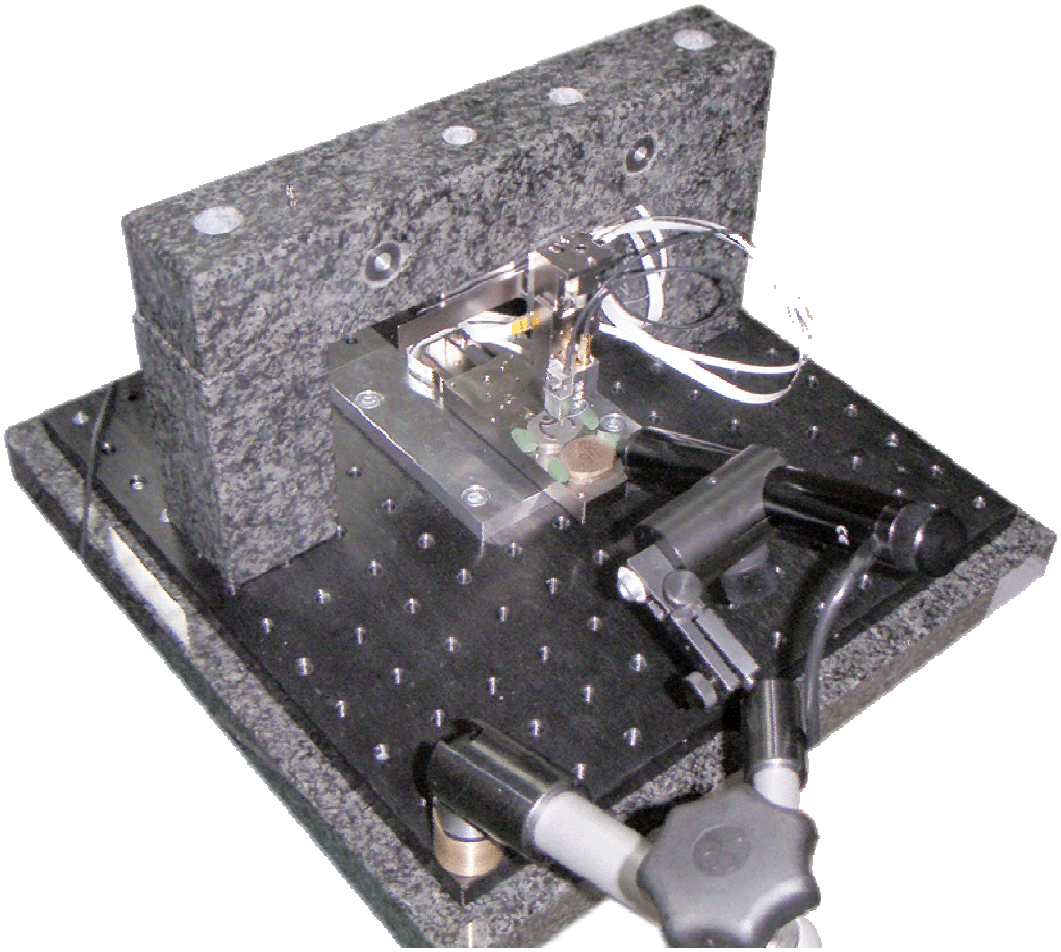
Klocke Nanotechnik



Nanorobotics

Forming the 3D-Nanofinger

Nanorobotics

forming

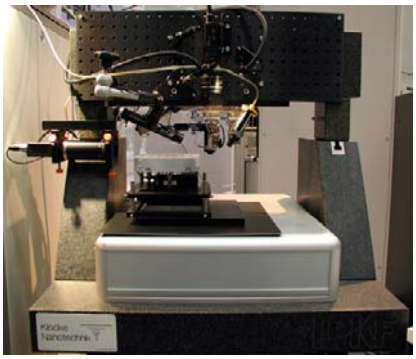
Micro Production Systems or Universal Testing Benches

with Nano-Resolution

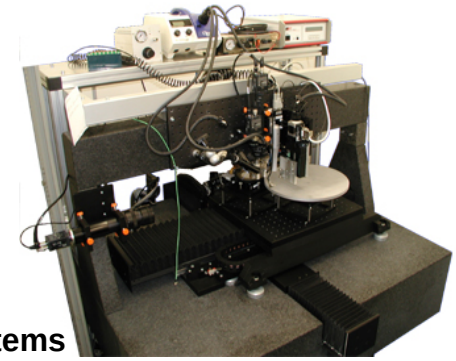
for automatic microassembly and interconnection technology

or as flexible universal system for development and testing

The Nanorobotics series offered by Klocke Nanotechnik is a comprehensive set of tools including electronics and software. A pool of more than 200 components offers plenty of different flexible system configurations as independent machines or for the integration in bigger Nanorobotics systems:



Universal Testing Benches



Micro Production Systems

The bigger systems can form e.g. Universal Testing Benches or Micro Production Systems:

3D-Nanofinger:

The 3D-Nanofinger is a device in-between Profilometers and 3D Coordinate Measuring Machines. The following table with typical values gives an overview about the different principles:

	Profilometer	**3D Coordinate Measuring Machines**	**3D-Nanofinger**
Axes with precise movement	2-dimensional (XZ)	3-dimensional (XYZ)	3 dimensional (XYZ and along a path)
Surface roughness measurement	Yes, in 2D	normally: No	Yes
Dimensional measurement	Yes, but only in one direction along an actuator axis	Yes, in X,Y and Z	Yes, in XYZ and along a path (e.g. a hole)
3D topography measurement	normally: No	normally: No	Yes
Sensor diameter	around 0.2 – 1 micron	around a few mm	around 30 nm – a few mm
Stroke	several cm in X, some mm in Z, sometimes more.	several cm in X,Y,Z	several cm in X,Y,Z and along a path
Objects to measure	Coarse structures, to be measured from one side along one fixed actuator axis	Coarse structures, to be measured from up to 5 sides	Coarse and fine structures from 1-5 sides, measurement along and into them, e.g. into thin holes or grooves => movement not only along the actuator axes.
Integration as module	No, only stand-alone machine	No, only stand-alone machine	Yes, e.g. into a SEM or FIB, into CNC machines, Universal Testing Benches, Micro Production Systems
Automation	No	No	Yes, within a series of more than 200 Nanorobotics components

The upper table may not be correct for an individual machine, but it describes general features of the different machine classes. In comparison with standard Profilometers the 3D-Nanofinger has three equivalent axes of movement and allows the measurement along a path, not only along one axis. This can be used to measure along inner and outer contours, hole diameters.
The metrology features of the 3D-Nanofinger include the following measurements:

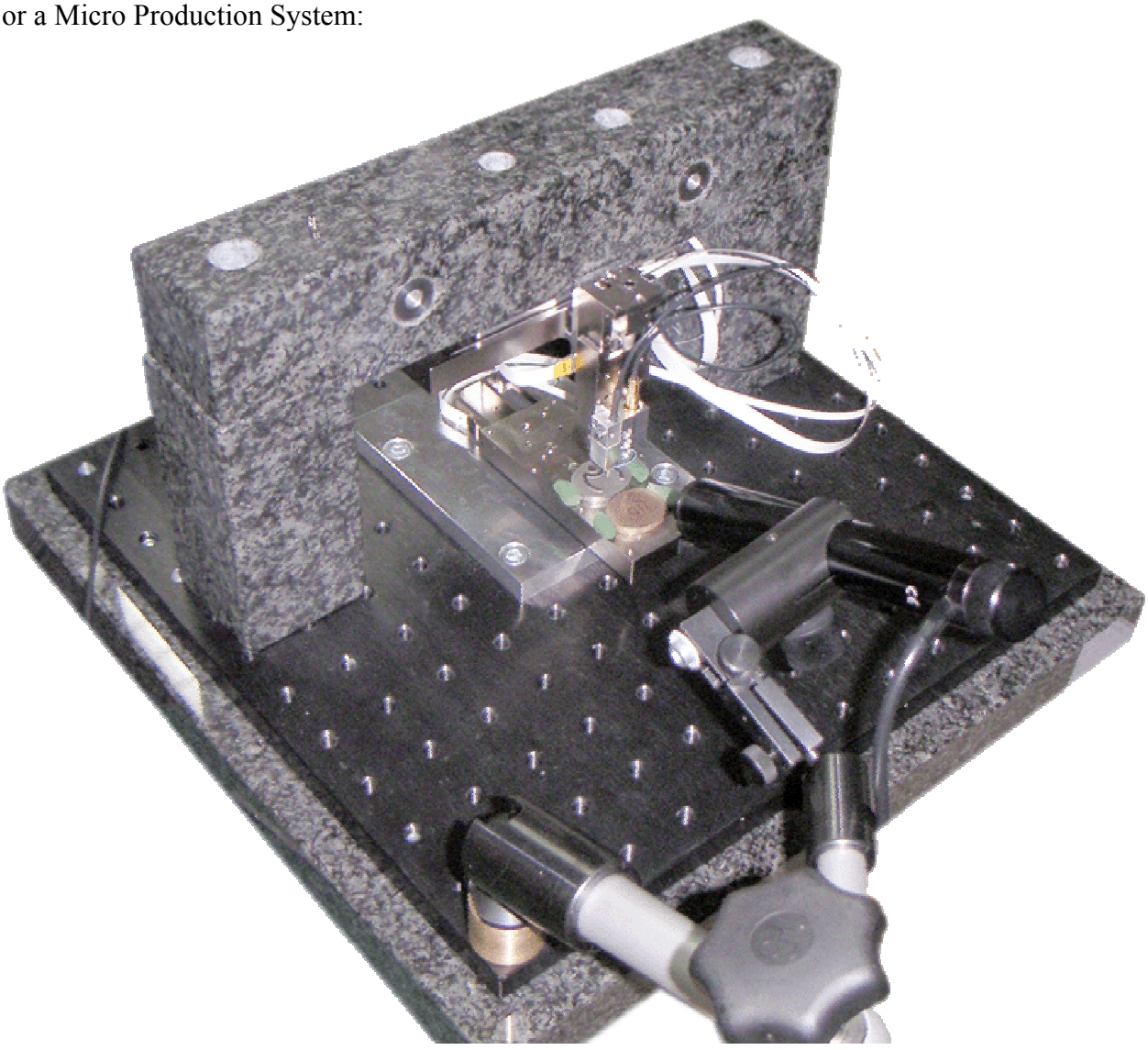
- Sample height
- Step height
- Linescans along an axis
- Linescans along a 3 dimensional path
- Inner and outer contour
- 3D surface topography
- Surface roughness, also along a path
- 3D-Topography, contour and roughness in holes or at side walls

Such measurements can be part of an automation process together with all other features of our Nanorobotics.
The resolution of this unique instrument is comparable with that of SPMs. The measurement range is as huge as that of Profilometers - but in 3D, not only in 2D.

With an optional double-head sensor it is possible to determine a thickness or inner distances of objects by differential measurements. In the same way complete inner structures of small objects can be measured (e.g. 2 opponent V-grooves of a linear ball bearing slide).

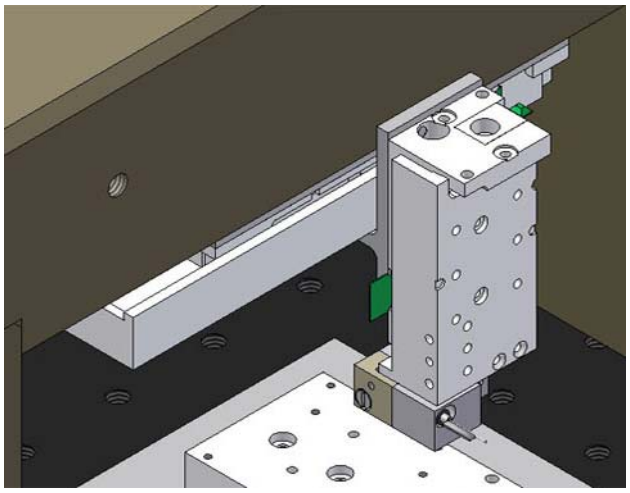
3D-Nanofinger arrangements:

The 3D-Nanofinger is available in several different arrangements. It can be used as stand-alone measurement machine or as module hanging at the Granite bridge of a Universal Testing Bench or a Micro Production System:



Arrangement with 50x50x20 mm^3 stroke and thermally compensated granite frame

Vertical sensor assembly



Sensor flipped horizontally

Mobile 3D-Nanofinger systems:

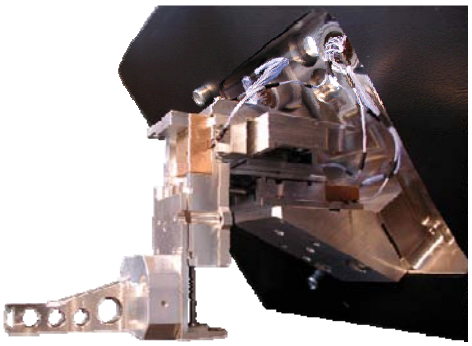
Since the Nanorobotics of this instrument is very small it is not vibration sensitive and can be used without expensive and huge damping systems. The damping system used for the mobile version is visible in the upper image.
Where? Well, have a look at the rubber feed on top of the suitcase…

In-situ 3D-Nanofinger systems:
3D-Nanofinger even fits into existing machines and expands their functionality in a completely new manner, as described in the following three examples:

Inside of CNC production machines:
A CNC grinding machine produces thousands of workpieces. At run time the diameter of the grinding tool shrinks continuously. When the 3D-Nanofinger checks the dimensions e.g. of each 5000'th workpiece, it can detect the resulting discrepancy and send an offset command to the CNC machine: online error correction.

The first real "dimensional SEM/FIB":
Another important example of in-situ solutions is the integration of the 3D-Nanofinger into Scanning Electron and Ion Microscopes (SEM and FIB) for dimensional measurements with Nanometer precision. The metrology features of a SEM/FIB are expanded to the third dimension by all features of the 3D-Nanofinger, measuring:

- Sample height
- Step height
- Linescans along an axis
- Linescans along a 3 dimensional path
- Inner and outer contour
- 3D surface topography
- Measurements in holes or at side walls
- Surface roughness, also along a path



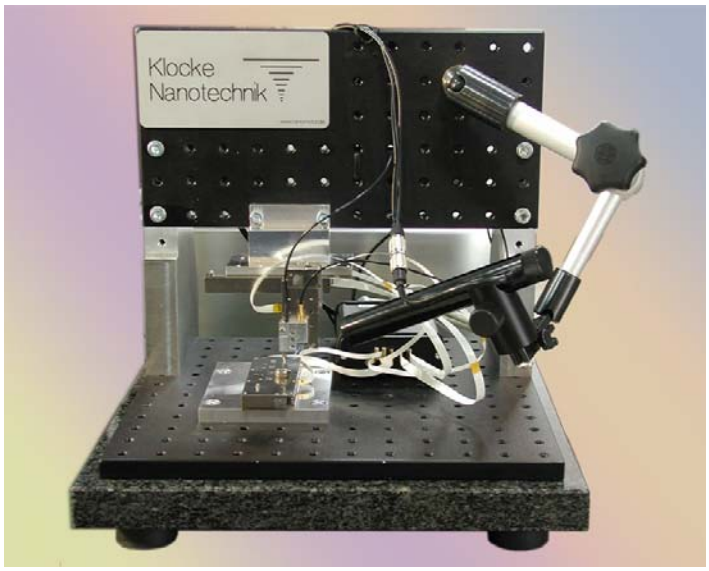
And in a SEM or FIB the automation of the upper tasks can be combined with the automation of the SEM/FIB functionality over the remote control interface of the SEM/FIB.

In a FIB the depth of structures can be determined immediately after producing them with the ion beam of the FIB: as in-situ quality control.

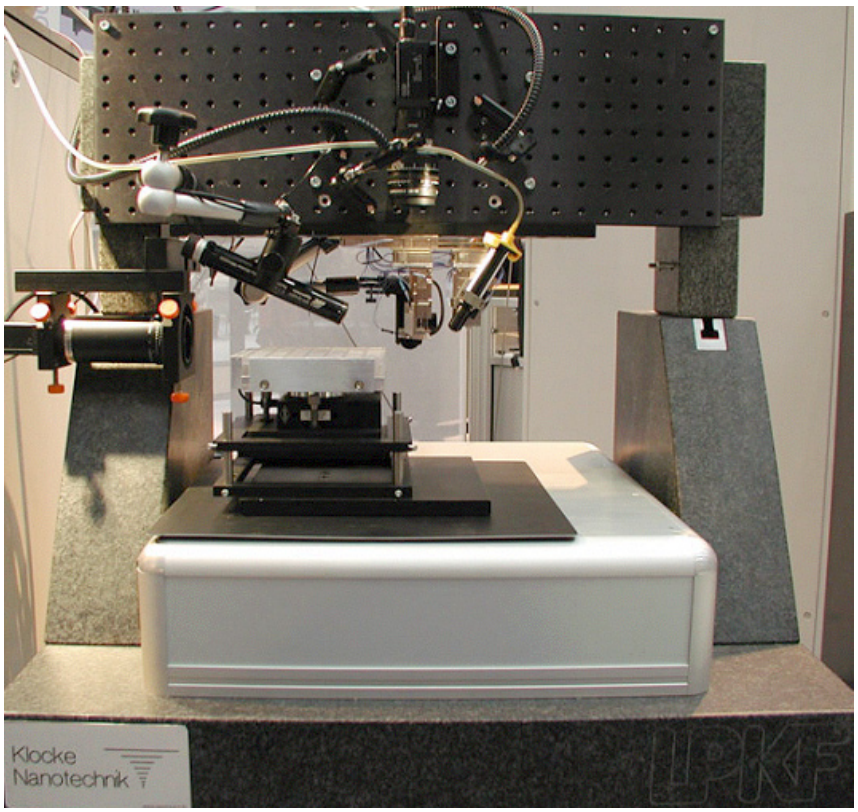
Measurements made with the "dimensional SEM/FIB" are described in the area "sample measurements".

Inside of Universal Testing Bench or Micro Production systems:

The following picture shows the 3D-Nanofinger within the first expansion step of a Universal Testing Bench:



This frame is optimised to incorporate several different Nanorobotics modules that can be easily fixed at the hole arrays of two optical bench plates. This system can grow step by step, e.g. up to the Universal Testing Bench shown in the next picture:



In the upper version the 3D-Nanofinger is fixed at the granite bridge and bigger samples or arrays of samples can be moved with the precise base stage over 100x100 mm^2 stroke. The resolution of the whole system is 50 nm.

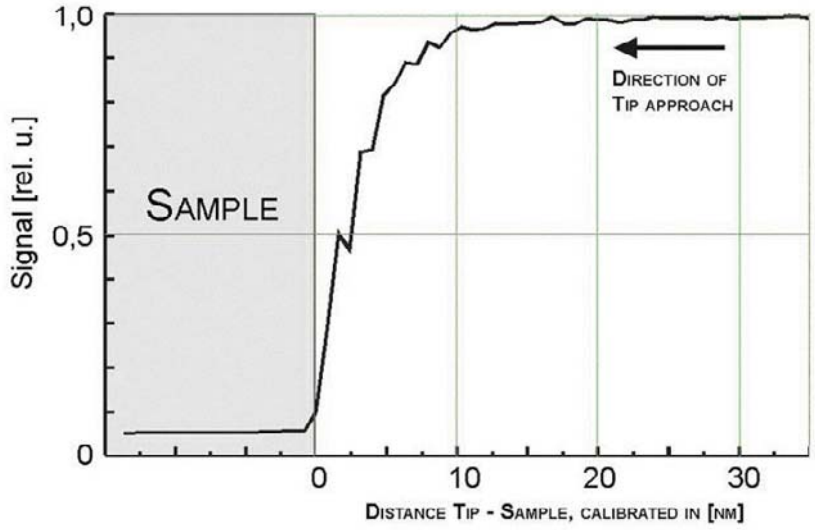
Basic features:

The following basic features of the 3D-Nanofinger are valid for all versions:

- Selectable stroke (stand-alone machine):
  X and Y = 10 - 50 mm or X and Y up to 350 mm with a big base stage
  Z = 10 or 20 mm
  The scan-axes can be defined freely: All axes are equal for the measurement!
- Measurement features:
  Resolution of movement: 1 nm
  Resolution of Nanofinger: 0.5 nm
  Plenty of different probe tips from tip radius < 100 nm up to e.g. ball shaped tips are available
- Comprehensive Software:
  Automatic sensor calibration and approach
  Diagram features, surface roughness and dimensional data processing
  Automation options (with our Process Control Sequencer)
- Selectable configuration:
  - XY-stage at the bottom or at a bridge
  - XZ-stage at the top and Y stage at the bottom (=> for XY stages with 50 mm stroke)
  - XYZ-Module above a bigger base stage

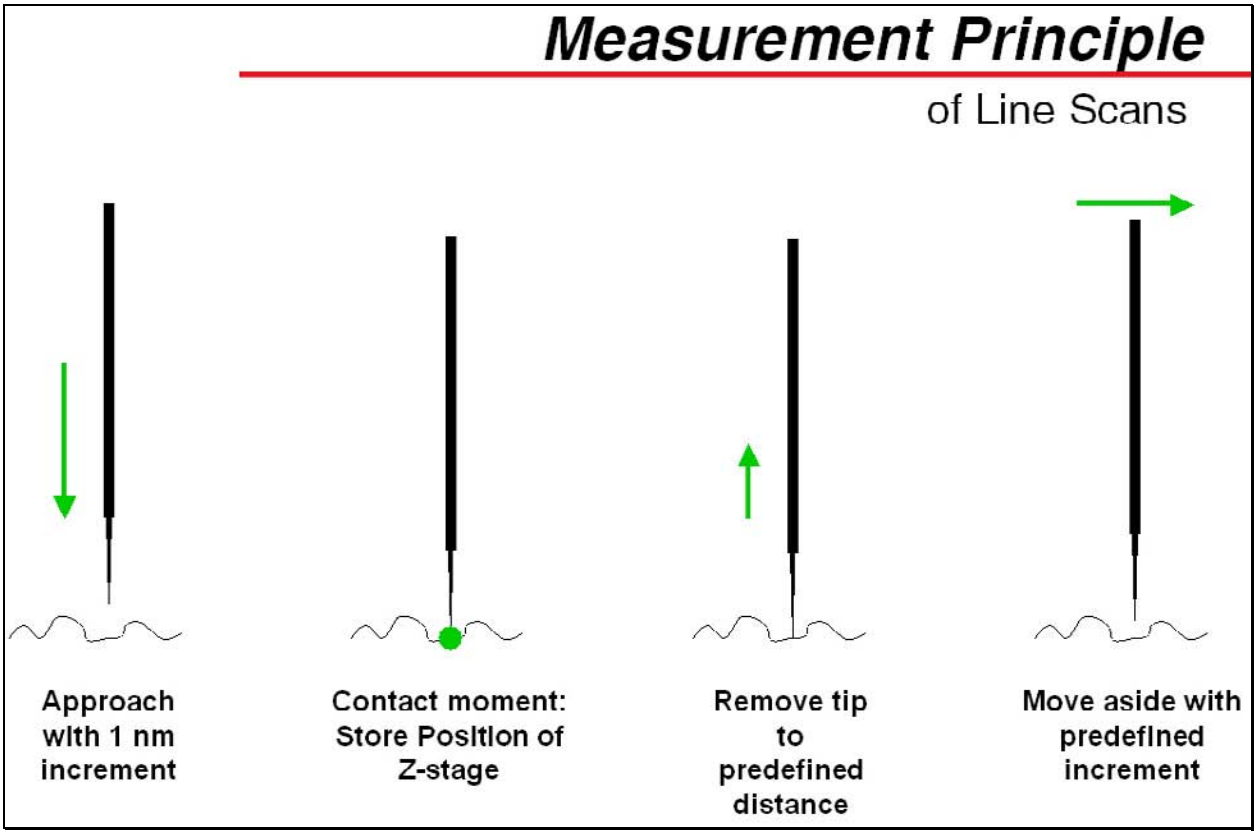
Principle of operation:

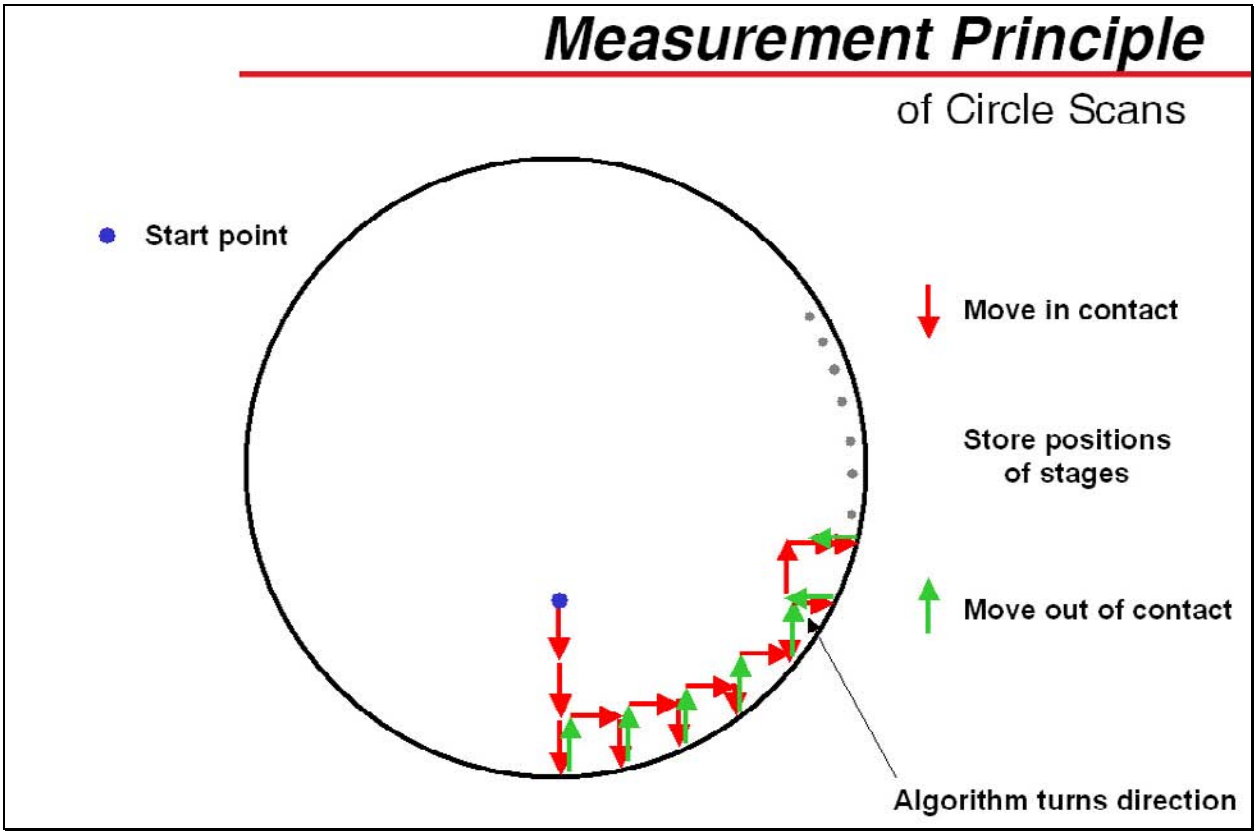
The central sensing element of the 3D-Nanofinger is a small MEMS device that detects the distance between probe tip and a sample. The graph describes the signal output of this device during a tip approach:



In a distance of about 10 nm the Nanofinger sensor "feels" the sample, without touching it. The shape of the intensity↔distance curve in the area between 0 nm (contact) and about 10 nm is independent from the properties of the sample, conductivity is not necessary. When the output signal is compared with a certain selectable level (e.g. 75% amplitude) this level is related to a well defined distance between Nanofinger and sample (in this example 5 nm). This signal can be used for the tip approach on isolating samples.

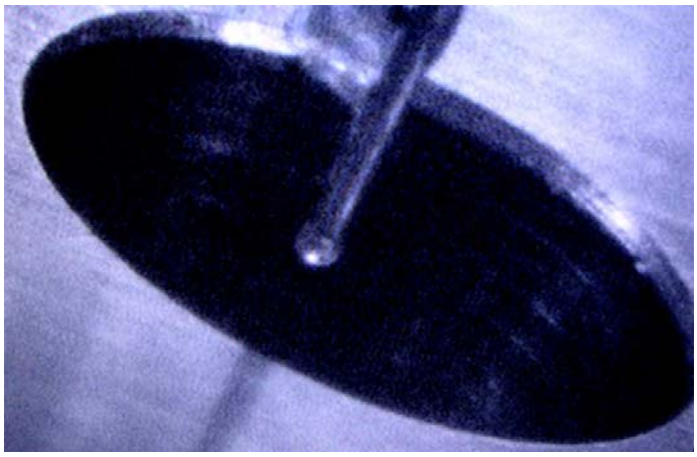
The Nanofinger uses a high speed electronics that reacts with a bandwidth of several KHz. To read a height information needs less than 1 ms. The electronics of the Nanofinger is compatible to our Network Controller and allows a closed loop positioning without burdening the master PC with the feedback:

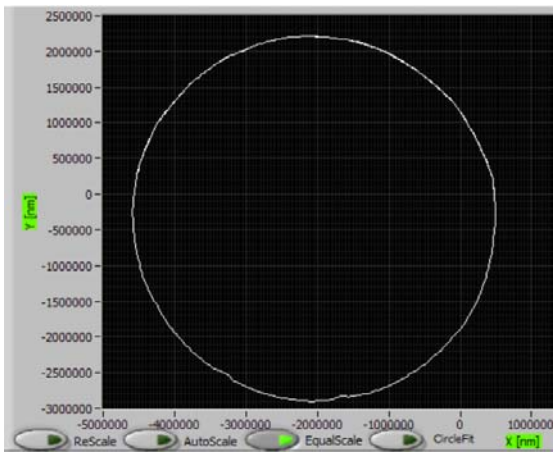




"Contact" in the upper pictures means: The pre-defined distance of a few Nanometers detected with the Nanofinger sensor. The upper algorithms are independent from the size of the increments. A point to point distance of a few Nanometers allows ultra high resolution measurements. A point to point distance of hundreds of microns or even a millimeter allows fast overview measurements or the fast precise detection of coordinates. The minimum increment is 1 (one!) Nanometer.

The following pictures show the dimensional measurement along an inner contour using a ball shaped sensor with calibrated diameter:





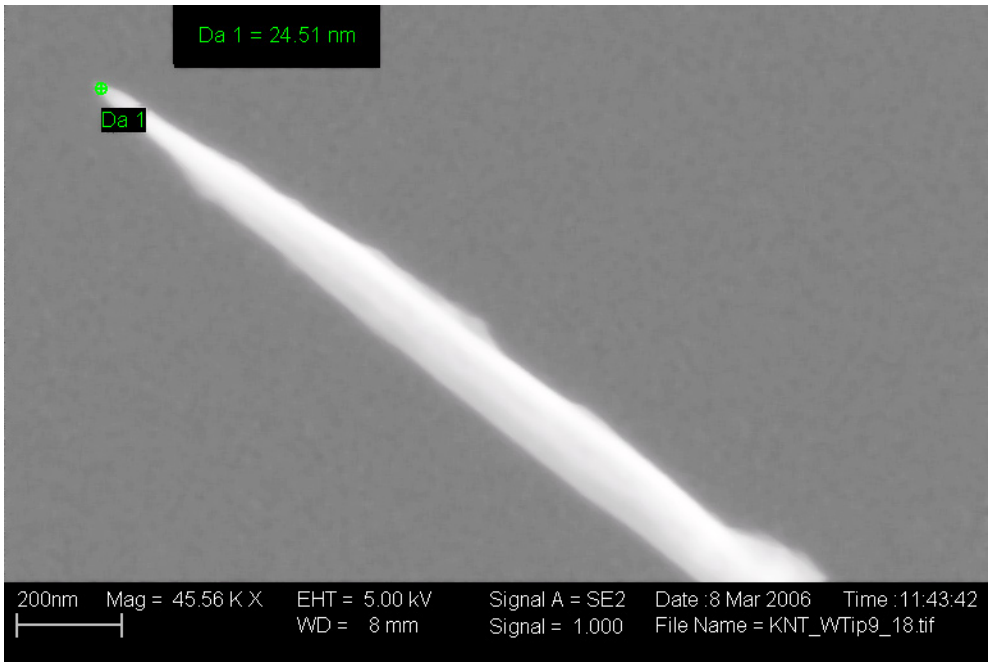
There are two ways to collect a 3D data field:

- With highest resolution over the whole stroke in XYZ => extremely big data field and several hours of measurement time. Advantage: after the measurement it is possible to zoom into that data set at any position by software to see the details.
- In low resolution to get the overview picture in screen resolution. Therefore a few kilobytes of data are enough. This can be done in some 10 minutes, depending on the size of the sample area. In a second step smaller sub-areas of the sample can be addressed to start a new scan only within that area (also in some 10 minutes), instead of zooming by software. This method is much faster, because only the regions of interest are measured in high resolution.

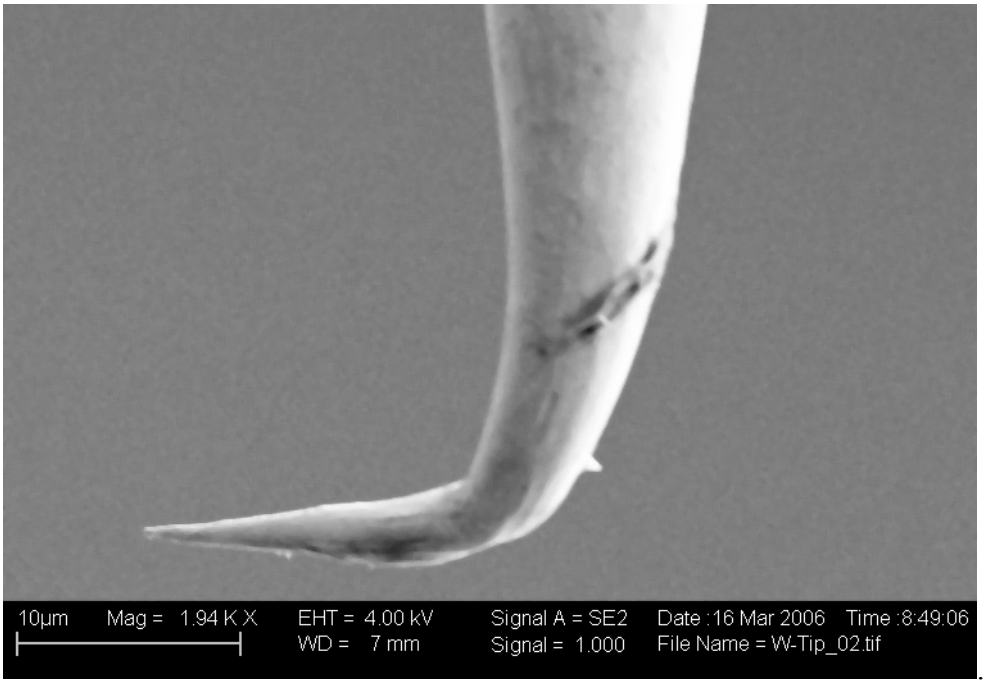
Nanofinger sensors:

The 3D-Nanofinger includes a tip holder that can carry plenty of different probe tips, from tip radius below 50 nm up to e.g. ball shaped tips. The wire shaped tips can measure deep into structures with high aspect ratios, to measure a surface roughness, a profile, dimensions or even a 3D image of a whole area, scaled in Nanometers. The ball shaped probe tips with well defined diameters are made for dimensional measurements.

The following SEM image shows the front end of a wire shaped tip. The tip diameter is 25 nm.



Such a tip can also have a bended shape at the end, e.g. to measure along a side wall:

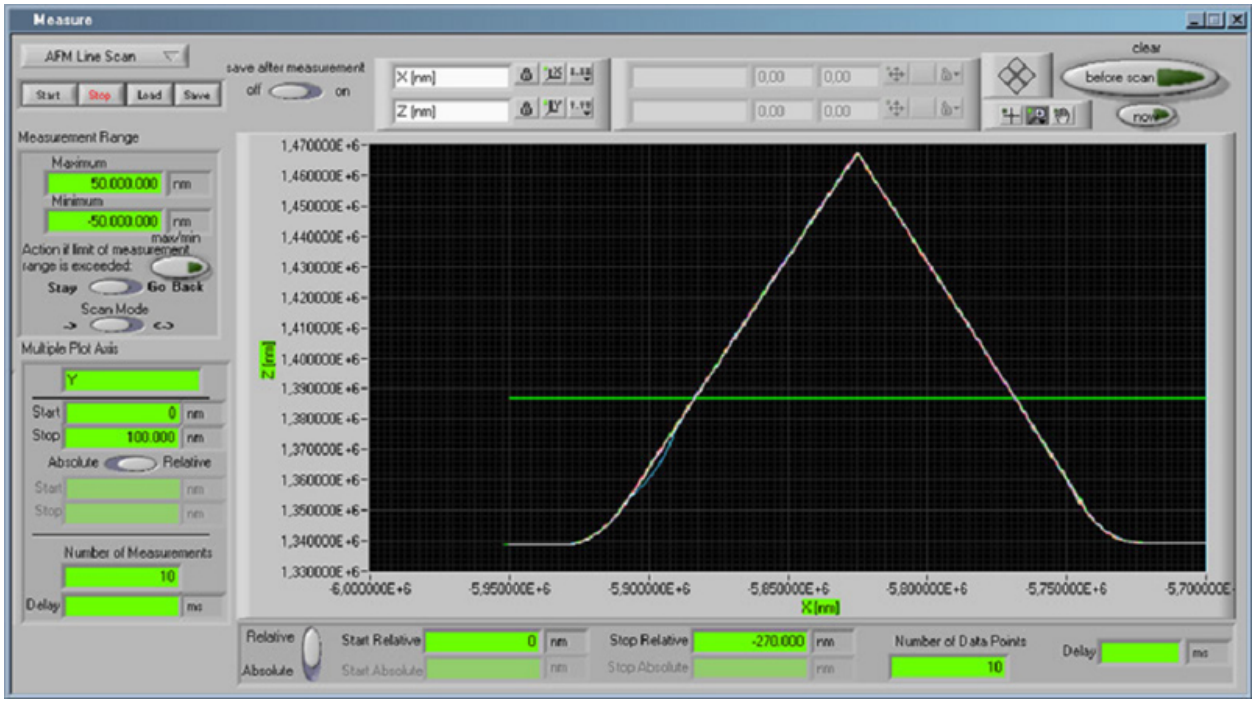


The following table describes some typical probe tips:

No	Mark	Description	Tip	Purpose	Parameters
1		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
2		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
3		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
4		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
5		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
7		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
8		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
14		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,38mm
15		probe, straight	sharp tip (<~500nm)	surface scanning	wire d = 0,125mm
17		probe, straight	flat tip	depth measurement only	wire d = 0,08mm
12		probe, hook	sharp tip (<~500nm)	linescan rectangular to surface	d = 0,125mm, hook < 1mm, length ~ 9mm
16		probe, hook	sharp tip (<~500nm)	linescan rectangular to surface	d = 0,125mm, hook < 1mm, length ~ 9mm
9		ball on stem	ball d = 0,12mm	contour (inside, outside)	stem: L ~ 1,5mm d = 0,07mm
11		ball on stem	ball d = 0,3mm	contour (inside, outside)	stem: L ~ 4mm d = 0,2mm
13		ball on stem	ball d = 0,3mm	contour (inside, outside)	stem: L ~ 2mm d = 0,2mm
6		cylinder	d = 0,3mm	contour (outside)	stainless steel tube
10		cylinder	d = 0,3mm	contour (outside)	stainless steel tube

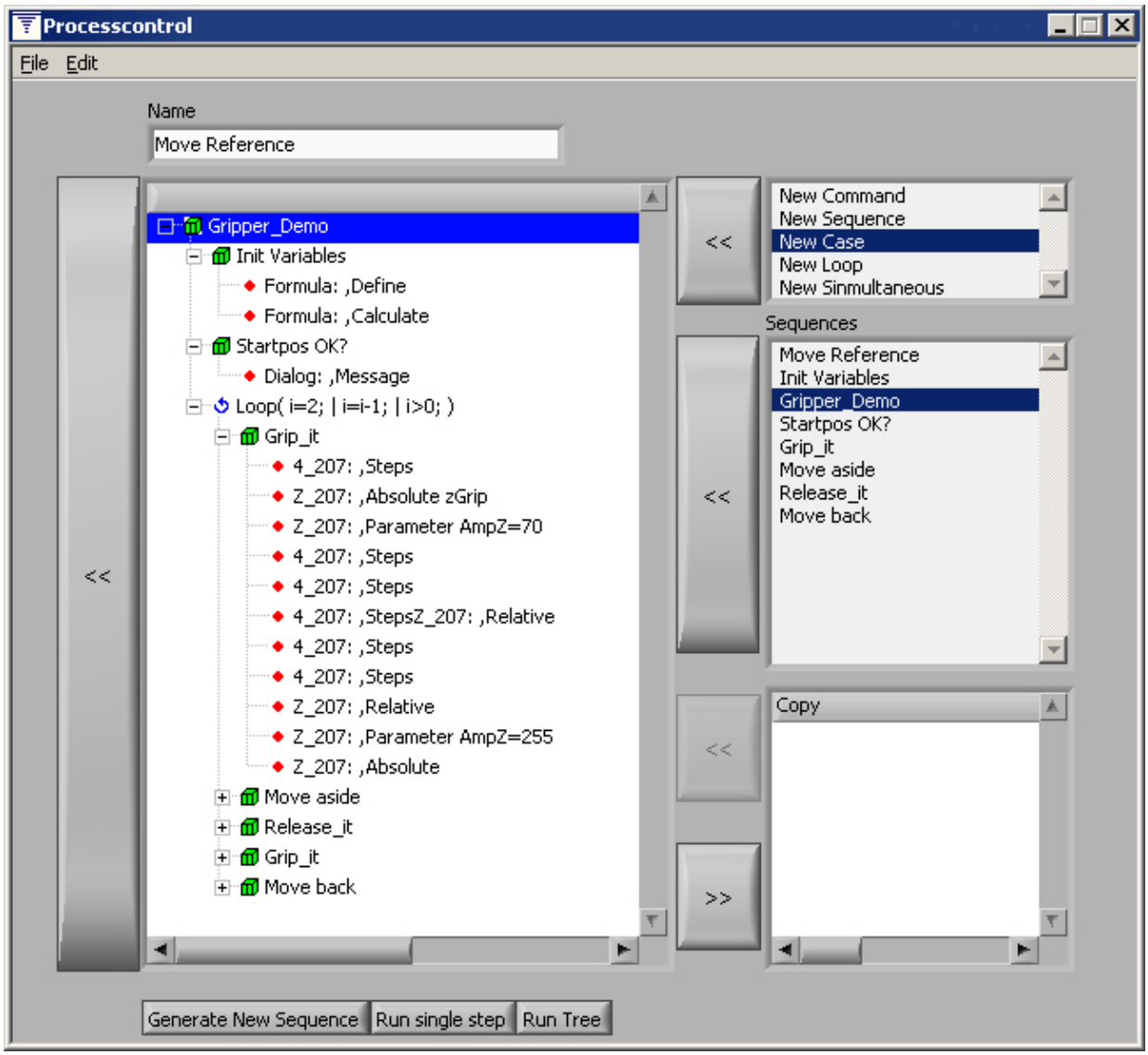
Control:

For topography, surface roughness and dimensional measurements the 3D-Nanofinger sensor is moved along a sample surface. It is possible to define the increments in all axes for selecting a good ratio between speed, scan path length and resolution. A software module allows the selection between the different operation modes.



A comprehensive set of post data processing functions delivering surface roughness parameters and object dimensions is available.

The functionality of the 3D-Nanofinger is included in our process control sequencer for automation:



With this powerful automation system it is possible to integrate the 3D-Nanofinger into comprehensive Nanorobotics systems, e.g. for the usage as inline quality control device in a Micro Production System.

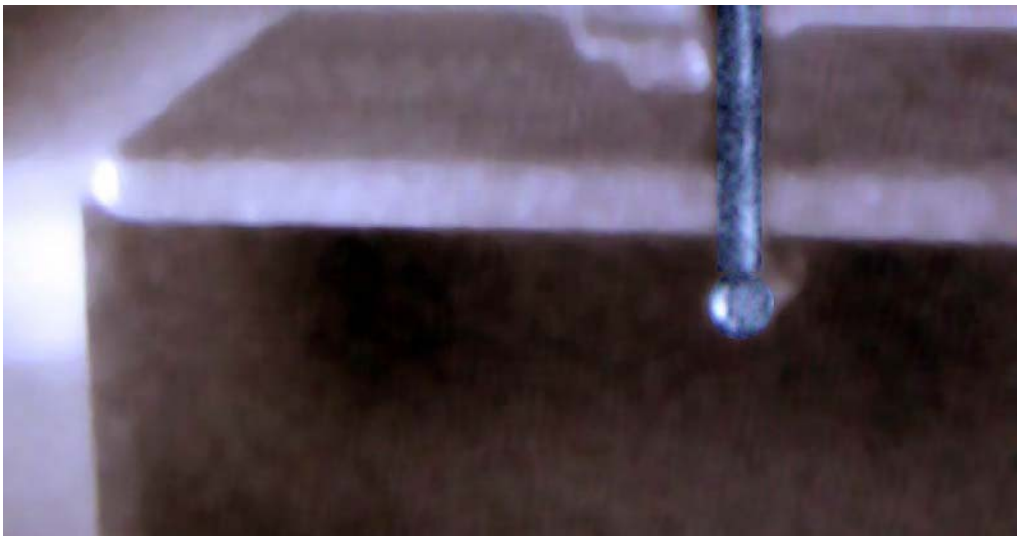
Sample Measurements:

The following measurements were made with the 3D-Nanofinger at customer samples as well as at certified samples that are traceable to a national standard.

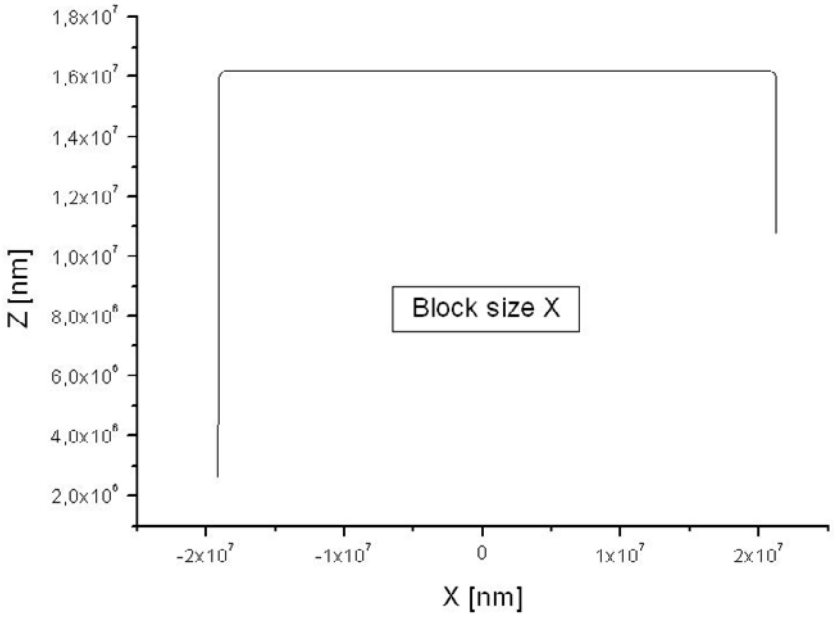
Attention:
The values described here are typical values of sample measurements, they are not identical with the guaranteed values of our product specifications!

1. Measurement of the outer size of a block:

Sample: Precise metal block previously measured with metrology instruments at a customer site:



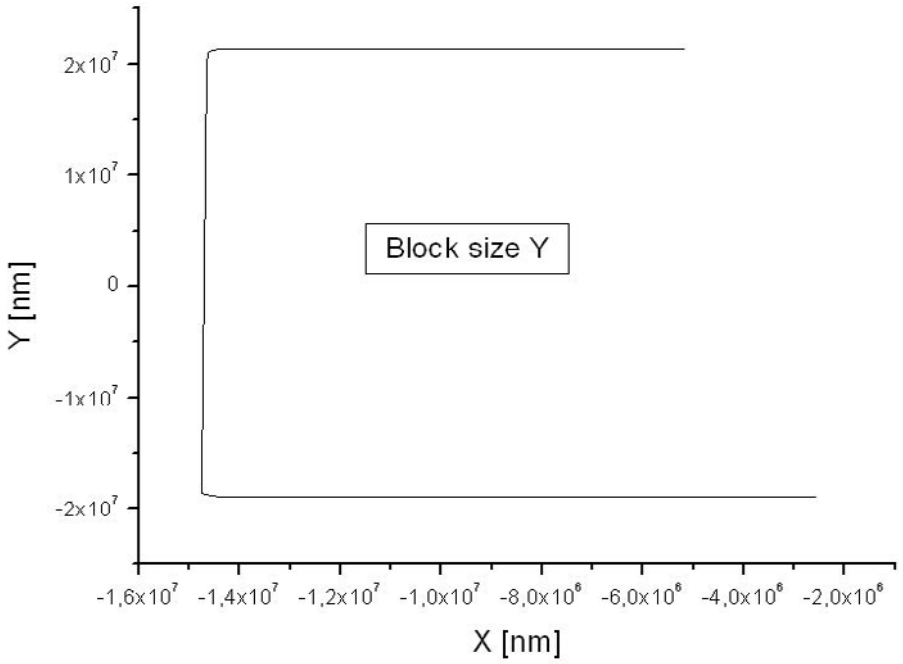
a) Size in X-direction:



Result:

Reference	3D-Nanofinger	Difference
40,000.080 um	40,000.129 um	0.049 um

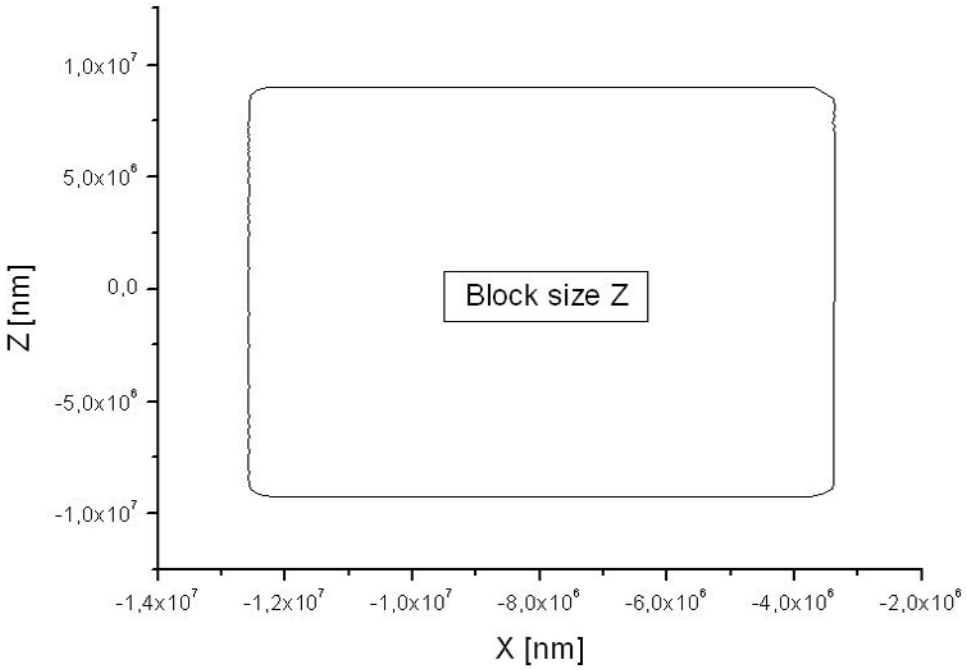
b) Size in Y-direction:



Result:

Reference	3D-Nanofinger	Difference
40,000.080 um	40,000.059 um	-0.021 um

c) Size in Z-direction:



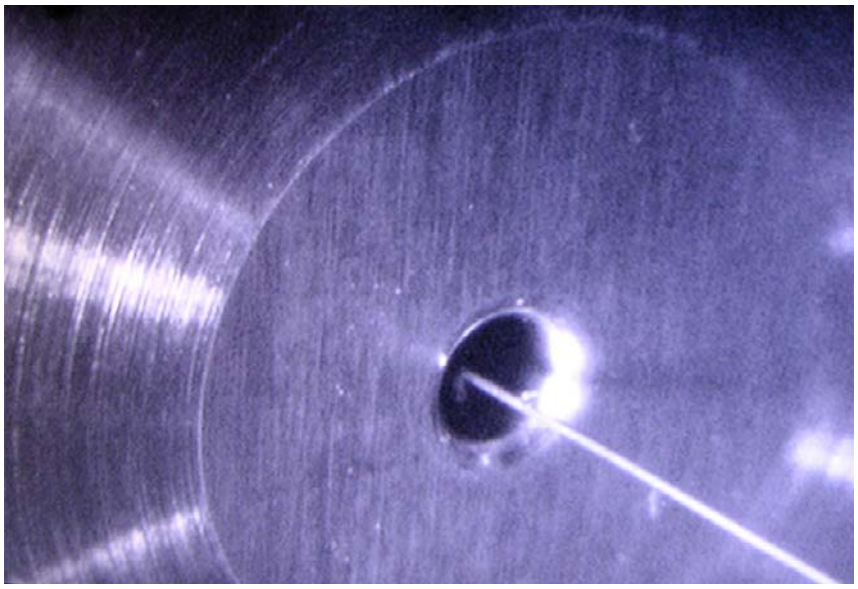
Results:

Reference	3D-Nanofinger	Difference
18,000.000 um	18,000.133 um	0.133 um

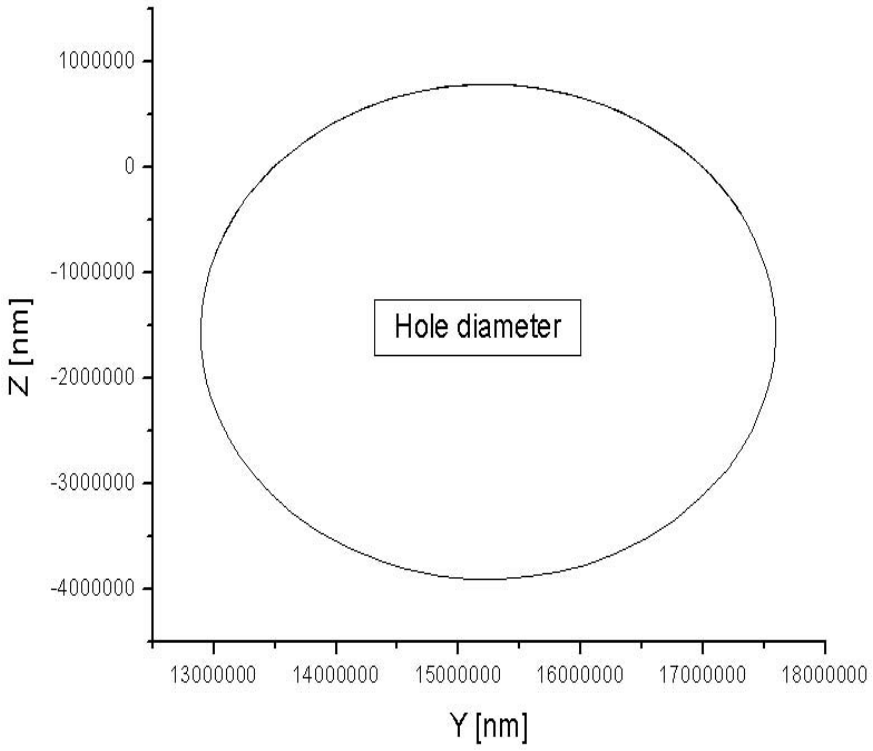
2. Hole diameter measurement:

In contrast to standard Profilometers the 3D-Nanofinger can measure along a path, e.g. to follow inner or outer contours. In the following case a hole diameter was determined.

Sample: Metal block with a small but deep hole:

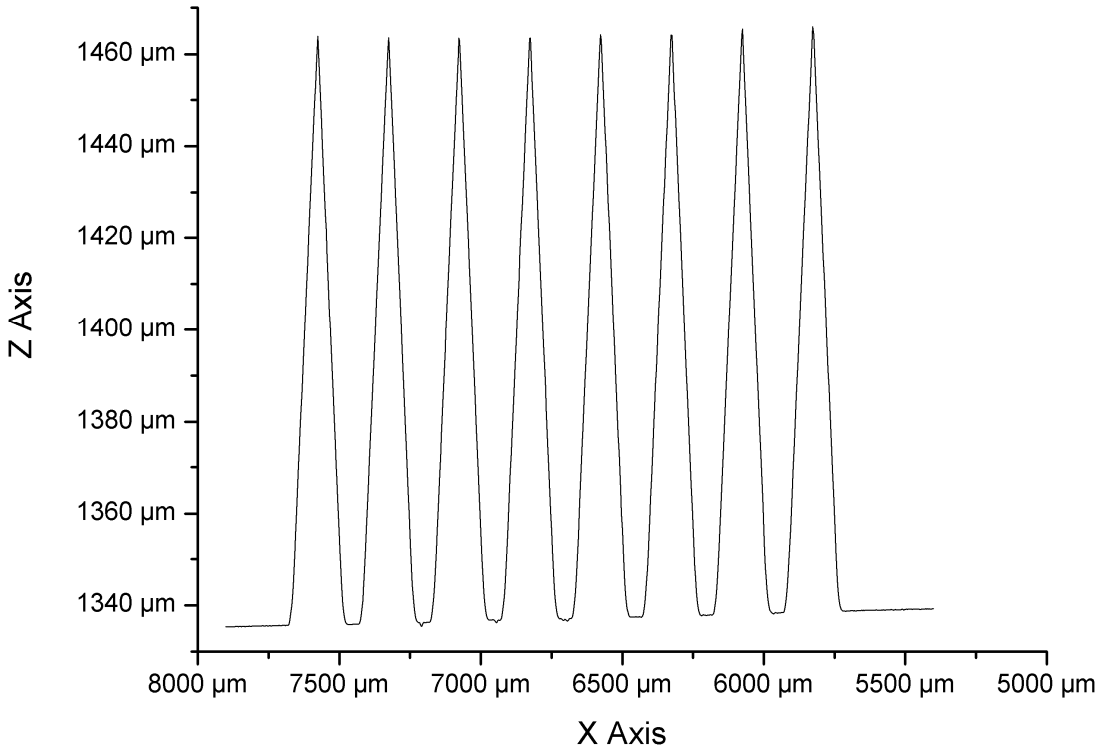


The following diagram shows the circle measurement of the 3D-Nanofinger made with the algorithm described in a previous chapter:



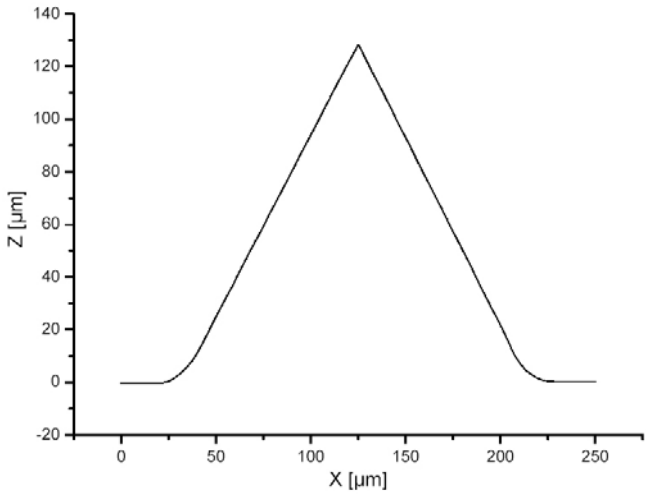
3. Linescan measurements into narrow structures:

The following measurements are made at V-grooves that were prepared as glass fiber guides:

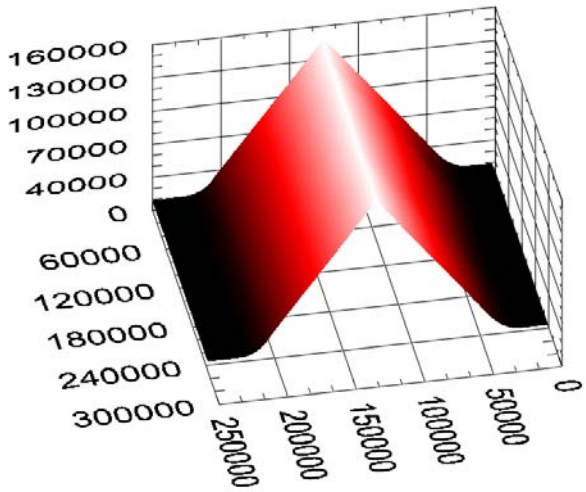


The upper linescan gives an overview about the array of V-grooves.

Linescan of a single V-groove:

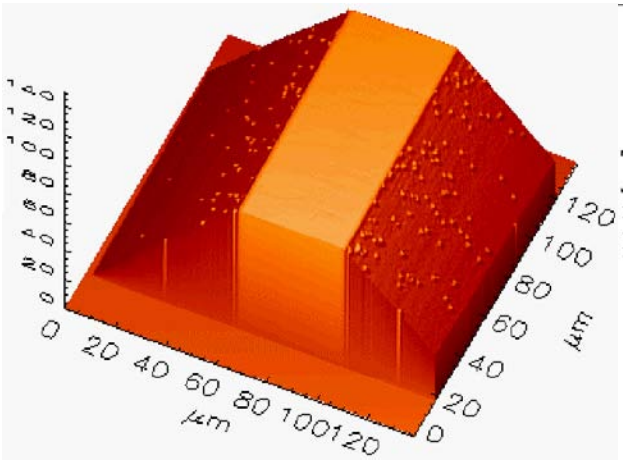


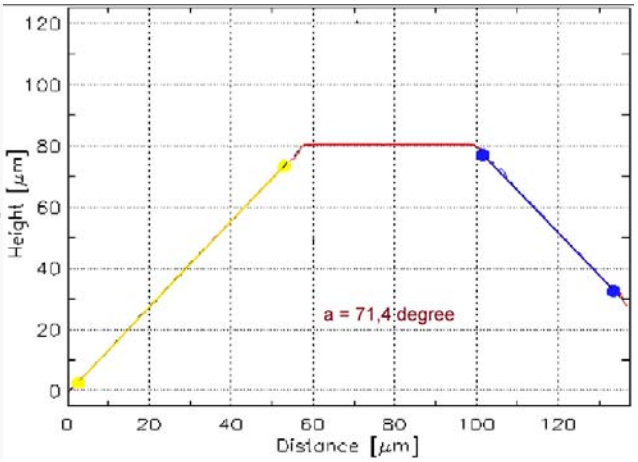
3D topography scan of one V-groove:



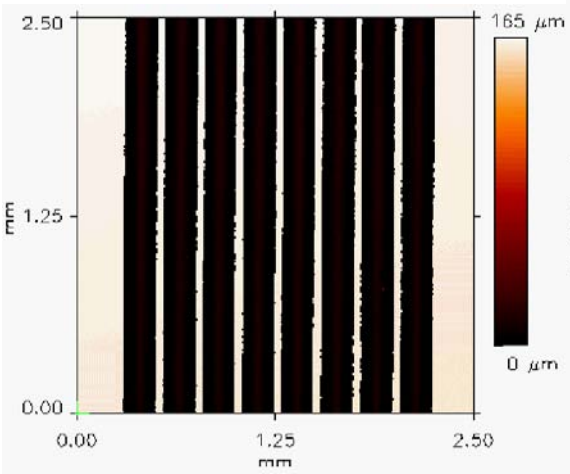
Other measurement methods are not able to measure along these sample structures.

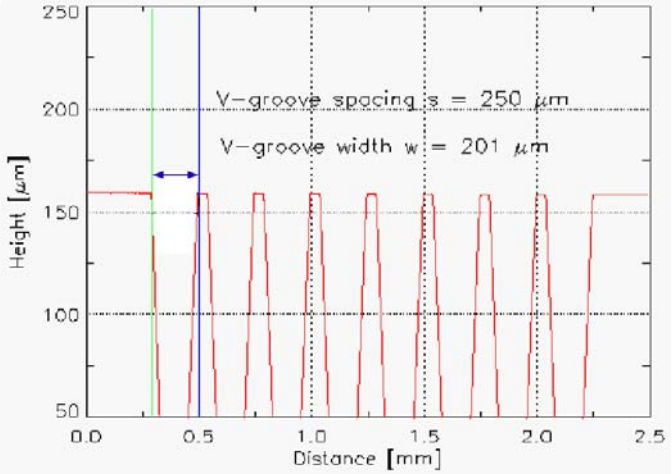
Confocal Microscopes cannot measure deep into the grooves:





A chromatic aberration sensor can measure deep into the grooves but delivers a wrong shape:



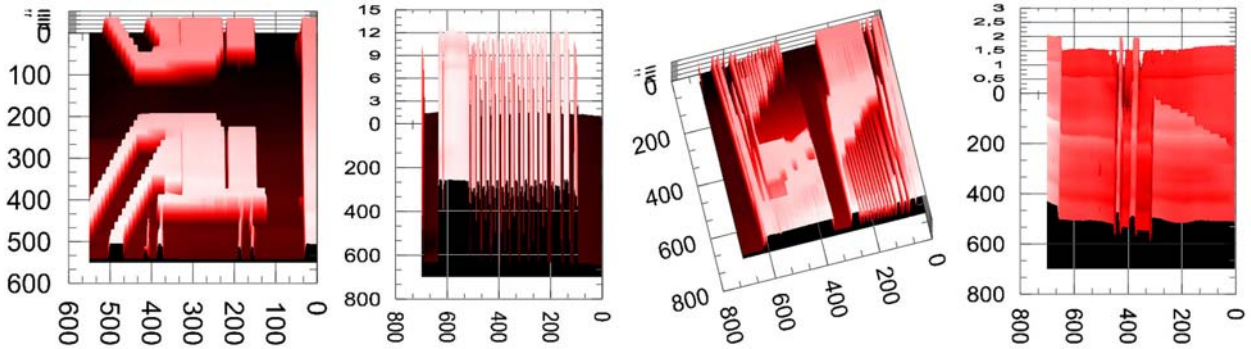


Results:	3D-Nanofinger	Confocal Microscope	Chromatic aberration sensor
Groove period	250 um		250 um
Groove angle	71 degree	71 degree	
Limitations	Tip shape has influence on the results, can be reduced by well defined tips or by calibration	Cannot measure into the grooves	Wrong shape of grooves

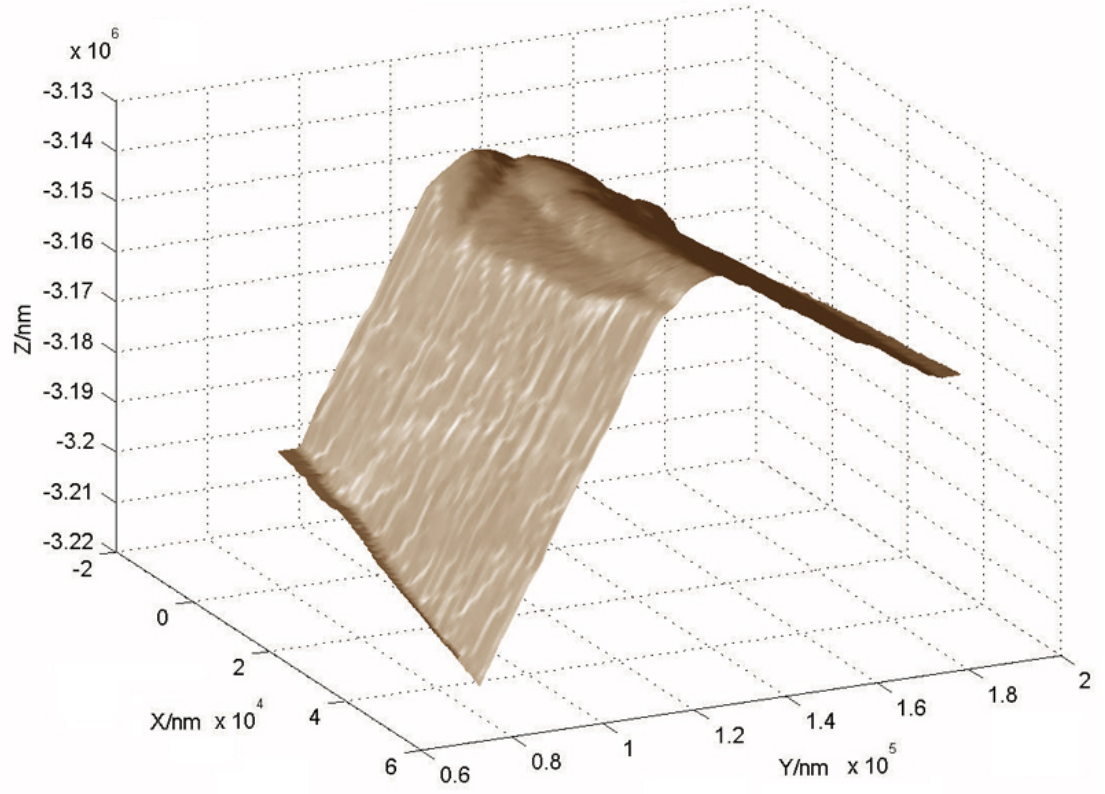
4. 3D-Topography images with ultra-high resolution:

In the last years wafer structures were realized, that include thin flexible structures operating as actuator when a voltage is applied across these structures. Examples for products including such devices are microgrippers. These structures are narrow with upright walls. Optical measurements cannot resolve such perpendicular structures and tactile instruments would just bend the flexible structures without resolving them. Since the 3D-Nanofinger is a "non-contact tactile instrument" it can resolve such sensitive structures.

The following 3D topography scans were made at such a MEMS device structured in silicon:



The next 3D topography scan was made at the knife edge of a cutting tool for CNC drilling and milling machines:



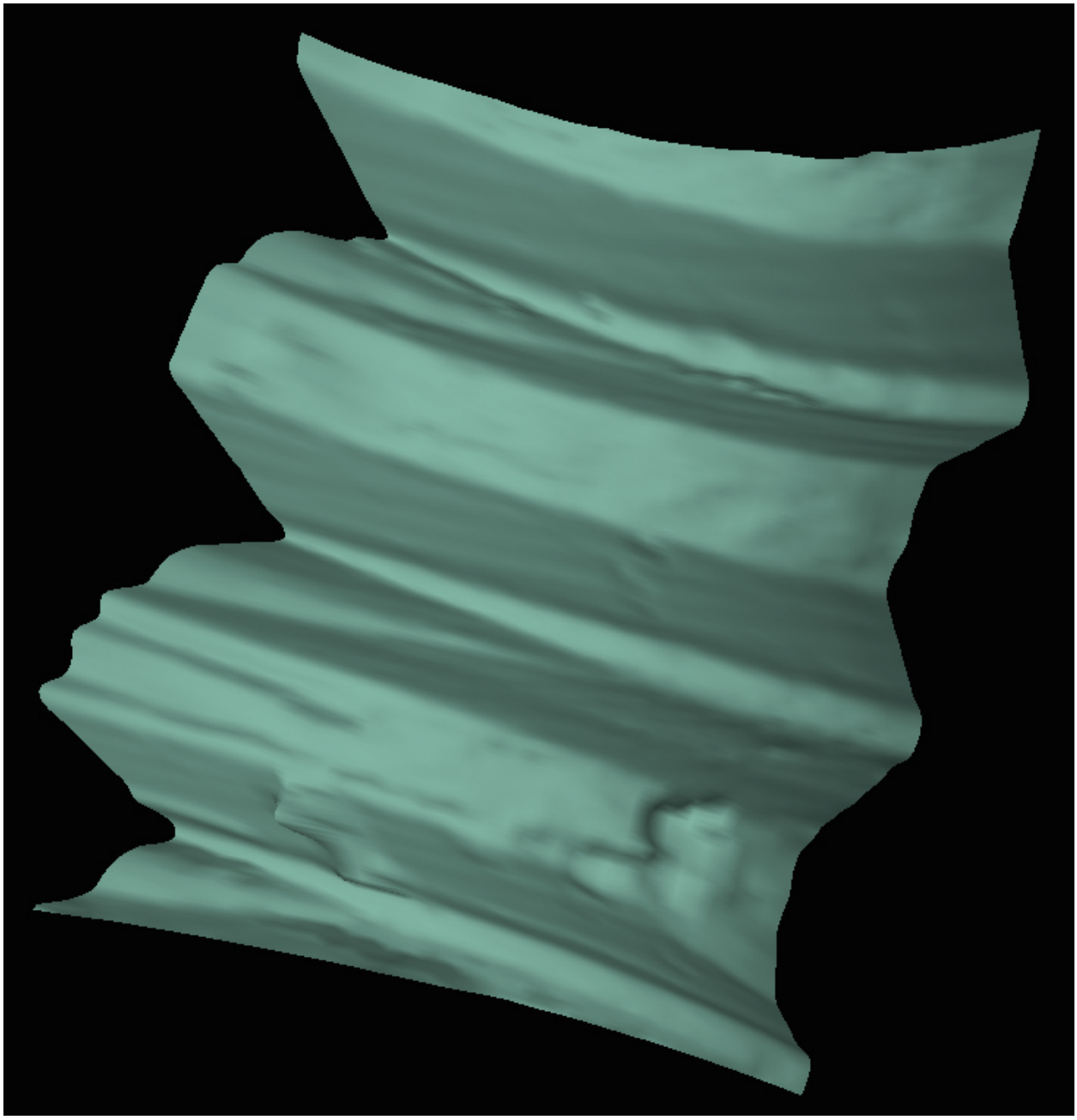
One Linescan would only show a nice smooth line, the knife edge seems to be fine. But the 3D-topograpy image proves that line by line a notch gets visible that causes a spontaneous breakage of this knife when it would be used. A profilometer measurement delivers the wrong result.

5. Measurements inside of small holes:

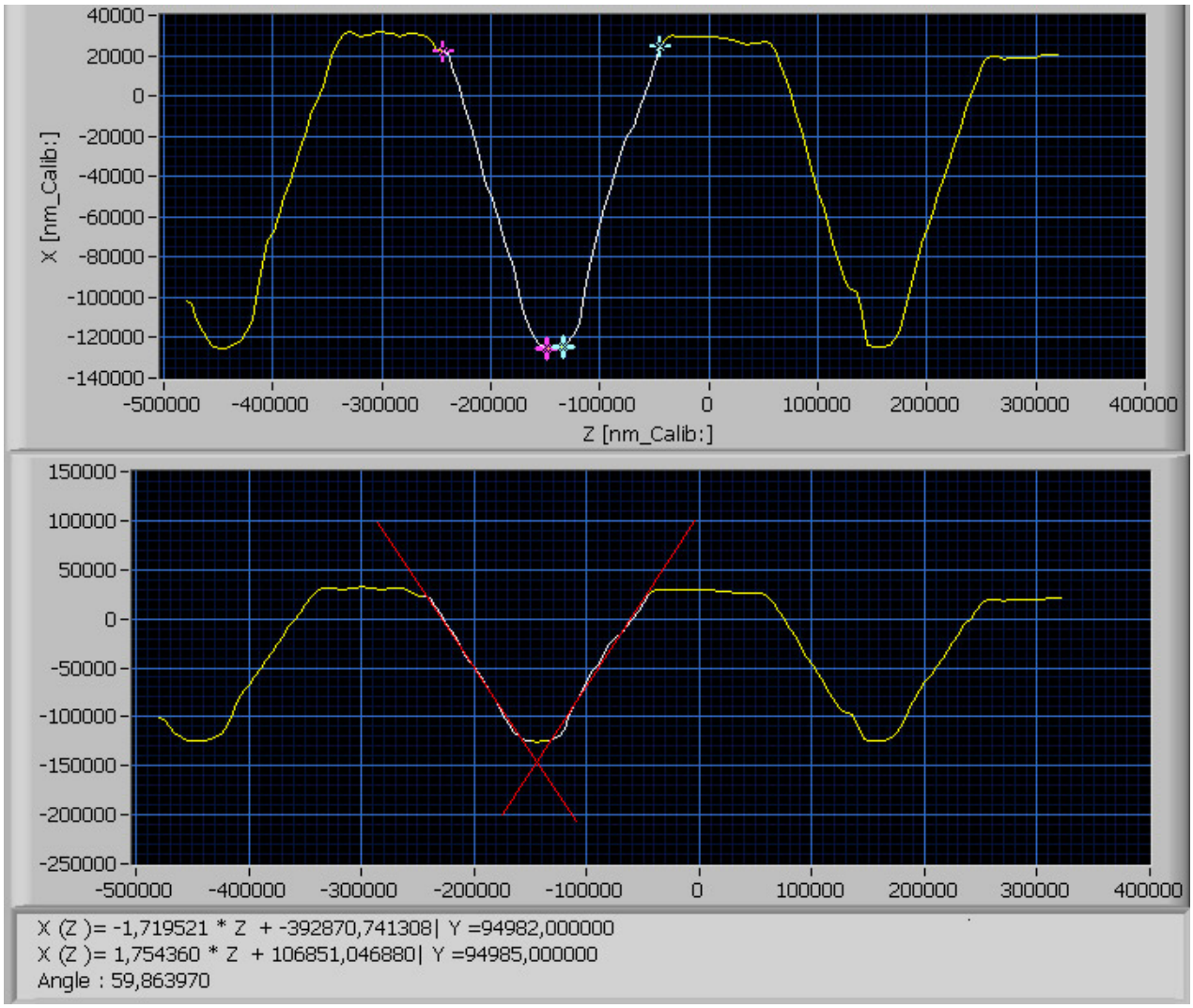
The 3D-Nanofinger can operate with a wide range of sensing probe tips. It is possible to measure with small sharp versions inside of small holes, even in 3D and into fine structures like windings.

The following dimensional measurements were made inside of an internal screw thread with 1.4 mm diameter cut into an alumina block.

The shape of the winding is visible in the following 3D data set:

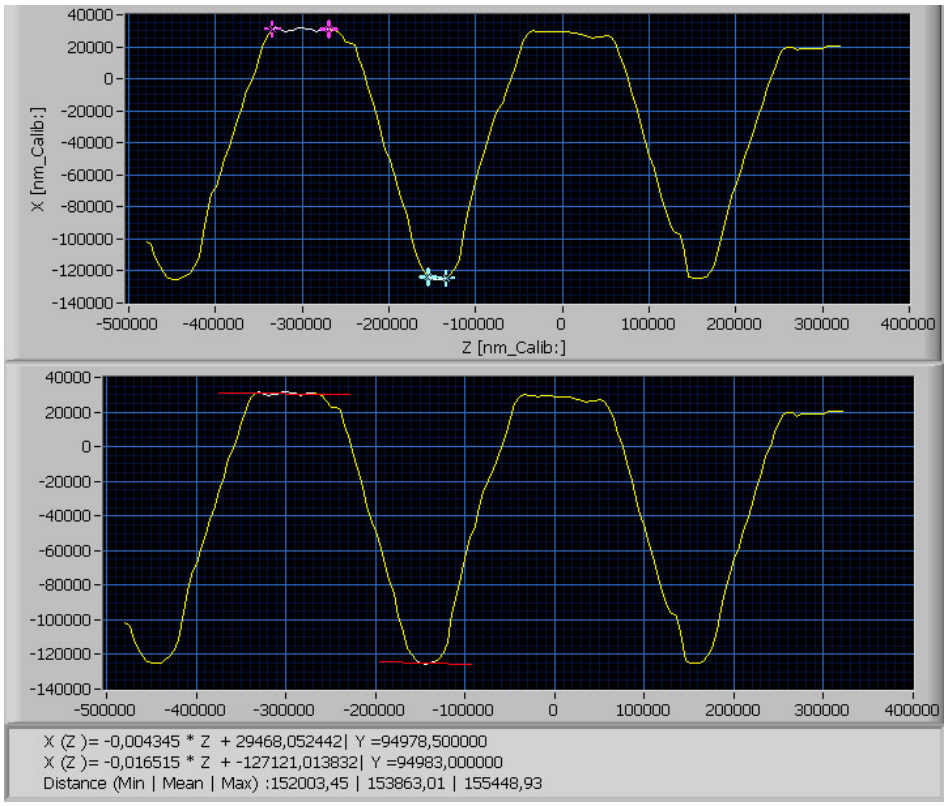


The following Linescans were performed through this winding area to measure some typical values of the screw thread. First the angle of each winding is measured by placing fit lines into the graph:

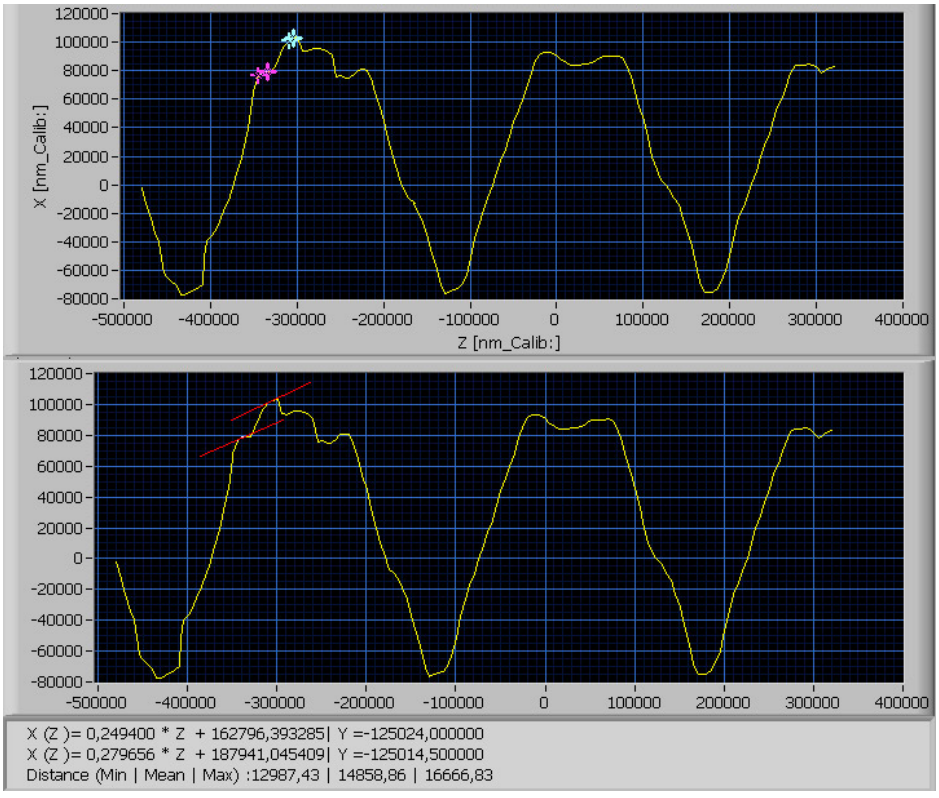


The resulting angle is 59.9 degree.

Scale bars can be placed into the diagram to determine distances. In this way the depth of the winding is determined to 153.8 microns. So the winding was drilled a bit too deep compared with the norm value, see next image:



A few areas in the 3D-image show small defects within the winding. Such defects are visible in the following Linescan:



The peak height of such a defect was determined to 15 microns.

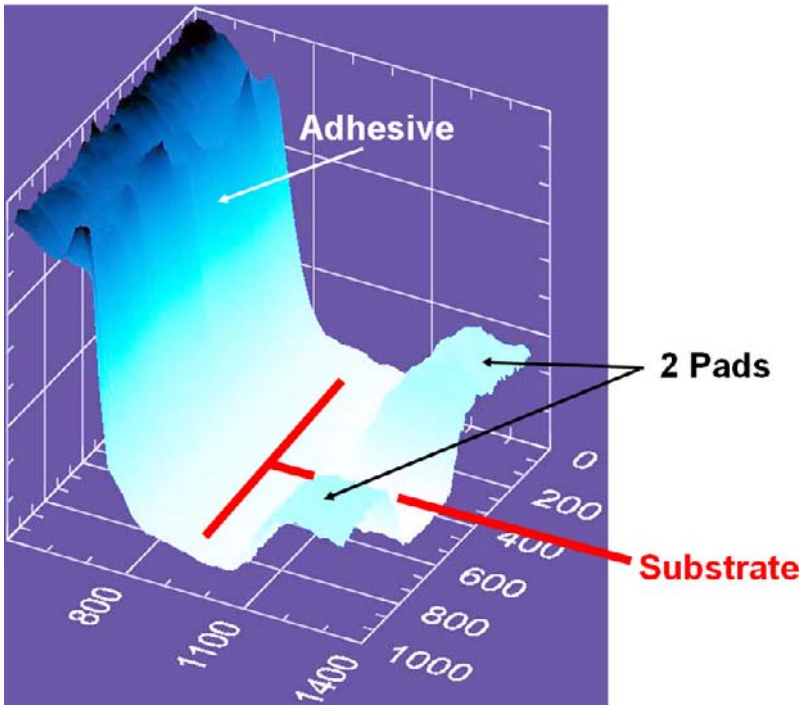
6. Quality control of PCB boards filled with SMD chips:

The production of electronics circuits creates a demand in new quality control instruments. When SMD chips are bonded onto printed circuit boards (PCB) several analysis tasks have to be fulfilled. A few examples are the measurements of:

- Misalignments of components
- Surface topography,
- Dimensions, spacing,
- Contours, component angles
- Roughness of bondings
- Defects and cracks
- Electrical properties by probing
- Adhesive quality with force-distance curves

SMD chips have a wide range of outer dimensions and are placed nearby each other on the board. So the space of tactile measurement instruments or current probing systems is very limited. In addition the SMD chips have no sharp vertical walls, they get smaller in size near by their bottom line. This fact avoids to resolve details of the bonding area between SMD chip, adhesive and PCB. The following 3D-Nanofinger measurements are one example out of several analysis tasks. In this case the SMD chips were fixed on PCB boards by micro adhesive bonding with a filled conductive adhesive.

To get an impression about the quality of the dispensed filled conductive adhesive a sample was prepared by micro adhesive bonding of single filled conductive adhesive dots onto a PCB. The PCB includes pure substrate areas, strip lines and contact pads:

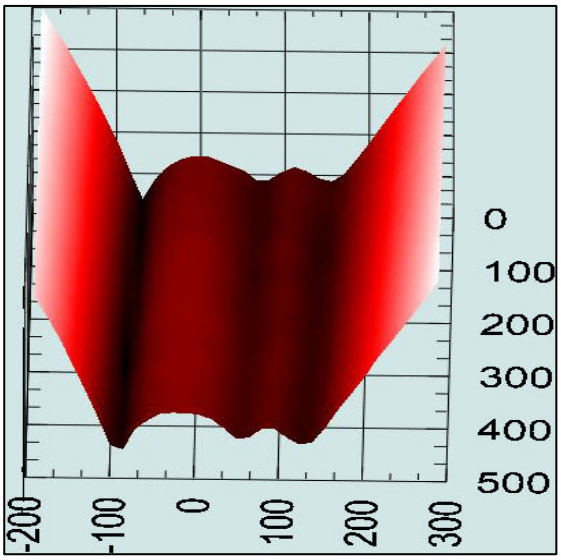


The upper image shows a 3D-dataset that is scaled in all 3 directions. Already this overview picture offers the dimensions of the components as well as the contour of the edge areas and the surface roughness of the filled adhesive.

Quantitative details can be gained by single linescans through this area, as shown with the next example:

The next sample includes an additional small SMD chip (a capacitor) that is fixed on the filled adhesive.

The transition between substrate, adhesive and SMD chip is hidden by the round shape of the SMD chip. Still it is possible to measure along this important area by using a tilted probe tip installed at the 3D-Nanofinger. When the PCB is small and can be handled outside of an automation process it can be installed under a tilt angle of e.g. 45 degree in the 3D-Nanofinger. Both options lead to the same result. The exact value of the selected angle is completely unimportant, because it will be removed later by software anyway.

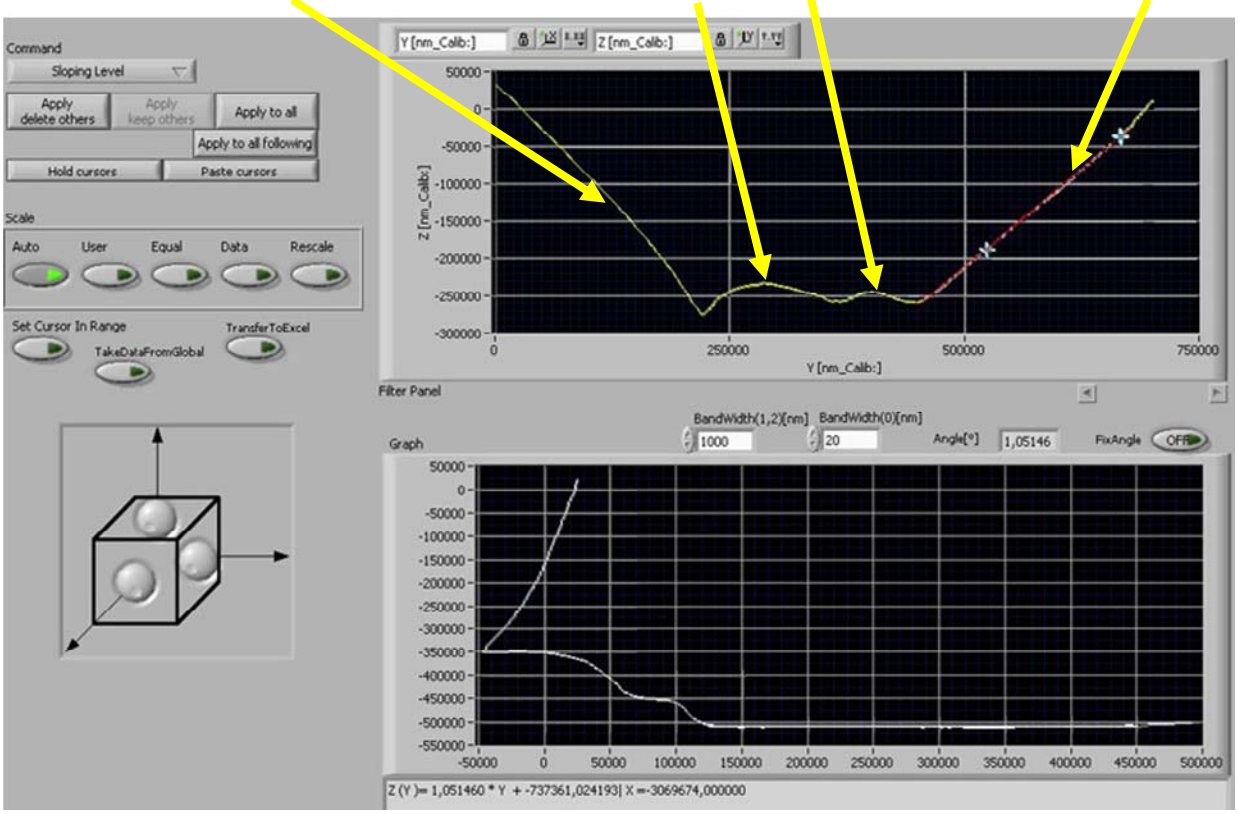


The left image shows the 3D-dataset in the area of SMD chip, adhesive, contact pad and substrate. It is scaled in all 3 directions, and the dimensions are traceable to international standards.

On the left side the SMD chip is visible, followed by two waves, first the adhesive second the contact pad. Then on the right a straight plane follows: the substrate.

A Linescan prepared through this 3D-area is shown in the upper window of the following image:

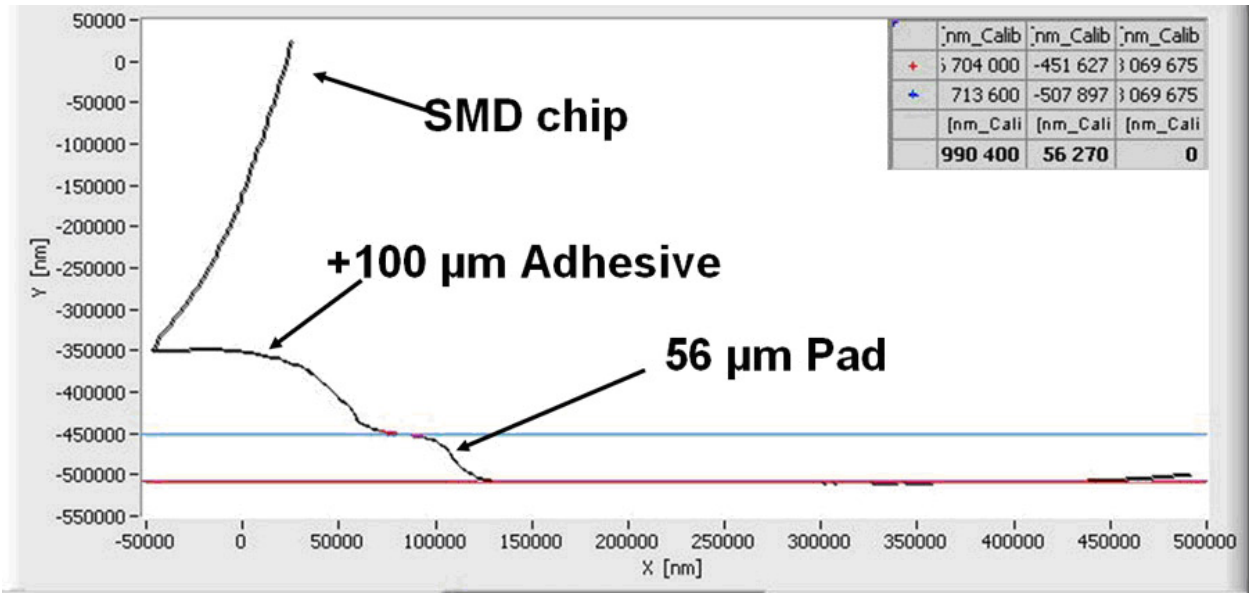
Left part of the line: SMD chip, Middle part of the line: adhesive + pad, Right part of the line: substrate).



In the upper Linescan a filter function called „Sloping Level“ is placed. Therefore two markers are placed with the mouse into the straight part of the substrate line. A straight line is calculated that forms the new baseline for the X-axis.

The result of this coordinate transformation is shown in the lower diagram window. The substrate is now exactly horizontal, and in the left part of the Linescan discloses that the SMD chip indeed has a round shape like an undercut at its bottom end. This Linescan proves that the 3D-Nanofinger can measure undercuts and resolve areas that are invisible from the top.

The following image shows this Linescan including measures:



Scale bars can be placed into the diagram to determine distances. In this way the height of the contact pads is determined to 56.3 microns. The adhesive has a thickness of 100 microns.

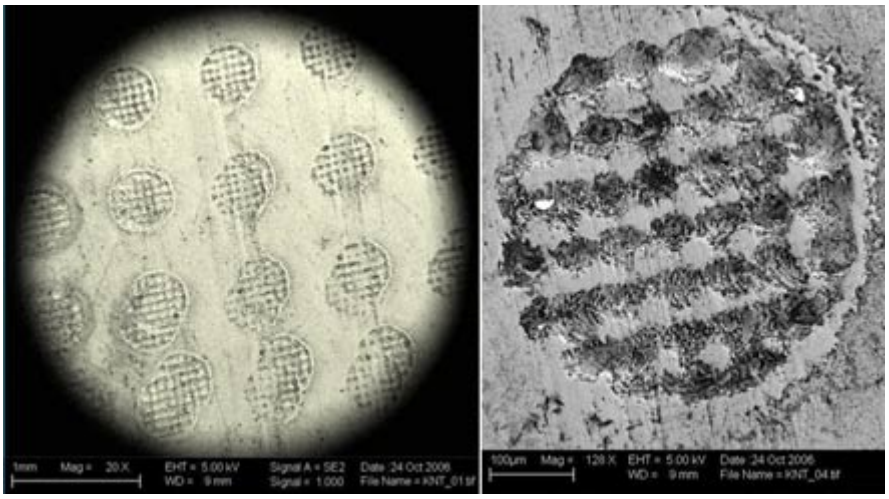
7. The Dimensional SEM/FIB:

The integration of the 3D-Nanofinger into Scanning Electron and Ion Microscopes (SEM and FIB) creates the first real "dimensional SEM/FIB" with Nanometer precision. The metrology features of a SEM/FIB are expanded to the third dimension by all features of the 3D-Nanofinger.

The following 4 examples show in detail the quality of this unique instrument:

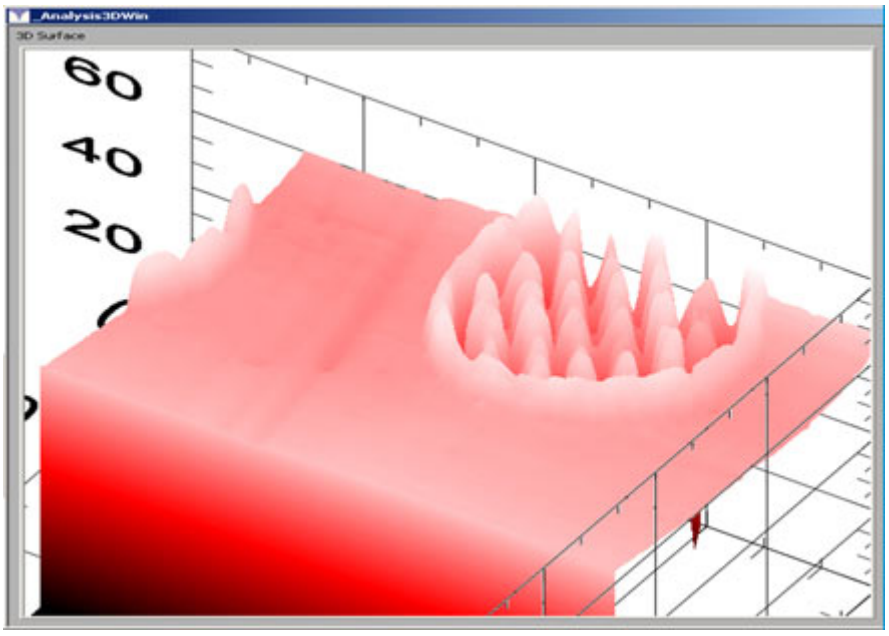
a) Wet clutch:

A customer from car industry tried to measure small structures in a wet clutch with standard Profilometers, optical Profilometers and the SEM. None of these measurements could provide a useful quantitative result. Only the Dimensional SEM could deliver profiles and 3D-topography datasets of these structures. These quantitative results are traceable to international scale and roughness standards. The following SEM images show the area of interest but cannot give a height information of these structures:



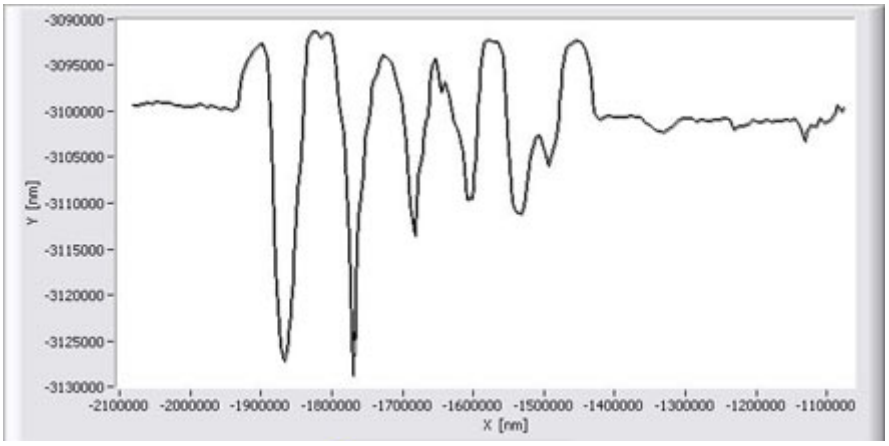
SEM image of the pattern area and a single imprint field

Next a 3D-scan was performed around one imprint field as identified in the upper right SEM image:



3D-scan around one single imprint field

The quantitative structure information is visible in linescans that can be performed through these structures and deep into the holes:

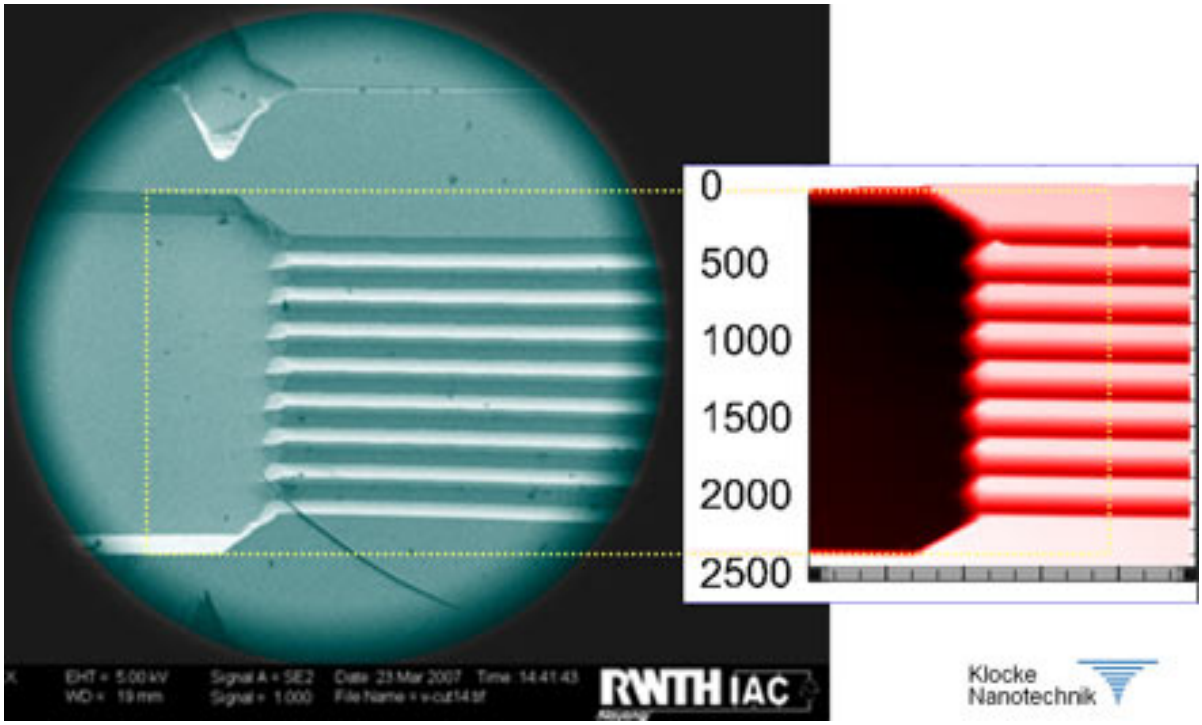


Single linescan across one of the imprint fields

Only the Dimensional SEM could prove, that within one imprint field each imprint has a different depth. The resolved fine structures offer more information about the production process of the imprint structures and its side effects, like grains around the imprints and material pressed aside.

b) SEM image of V-grooves and quantitative 3D dataset of the same area:

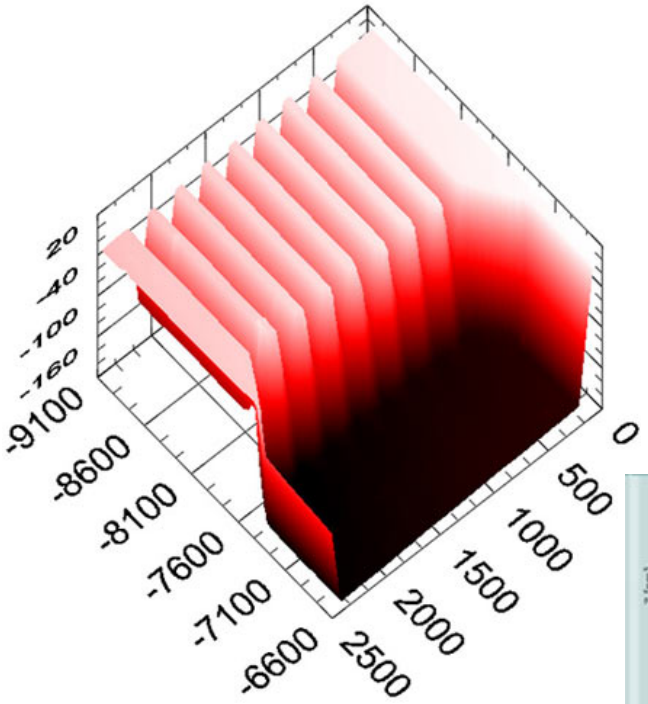
The following SEM image shows an array of v-grooves made in silicon within a medium sized area. This image only resolves the sample laterally, without any height or e.g. angle information. The 3D-image generated with the Dimensional SEM of the same are is shown directly in comparison:



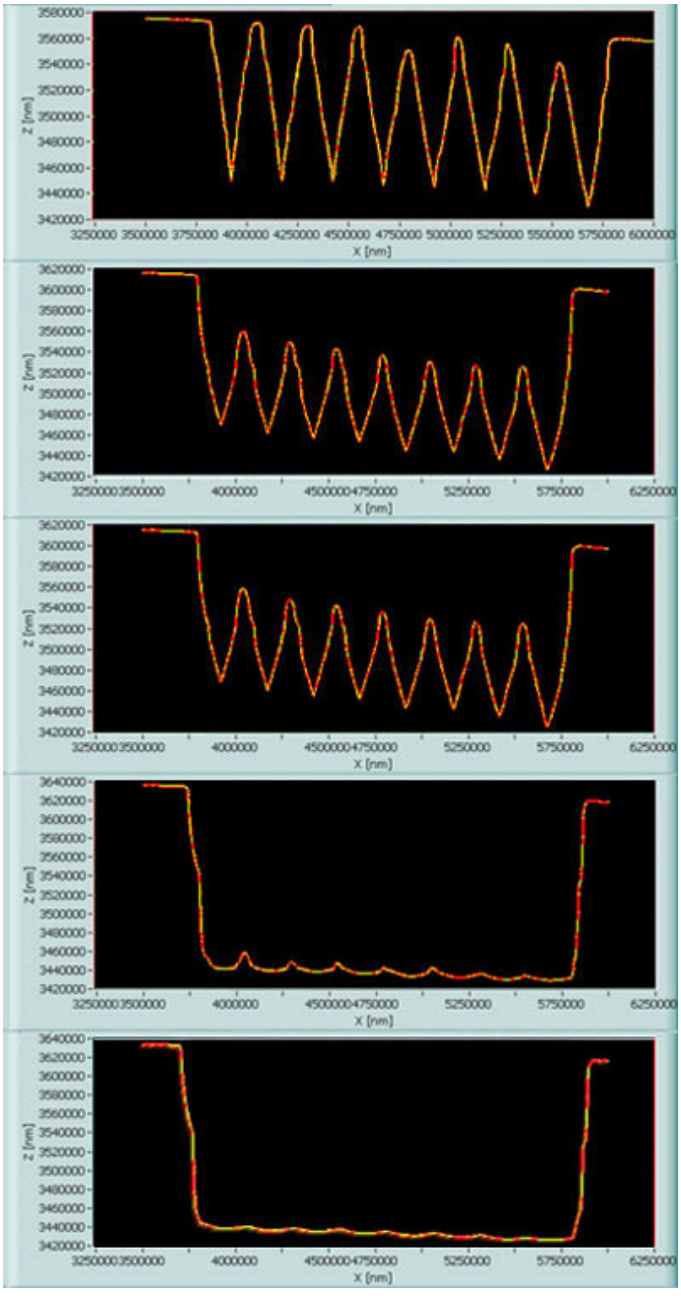
SEM image of V-grooves and quantitative 3D dataset of the same area

These quantitative results are traceable to international scale and roughness standards.

The following image shows a 3D-view of this dataset:



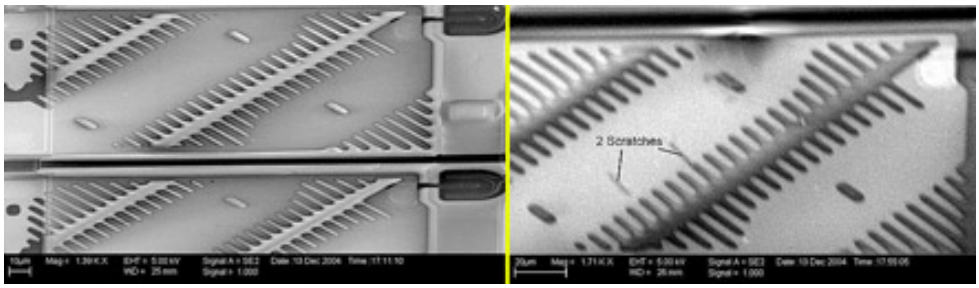
With our analysis software it is possible to rush through series of Linescans like making slices through this 3D image. The following series of Linescans show how structures are formed:



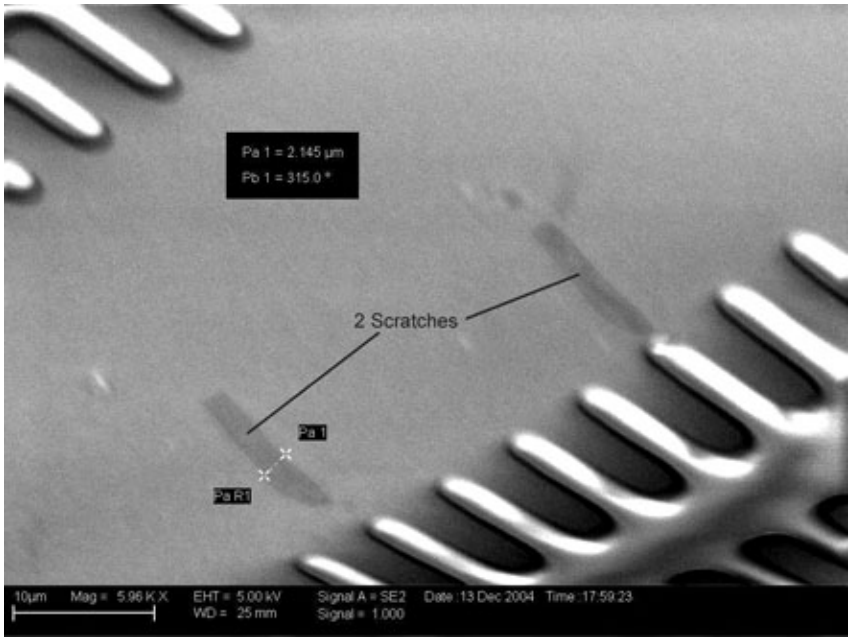
The set of Linescans shown on the right is scaled in [nm] and traceable to international standards. It starts in the area of the grooves and ends in the flat area of the sample. Each Linescan can be analyzed quantitatively, e.g. to determine the angles of the V-grooves or their depth.

c) Mechanical defects on a DVD:

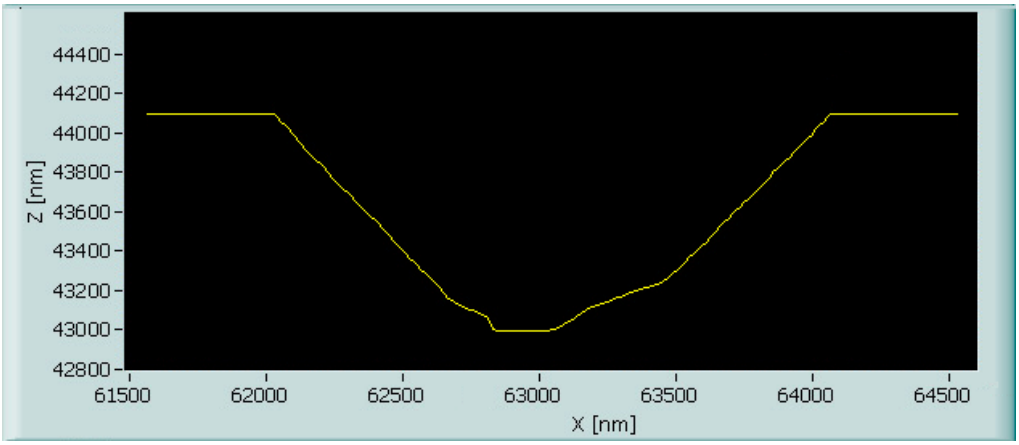
In a SEM it is possible to scan the surface of a DVD (digital video disk) for identifying mechanical defects. The following SEM image shows a bit area on the DVD on the left and a zoom into a smaller area that has two scratch shaped defects:



In the following SEM image the two scratches can be visualized and measured in XY, but the depth of the scratches cannot be determined:



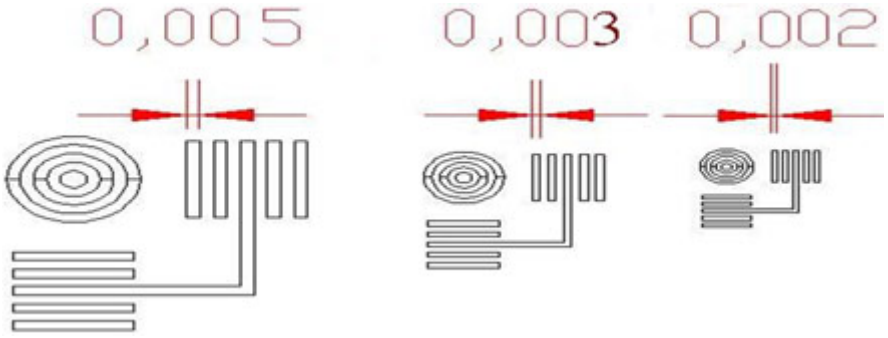
The quantitative structure information is visible in the following linescan performed through one of these scratches:



Only the Dimensional SEM can measure the depth and shape of such defects in DVDs

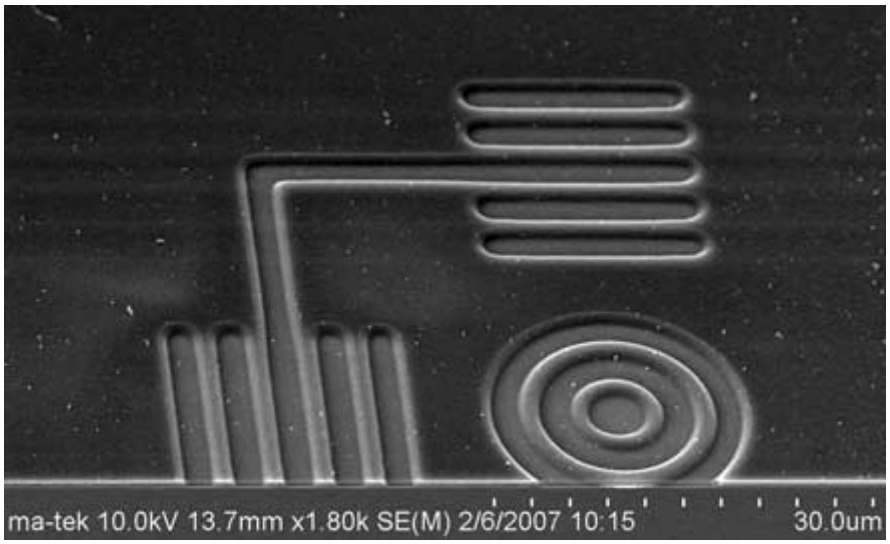
d) Flat panel display structures:

In a flat panel display production process small structures in glass samples are produced by a laser. The following sketch gives an overview about the lateral dimensions of these structures:



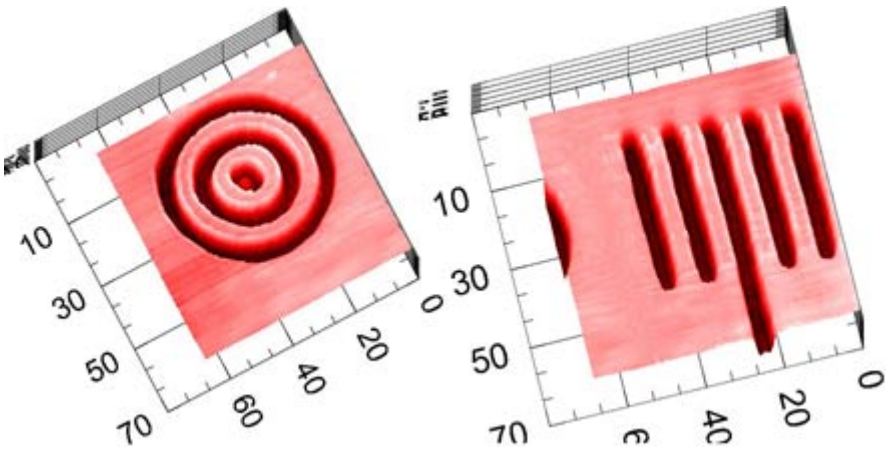
Flat structures on glass generated with a laser, scaled in mm

The SEM image shows the medium sized structure but the SEM alone cannot resolve the 3D information:



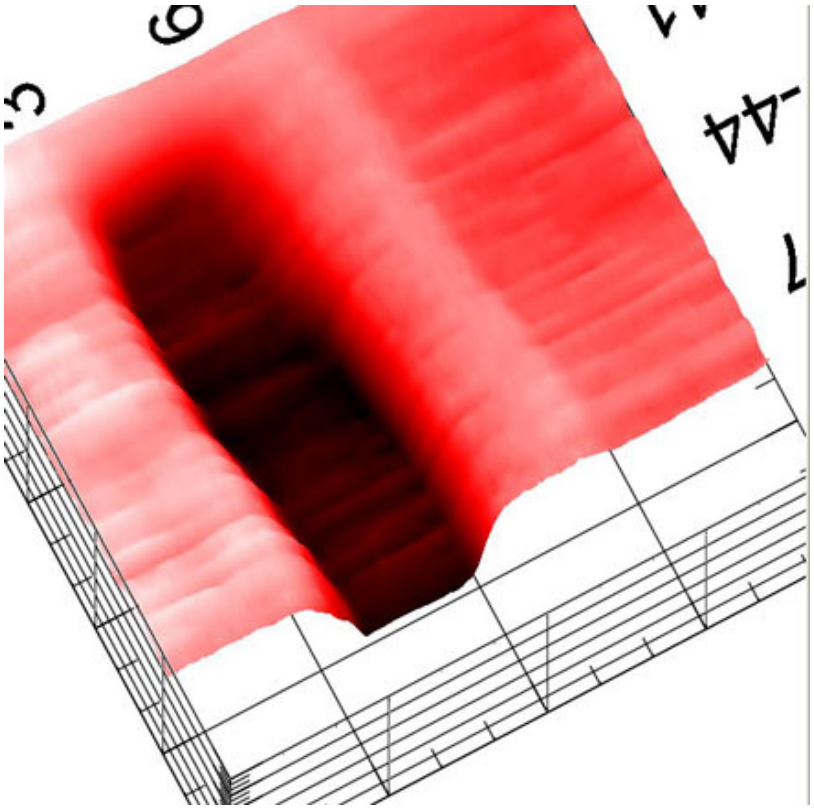
Biggest pattern with 5 um linewidth generated with a laser

The 3D-image of the circle area and a part of the line array generated with the "Dimensional SEM" is shown in the next picture. All axes are scaled and traceable to international standards:



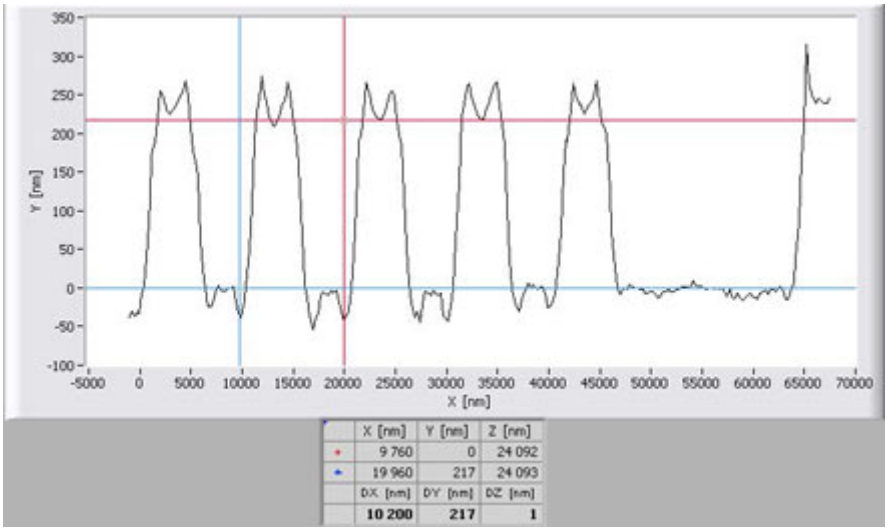
Biggest pattern with 5 um linewidth generated with a laser

The grooves in the 3D-scan appear deeper than they are, because the vertical (depth-) axis in the upper picture has a higher magnification than the two horizontal axes. A zoom into a small area of such a structure is shown in the next image including more details:



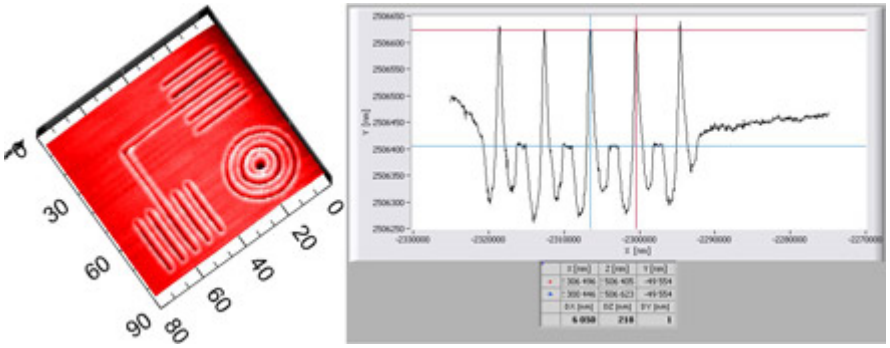
One line and its fine structure

In any area of the sample structure linscans can be measured. The following single linescan was made over an area of 5 linear grooves (big pattern). The depth of the grooves is measured with 217 nm, a value that is already below the wavelength of light. The distance between the grooves (periodicity) is measured with 10.200µm:



Biggest pattern: single linescan over the area of 5 linear grooves

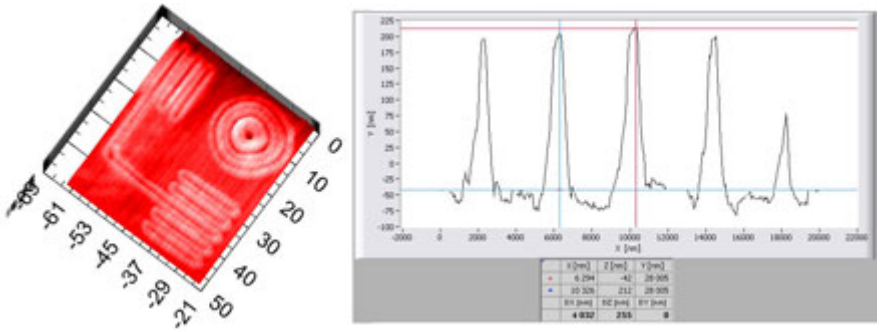
The next 3D surface scan was made over a complete medium sized pattern. The single linescan was made within the area of 5 linear grooves:



3D scan of the medium sized pattern together with a linescan

The lateral image size is 80 µm x 80 µm. The depth of the grooves is measured with 218 nm. The distance between the grooves (periodicity) is measured with 6.050µm. The linescan presents the fine structure of the lines and circles quantitatively and informs about the side effects of the structuring method, e.g. the small peaks beneath the grooves.

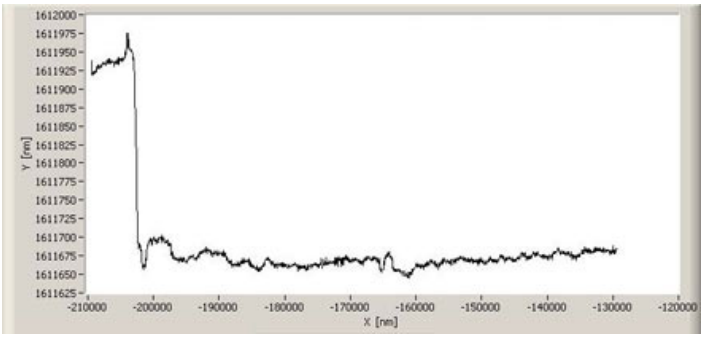
The next 3D scan was made over a small structure that is nearly invisible in the light microscope and can laterally only be resolved with the SEM:



3D scan of the small sized pattern together with a linescan

The lateral size of the whole image is 50 µm x 50 µm. The single linescan was made within the area of 5 linear grooves and shows that the lines are different in depth. The maximum depth of the grooves is measured with 255 nm, the minimum depth is measured with 238 nm. The distance between the grooves (periodicity) is 4.032 µm. The precision of this measured data is already in the range of Scanning Probe Microscopes. But SPM's cannot compete in range and functionality.

The upper measurements could not be performed with other machines in the market. And the next measurement is even more unique: The surface roughness measurement **WITHIN** a single of these grooves:



Calculated roughness values for this measurement:
Ra: 8.0 nm, Rq: 8.8 nm,
Rz: 20.1 nm, Rt: 35.5 nm

Parameters:
Lambda cut-off: 30 000 nm,
Measuring length: 12 694 nm,
Single measuring length: 2 549 nm

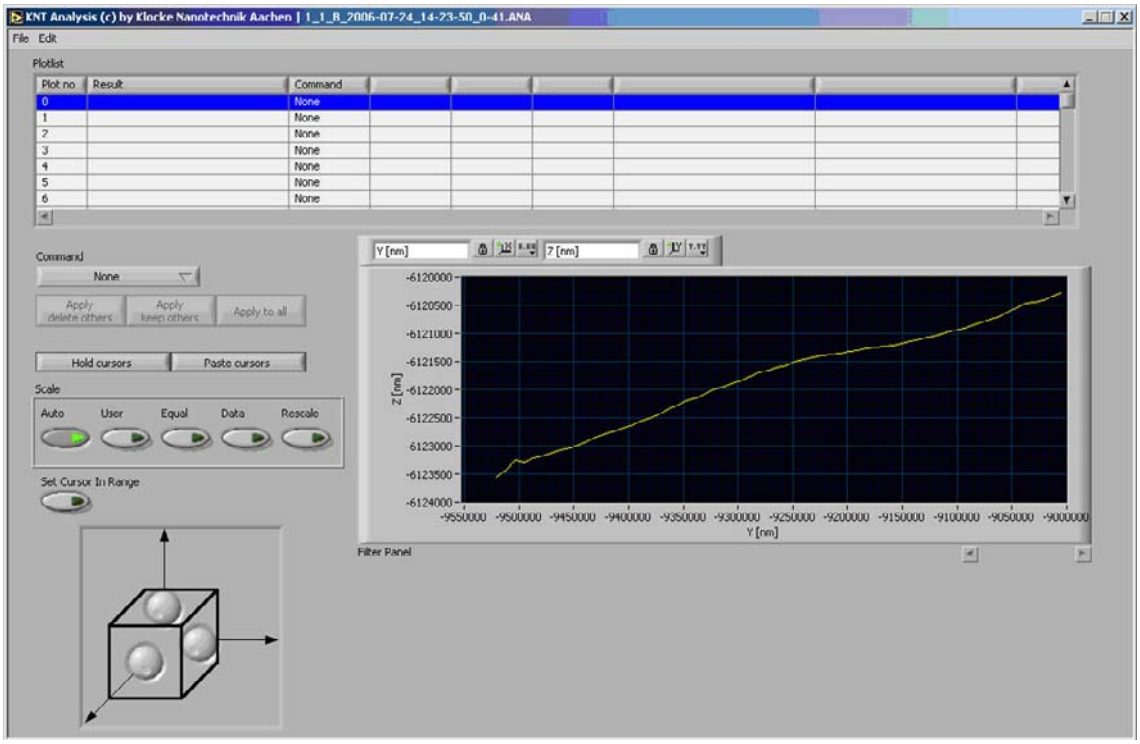
That's what we call a Dimensional SEM!

The upper descriptions of dimensional measurements prove the power of the 3D-Nanofinger. Neither a standard Profilometer nor a Coordinate Measuring Machine can deliver such calibrated 3D images: from micro-parts up to mm and cm sized objects.

Data Analysis after the measurements:

The Analysis software module allows post data processing of data sets measured e.g. with the 3D-Nanofinger. It is included as module in NanoControl. The data import can be from ASCII format files, like the data files of the 3D-Nanofinger with the file name suffix ".XYZ". Such a data file contains a whole array of scans with XYZ coordinates. The structure is that of TAB-separated columns. This file can also be opened easily with Excel or other data processing software systems. The Analysis software can store and open data sets also in its own compressed data format including the operations that were used in the Analysis program.

The main window of the "Analysis" software is shown in the next picture:

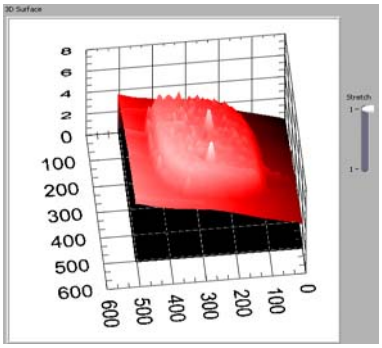


The upper area of the main window includes the plot list. Each row represents one XYZ dataset, e.g. forming one line of a surface profile. The whole set of rows in the plot list represents the content of one data file ".XYZ".

Below this plot list a diagram window shows the content of the plot list row that is marked with the cursor line. When a row is marked active by clicking on it with the left mouse button, it is possible to jump to the next row with the arrow keys ↓ or ↑, that is immediately displayed in the diagram window. By scrolling down with the arrow key ↓ it is possible to get a fast overview of the data file content.

In the diagram window of the upper picture the Y-axis was selected as horizontal axis and the Z-axis as the vertical axis. But the data set may have been collected in another direction. Then it is necessary to rotate the diagram axis relative to the XYZ axes of the data set. This is possible with the bottom left cube and its 3 buttons.

3D-images:

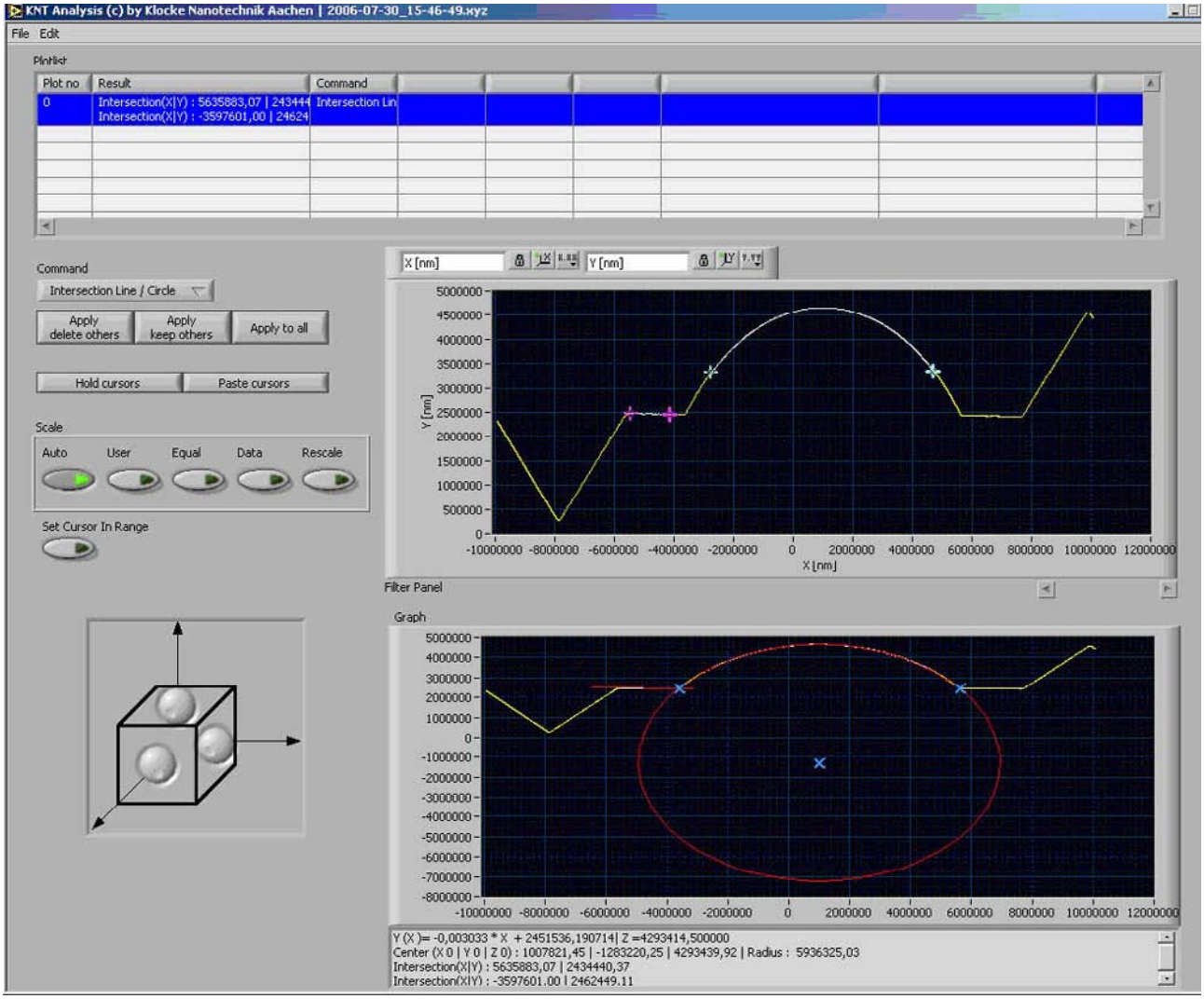


When arrays of linescans are available it is possible to show them as 3D-image:

The orientation of the 3D dataset can be modified by pressing the left mouse button and moving the mouse. Adding the ALT button allows to change the size. With the shift button the 3D dataset can be moved within the window.

Several filters data processing commands and algorithms for detecting surface and dimensional properties are included, for example:

Sloping Level, XY Offset, Roughness, Distance, Angle, Fit line, Best fit circle, Intersection Line – Line, or as shown in the next image: Intersection Line – Circle.



Several customer designed commands to resolve special sample features are prepared in addition. The command list will be expanded continuously, in particular to support the unique 3D-features of the 3D-Nanofinger.

For the most actual information see www.3D-Nanofinger.com