Introduction
When using the P-Series or HRP-Series profilers, the user sets up recipes that may include a variety of 3D measurement parameters. Although these parameters are discussed briefly within the Profiler Reference Manual, this Applications Note serves to provide greater mathematical detail regarding the equations used to generate the parameter values. Also included in this discussion are manual post-scan measurements based on 3D scan data.

Background
3D measurements are based on the unfiltered 3D scan data; these measurements do not include the applied Noise or Waviness Filters that the user defines within the Scan Recipe. The Noise and Waviness filters apply to 2D data only. The 3D data includes only the 3D Median Filter and any leveling that has been applied via 3D Line Leveling, 3D Planar (triangle) Leveling, and Histogram-based Leveling. 3D measurements may be calculated for the entire scan (Full Scale) and/or for a smaller user-defined sub-region (Boxed) within the original large scan. Note that any measurements calculated for a Boxed region use the Full Scale leveling plane as the baseline reference. The user may prefer to level the scan with respect to the boxed region of interest.

Definitions
The following pages list the 3D measurement parameters according to measurement category:
- General Parameters
- Roughness Parameters
- Bearing Ratio and Cutting Depth Parameters
- Manual 3D Measurements Parameters
- Histogram Depth Parameters
- Chemical-Mechanical Polishing (CMP) Analysis Parameters

A basic definition is provided along with the equation(s) used to generate the parameter values. In a calculation, x has M data points and y has N data points, and zi,j refers to the specific height value z at the location (xi,yj). The number of data points M and N used in the calculation depends upon the lateral dimensions of the region of interest and the recipe parameters selected.

The height value z depends on the step height calibration for the vertical range used for the measurement. Therefore, all parameters are based on the step height calibration unless noted. In the following calculations, the leveled z plane is defined as the reference plane, with height of 0, unless otherwise noted.

3D General Parameters
Within the General Parameters category, the 3D measurements...
include Total Indicator Runout [TIR3D], SlopeX, and SlopeY, 3D Peak (Sp) and 3D Valley (Sv). These measurements can be based on the full scan area and/or a partial boxed region.

**Total Indicator Runout** is defined as the difference between the highest and lowest points in the region, in units of length:

\[ \text{TIR3D} = z_{\text{max}} - z_{\text{min}} \]  

(1)

**SlopeX** is defined as the root-mean-square value of the surface slope in the x direction, in units of degrees:

\[ \text{SlopeX} = \tan^{-1} \left( \frac{1}{(M-1)(N-1)} \sum_{i=1}^{M} \sum_{j=1}^{N} \frac{(z_{i,j} - z_{i+1,j})}{\Delta x} \right)^{2} \]  

(2)

where \( \Delta x \) is the sampling step in x direction.

**SlopeY** is similarly defined as the root-mean-square value of the surface slope in the y direction, in units of degrees:

\[ \text{SlopeY} = \tan^{-1} \left( \frac{1}{(M-1)(N-1)} \sum_{i=1}^{M} \sum_{j=1}^{N} \frac{(z_{i,j} - z_{i,j+1})}{\Delta y} \right)^{2} \]  

(3)

where \( \Delta y \) is the sampling step in y direction.

**3D Peak (Sp)** is defined as the height difference of the highest peak from the reference z plane.

\[ S_p = z_{\text{max}} \]  

(4)

**3D Valley (Sv)** is the height difference between the lowest valley and the reference z plane.

\[ S_v = z_{\text{min}} \]  

(5)

### 3D Roughness Parameters

Within the Roughness Parameters category, the 3D measurements include:

- RMS Deviation [Sq]
- Arithmetic Mean Deviation [Sa]
- Skewness of surface height distribution [Ssk]
- Kurtosis of surface height distribution [Sku]
- RMS Slope [Sdeltaq]
- Ten Point Height [Sz]
- Density of Summits [Sds]
- Developed Interfacial Area Ratio [Sdr]

**RMS Deviation of a Surface** is defined as the root-mean-square value of the departures relative to a reference plane, the leveled z plane, in units of length:

\[ \text{Sq} = \sqrt{\frac{1}{(M-1)(N-1)} \sum_{i=1}^{M} \sum_{j=1}^{N} z_{i,j}^2} \]  

(6)

This parameter is insensitive to sampling interval but is sensitive to the sampling area and is indicative of surface roughness.

**Arithmetic Mean Deviation** is defined as the arithmetic mean of the absolute values of the surface departures above and below the leveled z plane, in units of length:

\[ \text{Sa} = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} |z_{i,j}| \]  

(7)

**Skewness** is defined as a measure of asymmetry of surface deviation about the mean Z plane, based on the RMS deviation. Skewness is a dimensionless quantity:

\[ \text{Ssk} = \frac{1}{\text{MN(Sq)^3}} \sum_{i=1}^{M} \sum_{j=1}^{N} z_{i,j}^3 \]  

(8)

A symmetric surface height distribution about the mean will yield \( \text{Ssk} \approx 0 \). If the data is weighted more heavily above or below the mean, \( \text{Ssk} \) will be positive or negative, respectively, as shown in Figure 1.

![Figure 1: Skewness of Surfaces](image)

**Kurtosis** is a measure of the peakedness or sharpness of the surface height distribution, in dimensionless units. It is a measure of the spread of the data. A Gaussian distribution has a kurtosis value of 3, a peak sharper than the Gaussian has a kurtosis value greater than 3, and a peak flatter than the Gaussian has a kurtosis value less than 3, as shown in Figure 2:

\[ \text{Sku} = \frac{1}{\text{MN(Sq)^4}} \sum_{i=1}^{M} \sum_{j=1}^{N} z_{i,j}^4 \]  

(9)

![Figure 2: Kurtosis of Surfaces](image)

**RMS Slope** is defined as the root-mean-square value of the surface slope. The surface slope at any point is described as:
Interfacial Area Ratio is defined as the percent increase of the interfacial (actual) surface area over the projected surface area. The interfacial surface area is calculated by summing the average area of each of the smallest sampling quadrilaterals, where the average area of a quadrilateral is defined as:

\[
100% \left( \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} A_{ij}}{(M-1)(N-1) \cdot \Delta x \cdot \Delta y} - 1 \right)
\]

where \(A_{ij}\) is defined as:

\[
A_{ij} = \frac{1}{4} \left[ (\Delta y^2 + (z_{ij} - z_{ij+1})^2)^2 + (\Delta x^2 + (z_{ij+1} - z_{ij})^2)^2 \right]
\]

The projected surface area is simply the scan area \((M-1)(N-1)\Delta x \Delta y\). Therefore, the increase in surface area is the interfacial area minus the projected area, and the interfacial area ratio is then expressed as:

\[
S_{dr} = \left( \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} A_{ij}}{(M-1)(N-1) \cdot \Delta x \cdot \Delta y} - 1 \right) \cdot 100%
\]
StepHeight =
\[
\frac{\sum_{i=1}^{N_1} \sum_{j=1}^{M_1} x_{i,j}}{M_1N_1} - \frac{\sum_{i=1}^{N_2} \sum_{j=1}^{M_2} x_{i,j}}{M_2N_2}
\]  \tag{19}

Histogram Depth Parameters

2D histogram depth analysis enables automatic measurement of step height(s) based on the use of a histogram to identify significant populations of data (modes). Histogram depth analysis can be separated into three functions:

- Data Selection Definition
- Bin Definition
- Depth Definition

Data Selection Definition allows the user to define regions of the scan to be included or excluded, using the cursors. The user can choose:

- All Data
- Data Within Measurement Cursors
- Data Outside Measurement Cursors

Figure 3 shows a copper CMP dishing, erosion, and recess scan. This scan is divided into two regions represented by the white and light gray areas, with the gray area representing the location of the cursors. This enables analysis of the dishing, gray area, by using Data Within Measurement Cursors. Analysis of the erosion and recess, white area, can be done using Data Outside Measurement Cursors.

Bin Definition allows the user to define the properties of significant populations of data. A histogram operates by placing each data point in the scan into a bin that represents the z-height range of that data point. The bins are then analyzed to find significant populations of data (modes). The parameters for bin definition include:

- Number of Bins
- Bin Z-Range Data Inclusion
- % for Qualifying Neighboring Bins
- Minimum Mode Population
- Minimum Depth

Number of bins is used to define the width (z-range) of each bin:

\[
W_{\text{bin}} = \frac{(z_{\text{max}} - z_{\text{min}})}{n}
\]  \tag{20}

where \( n \) is the number of bins, \( z_{\text{max}} \) and \( z_{\text{min}} \) are the maximum and minimum z-heights of the data included in the histogram. Figure 4 shows the change to the dishing histogram when the number of bins is increased from 30 to 60.
maximum of three modes, using the following recipe inputs and equations 21, 22, and 23:

- $B\%_i =$ % Qualifying for Neighboring Bins
- $M\%_i =$ Minimum Mode Population
- $M_D =$ Minimum Depth

$$M_1 > M\%_i \cdot \sum_{i=1}^{n} B_i \quad (21)$$

where $B_i$ is number of the data points in each bin and $M_1$ is the first mode. The bin(s) considered for inclusion in $M_1$ is the bin with the most data points, $B_1$, and the neighboring bins to the left and right, $B_{1L}$ and $B_{1R}$:

$$M_1 = (B_1 + B_{1L} + B_{1R}) \quad (22)$$

where $B_{1L}$ and $B_{1L}$ are included only if they are greater than the product $(B\%_i \cdot B_1)$. This process is repeated to find the second and third modes, $M_2$ and $M_3$, with the additional criteria to be considered a mode that:

$$(M_1 - M_2) > M_D$$

and

$$(M_2 - M_3) > M_D \quad (23)$$

Figure 5 shows how this algorithm is applied to the dishing portion of the scan in Figure 3, using $B\%_i = 50\%$ and $M_D = 500 \text{ Å}$.

To calculate the dishing in Figure 3, the user would select the Highest Plane as the Reference Mode and the Depth 1 as the difference between the Lowest Mode and Reference. To calculate the erosion and recess in Figure 3, white area, the user would first change to Data Outside Measurement Cursors and use similar bin definition values used in the dishing example. The erosion is calculated by selecting the Highest Plane as the Reference Mode and the Depth 1 as the difference between the Lowest Mode and Reference. The recess is calculated by selecting Depth 2 as the difference between the Depth 2 Mode and Depth 1 Mode, which results in measuring from the Lowest Plane to the Next Lowest Plane.

**CMP Analysis Parameters**

Chemical Mechanical Planarization (CMP) is commonly used in a copper process to remove excess plated copper through chemical and mechanical polishing of the wafer surface. Within CMP analysis, the 2D measurements include:

- $z_{\text{mean}} = \frac{1}{n} \sum_{i=1}^{n} z_i \quad (24)$

where $n =$ total number of data points in the bin(s) that are contained in the mode. Or the user can calculate the Percentile of a mode:

$$n_{\%} = \frac{P}{100} \cdot N + \frac{1}{2} \quad (25)$$

where $P =$ percentile and $N =$ total number of data points in the bin(s) contained in the mode. The $z_{\%}$ is the height which results from the ordered rank of the z-height values within the mode that is closest to the $n_{\%}$ value.

The modes are also differentiated either by the z-height, such as Highest Plane or Lowest Plane, or by the number of points in the mode, such as Most Populous Plane. The user then defines one of the modes as a reference and the step heights Depth 1 and Depth 2 are calculated relative to the reference or relative to each other.
Dishing
Erosion
Recess
Edge-over-Erosion

The CMP algorithm includes the same Data Selection Definition option described earlier in the Histogram Analysis section.

In the Feature Definition section, the user can define the Minimum Width of the dishing or erosion pad and a Noise Filter, both improve the accuracy and stability of finding the CMP features. The Minimum Width should be set to about 75% of the actual pad width. The Noise Filter smoothes the profile such that features are easily identified from roughness and noise. Similar to Feature Detection, the Noise Filter is only used as an aid to find the features, but does not impact the calculation of the CMP parameters.

Dishing is defined as the height difference between the field dielectric and the metal pad. The metal pad surface height is the mean height calculation as shown in Figure 6.

Erosion is defined as the height difference between the field dielectric and the erosion pad dielectric. The erosion depth is the height difference between the reference surface and the average of local maxima in the middle 50% range of the CMP feature as shown in Figure 7.

\[ z_e = z_{ref} - \frac{1}{n} \sum_{i=1}^{n} z_{\text{max}_i} \]  

where \( z_{\text{max}} \) is the local maxima in the measurement region and \( z_{\text{ref}} \) is the field dielectric surface.

Recess is defined as the height difference between the erosion pad dielectric and the recess metal. The recess height is the height difference of the average of local maxima and minima in the middle 50% range of the CMP feature, as shown in Figure 7.

\[ z_r = \frac{1}{n} \left( \sum_{i=1}^{n} z_{\text{max}_i} - \sum_{i=1}^{n} z_{\text{min}_i} \right) \]  

where \( z_{\text{max}} \) is the local maxima and \( z_{\text{min}} \) is the local minima in the measurement region.

Conclusion

This applications note has described the 3D measurement parameters available in the P-series profilers: P-7 and P-17 and HRP-series profilers: HRP-250 and HRP-350. Additional applications notes are available to describe the 2D measurement parameters as well as the 2D and 3D parameters available in Apex Advanced Analysis software.