measuring the volume of a 2D feature. Surface leveling can be done as follows:

- Right Click on the 2D Composite View and select 'Add Reference Surface'. Three boxes appear on the 2D Composite View image, with lines connecting their center points. The triangle formed by these lines defines the reference surface. Figure 20 shows the leveling boxes for a surface with a known step feature running down the center of the image.
- Change the size of a box by clicking and dragging on a corner of the box.
- Move a box by clicking and dragging the crosshair at the center of the box.
- Avoid including anomalies such as bumps or pits inside the boxes, but features inside the triangle will not matter since only the three center points define the leveling plane.
- Observe the line profile pane for assistance. Vertical and horizontal lines are drawn through the center points of the boxes in the 2D Composite View pane, six lines in all. One line is the active line and is colored green; the profile of this line appears in the 2D Line Profile pane. The active profile changes as you click on different lines. These profiles help you to decide where to move the leveling boxes. As shown in figure 20, the boxes are all positioned on the base surface and not on the step feature.
- In the right-click menu, select Level Surface. The plane defined by the box center points is now the zero height plane.
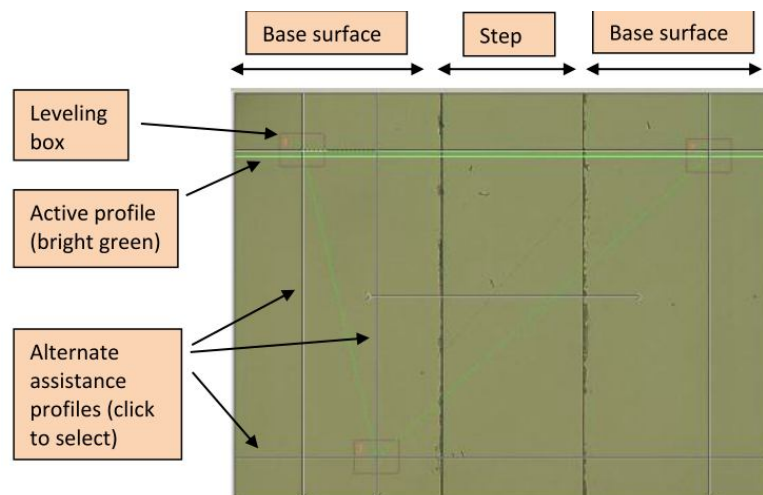

Figure 20. Leveling boxes for setting reference surfaces

3.5.4   Step Height between two areas

To provide more averaging, it may be useful to calculate the height difference between large areas on the sample surface. The process for doing such measurement is as follows:

- First, set the reference plane using the surface leveling procedure.
- In the right-click menu, select Boxes Step Height. One red rectangle appears on the 2D image.
- In the right-click menu, select Add Area Box. A second red rectangle appears on the 2D image and new calculations appear in the Analysis Report.
- If desired, add a third box in the same way. The maximum number of boxes is three.
- Change the size of a box by clicking and dragging on a corner of the box.
- Move a box by clicking and dragging the crosshair at the center of the box.

The Analysis Report displays the average height of each box, the length and width of each box, and the height difference between each pair of boxes. Each box is labeled 1, 2, or 3 in its upper left corner. An example of box step height analysis is shown in Fig. 21.
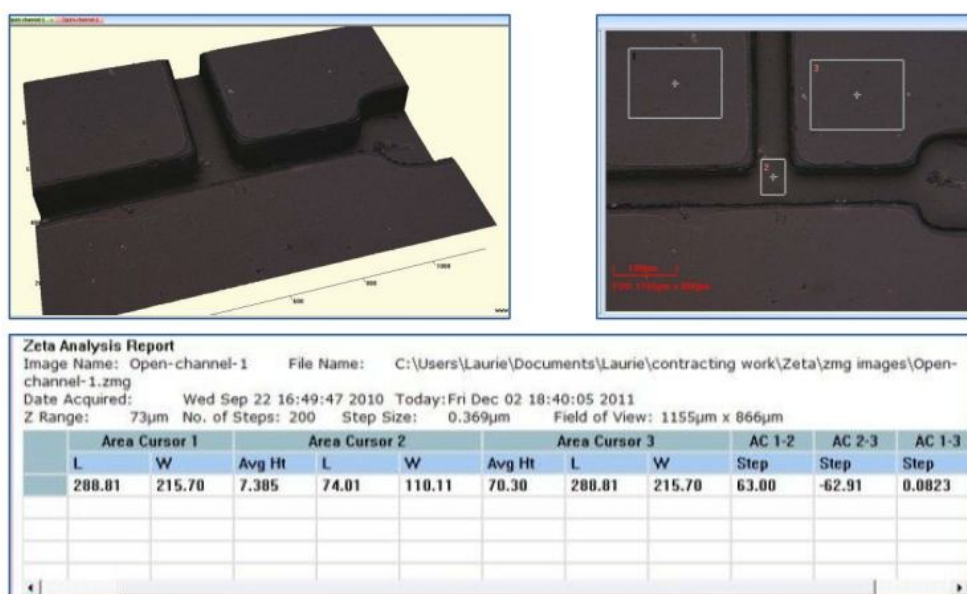

Zeta Analysis Report
Image Name: Open-channel-1   File Name: C:\Users\Laurie\Documents\Laurie\contracting work\Zeta\zmg images\Open-channel-1.zmg
Date Acquired: Wed Sep 22 16:49:47 2010 Today:Fri Dec 02 18:40:05 2011
Z Range: 73µm No. of Steps: 200   Step Size: 0.369µm   Field of View: 1155µm x 866µm

	Area Cursor 1		Area Cursor 2			Area Cursor 3		AC 1-2	AC 2-3	AC 1-3
	L	W	Avg Ht	L	W	Avg Ht	L	W	Step	Step	Step
	288.81	215.70	7.385	74.01	110.11	70.30	288.81	215.70	63.00	-62.91	0.0823

Figure 21. Box Step Height Analysis

3.5.5 Roughness Measurement
Roughness is a statistical measure of surface height variation, usually over a small length scale. Zeta software provides eight standard roughness parameters as shown in table 2 for each analysis region.

Table 2. Roughness Parameters

Parameter	Meaning
Ra	Arithmetic average of deviations from the mean
Rq	Root mean squared value of deviations
Rpv	Maximum peak to valley difference
Rp	Maximum peak height
Rv	Maximum valley depth
Rz	Average of (Rp – Rv) from five sections
Rsk	Skewness (asymmetry of distribution)
Rku	Kurtosis (shape of distribution peak)

Roughness analysis can be done by either one of these ways:

- Position the mouse cursor within the 2D Line Profile pane and right click to bring up a menu, then select Roughness.
- Check the checkbox labeled Roughness, located on the right side of the toolbar in the Analysis tab.

A typical roughness analysis window is shown in Fig. 22. The 2D Composite View pane is used to define the locations of cross section lines exactly the same way as for step height analysis. However, the analysis regions for roughness are defined with markers, not cursors. To analyze roughness, follow these steps:

- In the 2D Composite View, create a cross section with the desired orientation, length, width and position.
- Move markers 1 and 2 until they enclose the first area for roughness analysis. Observe the results in the Analysis Report; they change as you move the cursors.
- If you would like to analyze another portion of the same profile, add two more markers to the profile and move them to enclose the second analysis area. Add a third set of markers if desired.

For each pair of markers, a set of eight roughness parameters is calculated. The example in figure 22 shows that the region between markers 1 and 2 is much rougher than the region between markers 3 and 4.

Roughness of a surface may be very uniform or very non-uniform. Sometimes it is appropriate to calculate roughness over an area instead of a line in order to capture the average qualities of the region. From the 2D composite view, 'Boxes Roughness' can be selected from the right click options and corresponding data will be updated in the analysis pane. Upto three boxes can be added for such

analysis. Roughness parameters for an area are written with the initial letter of S instead of R to denote that they indicate roughness for a surface instead of a line.

Figure 22. Roughness Analysis

3.5.6 Waviness Correction

Waviness refers to long-wavelength curvature of the surface. It affects the roughness calculations if its scale approaches the roughness analysis length. The Zeta 3D software provides a way to reduce the effect of sample waviness on a line profile. Steps for waviness correction are as follows:

- Create a cross section for analysis and move markers 1 and 2 to the boundaries of the region of interest. When waviness correction is applied, only markers 1 and 2 are analyzed even if other markers are present.
- Move the waviness slider control from left to right. The control is shown in Fig. 23 and it is located under the Roughness checkbox in the toolbar. The far left slider position causes the value of zero to be displayed in the numeric field; this means that no waviness correction will be applied. As the slider moves to the right, the numeric value increases and the amount of correction increases.

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- Observe the 2D Line Profile graph as the slider moves. A green line is drawn through the original data to show the underlying surface, as calculated using the amount of waviness correction selected by the slider position. The underlying surface height is subtracted from the original data to produce a corrected profile, which is drawn in red. This is shown in Fig. 24.

The waviness correction applies to the shape of the 2D profile graph. This is different from the use of the 3D image Gaussian filter, which applies to the entire scanned surface.

Figure 23. Waviness Control Option
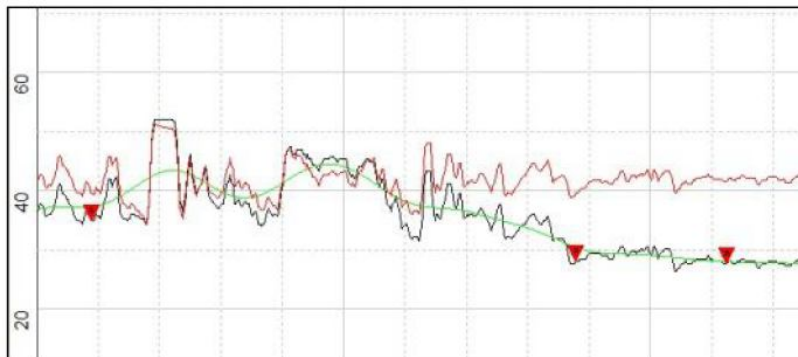
Figure 24. Example of waviness correction

3.5.7 Measurements in lateral dimensions

Two-dimensional Zeta images can be used to measure lateral dimensions of features on the surface. Either the microscopic image or the composite image after the complete scan can be used for such measurements. For the microscopic image, the either image may not be in focus as in the composite image case. There are various measurement options that can be used by either right-clicking the 2D image or from the tool bar of the 2D image window. Measuring area or volume of features on the sample surface can also be accomplished with Zeta 20 microscope. The procedure is more complex,

but it allows user to make repeated measurements on similar features more quickly than the manual method using drawing tools. The steps for area or volume measurement are as follows:

- Set a reference surface as described in the section Surface leveling. To calculate feature volumes accurately, the reference surface must be a plane at the base of the features.
- With a 2D composite image in a full-screen view, right click to bring up the menu. Select Measure, then select Region in the drawing tools menu. A dialog box titled 'Region Grow' appears, as shown in Fig. 25.
- Start with Region 1 in the pulldown menu; you can define up to two regions.
- Choose either Color or Z Height for the selection method. Experiment with both methods to decide which one works best for a given sample. Each option uses slider controls to set the upper and lower thresholds for selection. Color has three pairs of sliders labeled Red, Green and Blue; the Move All checkboxes enables faster operation by moving the three related sliders together. Z Height has one pair of slider controls.
- Use the slider controls to change the upper and lower thresholds. Start with the controls in the middle of their ranges. Do not close the dialog box.
- Click on a feature in the 2D image. A red outline will appear that defines the boundaries of a region with the properties defined by the sliders. Every feature is labeled with an index. As soon as a feature is defined, a results table appears to the right of the image pane, as shown in Fig. 26. The reported parameters for each feature are the X and Y locations, the major and minor axis lengths (in microns), the area (in square microns), the volume (in cubic microns), and the X and Y locations of the highest point of the feature.
- If the outline is not good enough, delete it by right clicking on the feature and selecting Delete in the menu. The data is also deleted.
- Change the upper or lower color thresholds and click on the feature in the image again. This is an iterative procedure; keep moving the sliders until you are satisfied with the red outline.
- Click on all features of interest in the 2D images to add them to the list. Adjust thresholds as needed to optimize the boundaries for each feature.

Since data does not update automatically when the settings are changed, every feature in the data list might have been defined using a different parameter (color or height) and different slider settings. Two complex surface can be considered for analysis by using the 'Combine 2 regions' option in which both the regions can be totally different settings.
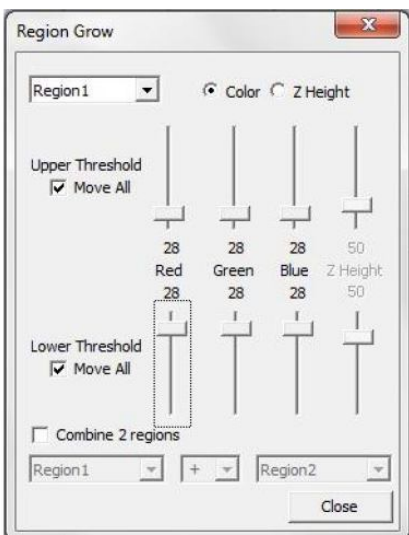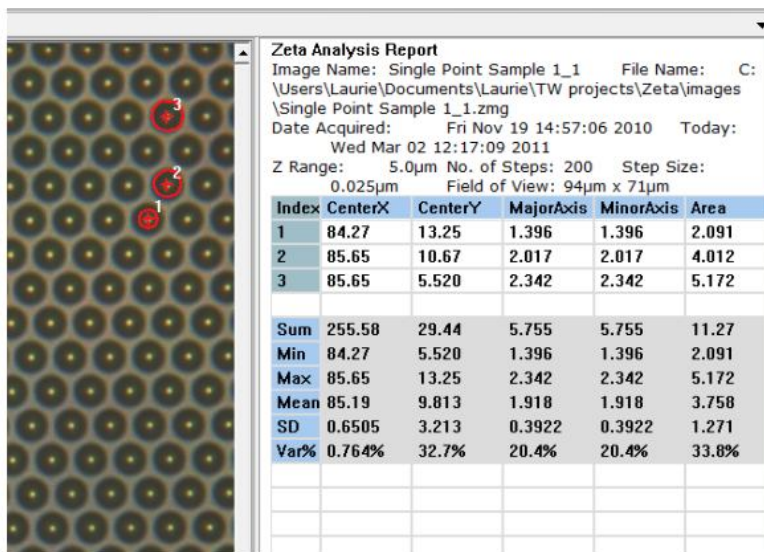
Figure 25. Region Grow dialog box

Figure 26. Measure by Region example

3.5.8 Important Recipe Parameters

In addition to the parameters related to image focusing presented above, there are additional important parameters which need to be understood for making measurements across different types of samples. The various parameters are shown in figure 27.

3.5.8.1 Image Quality Parameters
These parameters are usually left at their default settings but may be changed for special purposes.

- Min Contrast and Min Intensity is used to reduce noise; zero is the default.
- Smooth checkbox selects whether to use smoothing on the 3D image; the default is yes (box checked).
- 3D Extraction defaults to Standard.
- Visual Quality is a slider control that ranges from 0 to 100. If you reduce the quality below 100, the system stores a color picture less often than it stores the Z-dots image (which contains the actual height information). For example, if the value is 20, then a color image is stored every five measurement steps. The final 2D and 3D images will be less sharp visually, however the underlying surface height accuracy is not affected. Reducing the Visual Quality allows the use of more measurement steps.
- Shutter1 defaults to 400ms (for the 1/3-inch camera), which is good for most samples. If the image is too bright, decrease this value, and if it is too dark, increase it, but not above 750ms.
- Gain1 defaults to 75 (for the 1/3-inch camera), which is good for most samples. If the image is too bright, decrease this value, and if it is too dark, increase it.
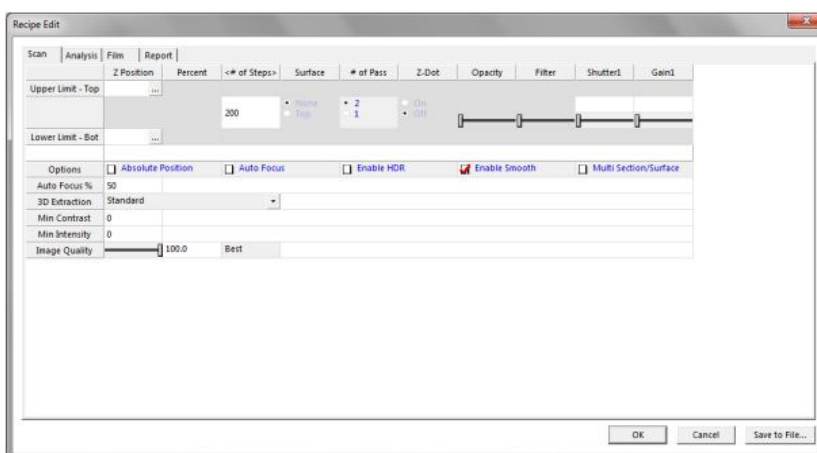

Figure 27. Scan options under the Edit Recipe Tab

3.5.8.2 High Dynamic Range Scanning Parameters

Some surfaces are more difficult to scan than others. For example, on some solar cell wafers, metal contact lines have very high reflectivity (greater than 90%) while the adjoining nitride regions have extremely low reflectivity (less than 1%). Imaging such a surface in one scan requires the system to have a large dynamic range, while maintaining the required vertical resolution to create a good Z-profile. The Zeta solution is a scanning technique that includes the use of two different camera settings and an algorithm for optimizing the quality of the image at the interface between high and low reflectivity regions. To enable HDR (high dynamic range) scanning, check the checkbox labeled "Enable HDR." This causes two more slider controls to appear. They control the shutter and gain for the second camera setting. The procedure for HDR (high dynamic range) scanning is as follows:

- Open a recipe for editing and check the Enable HDR checkbox.
- Turn Focus Assist off.
- Follow standard procedures to load a sample, find the feature of interest, and focus on the sample.
- Adjust the illumination until the bright features in the surface are not over saturated while the dark features are visible.
- Turn Focus Assist on.
- In the Recipe Edit dialog, use the Shutter1 slider control to increase the shutter to 700, then use the Gain1 slider control to increase the gain until the low reflectivity surface near a high reflectivity feature is well illuminated.
- Use the Shutter2 and Gain2 sliders to decrease both values until the high reflectivity surface is not saturated and is clearly visible (During the installation it was recommended to set the gain value for both shutters to 75).
- Click OK to close the recipe editor.
- Follow the standard procedure to set top and bottom of the scan range.
- Click Scan in the Scan Dialog.

3.5.9 Standard Recipes

3.5.9.1 Pyramid Recipe

Pyramids analysis is a recipe for textured solar cell substrates. Anisotropic wet etching of monocrystalline silicon creates a series of pyramid structures which serve to enhance the absorption of light. This light trapping effect increases solar cell efficiency. Fig. 28 shows an example of a Zeta-20 scan of a textured silicon wafer for solar cell manufacturing. The size of the pyramids in the vertical and lateral dimensions affects the quality of devices manufactured on the substrate. The Zeta-20 Pyramids

recipe analyzes the quality of textured substrates by counting the pyramid structures and measuring their heights.

Scan the sample with the following conditions:

- 1/3-inch camera with either the 0.35X or 0.5X coupler or 2/3-inch camera with the 0.5X coupler
- 100X objective
- One-pass scan with Focus Assist turned off

Image files may be saved for later analysis. Load the Pyramids recipe. Then, in any 3D image window, click on Z Analysis in the Image Type group on the toolbar. An analysis such as the one shown in figure 28 appears. The analysis is based on the 2D composite image; the 3D image is presented for illustration only. The software finds the peaks of the pyramids in the field of view and marks them with a red cross, as shown in figure 29. The 2D line profile is a conventional cross section, but the results pane shows the Pyramids analysis. The results include the following parameters:

- <u>Size</u> is the lateral size of the pyramids in microns, showing the mean and standard deviation of all pyramids counted.
- <u>Height</u> is the vertical size of the pyramids in microns, showing the mean and standard deviation. The baseline surface is calculated as the height for which 5% of the field of view is below it. The pyramid heights are measured with respect to the baseline surface.
- <u>Count</u> is the number of pyramids in the field of view. The density is also calculated.
- <u>Surface Area</u> is the total surface area of all pyramids in the field of view (FOV), while Ratio is the pyramid surface area divided by the area of a plane the size of the FOV.

Right click on the 2D image pane or the line profile plane to display histograms for the size and height parameters, as shown in figure 30.

ge:	14µm No. of Steps: 150		Step Size:	0.096µm		Field of View: 127µm x 9	
Size		Height		Count		Surface Area	
Mean	StdDev	Mean	StdDev	FOV	/mm2	FOV	Ratio
5.334	1.243	4.868	1.496	243.0	19934.55	17727.93	1.454

Figure 28. Analysis window for pyramid recipe
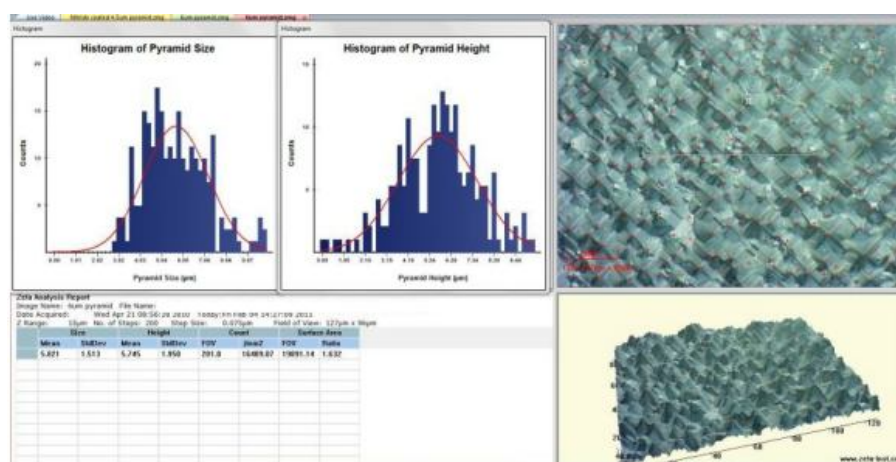
Figure 29. Pyramid locations after analysis

Figure 30. Histogram screen for pyramid recipe

3.5.9.2 Finger Width Measurement Recipe

A common solar cell design consists of a semiconductor wafer with metal contact lines on the surface. The substrate has been processed to absorb light and convert it to electricity, and the metal lines serve as electrical contacts. The metal contact finger dimensions must be tightly controlled in order to maintain low contact resistance without covering too much of the wafer surface. Fig. 31 shows a Zeta 3D image of a solar contact finger. The background semiconductor has very low reflectivity because it is designed to absorb as much light as possible; often it is coated with silicon nitride. The metal line has very high reflectivity. Measuring both surfaces in the same scan can be difficult for many instruments, but the Zeta-20 uses High Dynamic Range scanning to optimize imaging for both surfaces.

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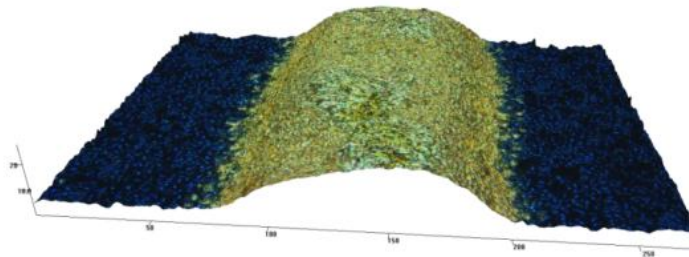
Figure 31. 3D image of metal finger on a solar cell

Choose an objective that produces an image in which the metal line occupies between 10% and 50% of the field of view, oriented vertically. The recipe displays guide boxes on the live video image to indicate approximately where the background and metal areas should be placed. Then follow the steps listed below:

- Load a Solar Finger recipe.
- Focus on the wafer surface and adjust Shutter 1 and Gain 1 to see the nitride surface.
- Next focus on the metal line and adjust Shutter 2 to see details in the metal surface. Gain 2 must be the same as Gain 1.
- Take the scan. Two images are taken at every Z height, one using Shutter 1 and Gain 1 and the other with Shutter 2 and Gain 2. (Due to the constant switching of illumination conditions, a High Dynamic Range scan exhibits more flashing than other scans.) For every pixel, the two images are examined and the pixel in best focus is chosen. In this way the background surface is imaged with Shutter 1 and Gain 1 while the metal surface is imaged with Shutter 2 and Gain 2.

After scanning, an analysis screen similar to the one in Fig. 32 appears. Ten cross sections cross the metal line. One set of cursors defines the background surface height, while a second set of cursors defines the metal line height. In the analysis results, the step height between the two sets of cursors is calculated for each of the ten cross section lines, as shown in Fig. 33. The width of the line is also displayed, and statistics for the ten data sets appear at the end of the list. The area and volume of the metal line in the field of view are shown in the heading.
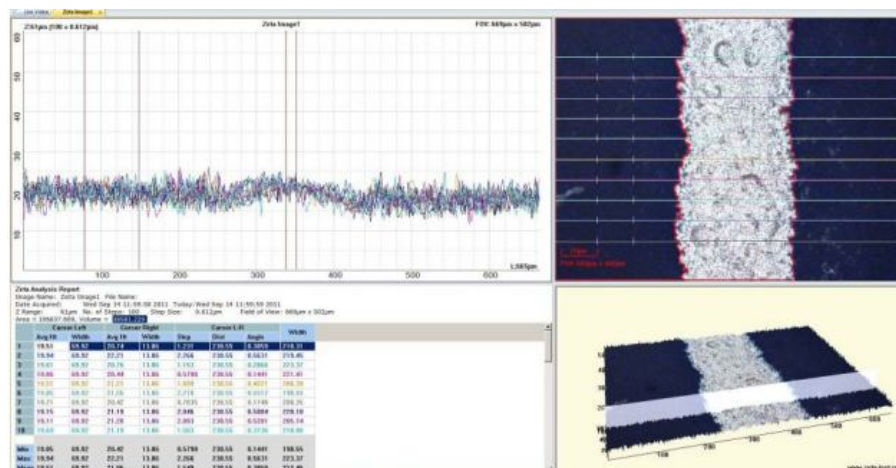
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Figure 32. Result of solar finger recipe

Figure 33. Details of the finger analysis

4. Standard Operating Procedure

Most of the features and operating steps with the Zeta 20 3D microscope have been covered in previous sections. The aim of this section is to outline the step by step operation of the microscope to ensure proper measurement with correct settings. The detailed flow of operation is explained in table 3 below.

Table 3. Standard Operating Procedure for the Zeta 20 3D microscope.

No	Steps	Points to keep in mind
1	Turn ON the mains switch for Zeta 20 and computer system.	Be careful while removing the cover from the system so that the cable is not loosened.
2	Switch ON the computer and wait for 30 seconds after logging in.	Always turn on the computer system before the microscope.
3	Turn ON Zeta 20 3D microscope.	Always turn on the microscope after the computer system. Check the connections from Zeta are not loose.
4	Click on the 'Zeta 3D' icon on the desktop to run the software.	
5	Enter the login name and password to come to the main page of the software.	Please wear hand gloves before operating the instrument.
6	Set the objective to lowest magnification i.e. 20x in our case.	Ensure the corresponding magnification is selected in Live Image. By default a magnification of 0x0 is indicated.
7	Place the sample under the objective with help of tweezers.	- Use the X-Y stage and angular movement to select the appropriate area for observation. - Please don't load the sample with hands as it might damage the objective.
8	Move the objective towards the substrate via the 'Down' button in the 'Live Image' tab till the objective moves down to a safe operating distance.	Spacebar has to be kept pressed continuously during this time interval
9	Move the objective manually via the Page Up/Page Down, F3/F4 or by placing the mouse in the focus wheel box and rolling it up or down to be close to the sample.	Page Up/ Page Down moves the objective at medium speed, while F3/F4 moves the sample at high speed.
10	When the head is almost at working distance from the sample, uncheck the checkbox labeled 'Fast' in the Scan Dialog to reduce the Z movement speed in all mouse and button operations.	Be careful not to crash the optical head into the sample. If you cannot see an image in the live video window, look at the objective to make sure that its height above the sample is approximately the same as the expected working distance.

11	For relatively flat samples, turn on the Focus Assist to see the grid lines (Z-dots) and adjust the focus. Once focused, turn off the Focus Assist.	Under focused condition, the dots will be clearly visible and vice-versa.
12	Depending on the feature size to be observed, select the magnification to either 100x or 20x.	Focusing has to be adjusted if other magnification objective is selected.
13	Load a specific Recipe if saved previously or preloaded.	Follow the steps as discussed for the corresponding recipes before.
14	Adjust the brightness by moving the mouse up/down in the image brightness box to ensure proper illumination of the sample. Also turn on the focus assist and check for sufficient illumination.	The sample should not be over or under illuminated as it will lead to loss of features and resolution.
15	For samples like metal finger, adjust the light intensities as discussed in the High Dynamic Range Scanning section.	Gain for both the shutters should be set to75.
16	Set the top limit of scan by moving the objective up and ensuring the image is completely out of focus.	-Focus Assist can be used for relatively flat samples.
17	Set the lower limit of scan by moving the objective down and ensuring the image is completely out of focus.	- Unchecking the 'Fast' in Scan Dialog is recommended during setting of the limits.
18	Check the Range, Step size and Number of Steps in the dialog box.	Ensure the step size is not below the minimum limit. Number of steps can be changed later for better results.
19	Perform the Scan by clicking on the 'SCAN' icon.	Don't perform any other operation on the system during the scan.
20	Analyze and Save the data as per the requirements with the features described previously.	- Do not open more than 4 windows during each analysis run. - Be careful while analyzing the data at different points and areas of the sample to ensure proper observations are being made. - Save the data in your corresponding department and respective folder.
21	Turn off the software by closing from the top right corner close icon.	Allow the objective to be repositioned to its initial position as prompted by the

		software.
22	Remove the sample with help of tweezers from the chuck.	- Please don't remove the sample with hands as it might damage the objective. - Don't Forget to take the samples after the measurement.
23	Take the data on a CD.	Taking data via USB is not allowed.
24	Turn OFF the computer system.	Always turn off the computer system first.
25	Turn OFF the Zeta microscope.	Always turn off the microscope last.
26	Turn OFF the mains switch of the microscope and computer system.	Cover the instrument after turning off the systems.
27	Make an entry in the log book and also update the same online	Please report and update any issues or observations regarding operation of the instrument

5. Commonly Observed Errors with the instruments

5.1 Markers Bug

Sometimes the markers tend to freeze and not move as shown in figure below. The work around is to close the analysis window and redo the scanning. The problem is not much observed since the software was updated.
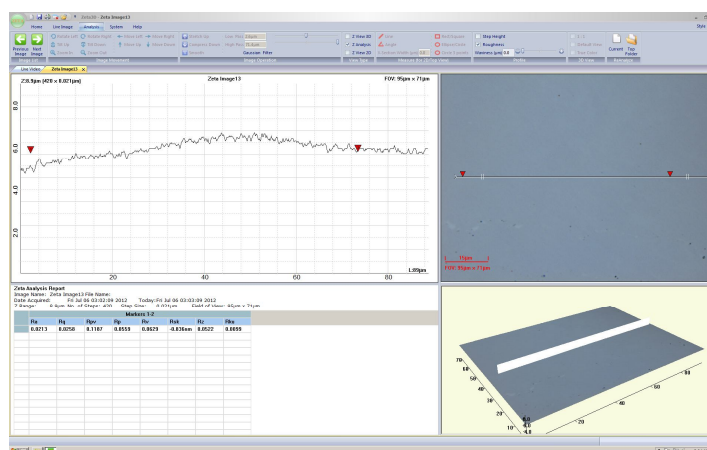

Figure 34. Marker Error with marker frozen at undefined position

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5.2 White and Green Screen on startup

At times after starting the instrument, white or green screens were observed. Also a dll error can also be indicated at times. Based on our experience, it seems these errors are related to lose connections from the instrument. So please ensure that the connections are not loosened while removing the cover or turning on the system mains.
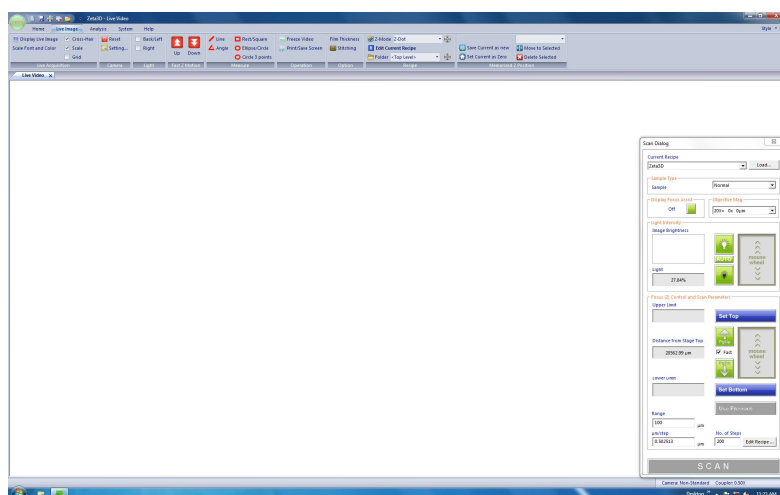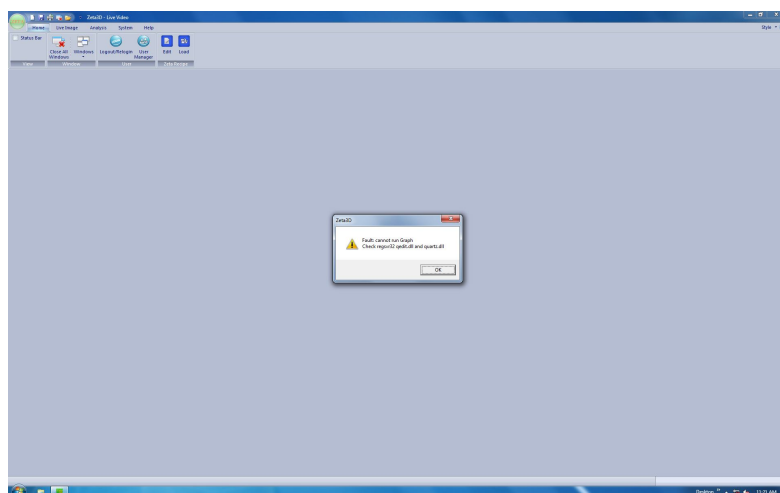

Figure 35. White Screen observed after start up

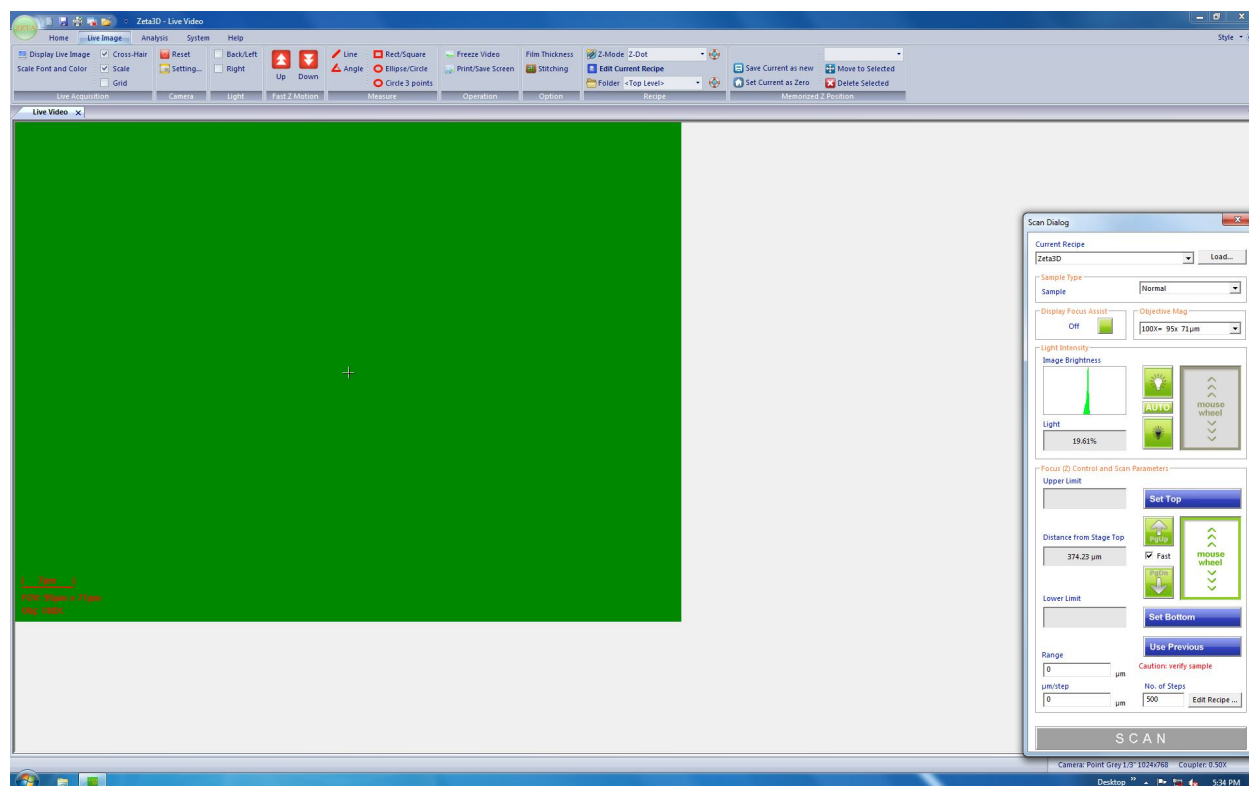**Figure 36. Dll Error associated with the white screen error**

Figure 37. Green Screen Error observed during start up

6. References

1) Zeta-20 Optical Profiler Operation Manual.

7. Revision Details

1) **Version 1.0**- Initial Draft of the Manual prepared by Mehul C. Raval.
2) **Version 1.1**- Updated the SOP and included some commonly observed errors.