AFM Integration in Production as Metrology Tool

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About VSL

- **National Metrology Institute** of the Netherlands: appointed by the Dutch government to maintain and develop the *national measurement standards*

- **Research institute** in the field of metrology

- Provides *metrology services* to customers

- Contributes towards the reliability, quality and innovation of products and processes

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Traceability to SI

**Definition of metre:** length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second

Primary realisation of metre

- Primary standard of time ("Dutch second")
- Frequency comb
- Primary standard of length ("Dutch metre")

Secondary measurements

- Laser interferometer

Traceable measurement of displacement, size etc.
VSL traceable AFM

- Directly traceable via built-in **interferometers**
- **Single nm** uncertainty
- **1 mm³** measurement volume
- **3D probing system** based on photo-thermal excitation

![Image of VSL traceable AFM setup]

**Photo thermal actuation**

- **AFM cantilever**
- **Quadrant detector**
- **Deflection detection**
- **635 nm Laser diode** (~ 0.5 mW)
- **405 nm Laser diode** (~ 0.5 mW (DC) ~0.1 mW (AC))
- **Multi frequency lock-in amplifier**
- **Computer**

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Natural habitat for traceable AFM

Environmental specifications Nanolab

<table>
<thead>
<tr>
<th>Metric</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>20,0 °C</td>
</tr>
<tr>
<td>Spread</td>
<td>0,1 K</td>
</tr>
<tr>
<td>Max deviation per hour</td>
<td>0,1 K</td>
</tr>
<tr>
<td>Max deviation per day</td>
<td>0,1 K</td>
</tr>
<tr>
<td>Max gradient (3D)</td>
<td>0,1 K</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>45 %</td>
</tr>
<tr>
<td>Spread</td>
<td>5 %</td>
</tr>
<tr>
<td>Air speed</td>
<td>&lt;0,05 m/s</td>
</tr>
<tr>
<td>Excess pressure</td>
<td>20 Pa</td>
</tr>
<tr>
<td>Air quality</td>
<td>ISO 7 (locally ISO 6)</td>
</tr>
<tr>
<td>Vibration level</td>
<td>70 nm [2-30] Hz 0,001g [30-200] Hz</td>
</tr>
<tr>
<td>Sound level</td>
<td>45 dB(A)</td>
</tr>
</tbody>
</table>

How to bring this to the production line?
automated in-line metrology for nanoscale production

- Bring an AFM and a white light interferometer to products in a production line
- Perform reliable measurements on the nm scale
- In the presence of vibrations, thermal drift, contamination

www.aim4np.eu
Critical quality parameter: $Sq$

- Product case studies: injection moulding and thin film organic solar cells
- $Sq$ identified as critical quality parameter

$$Sq = \sqrt{\frac{1}{A} \iint_A \left[ z(x, y) - z_{\text{ref}}(x, y) \right]^2 \, dx \, dy}$$

ISO 25178-2:2012

- Measurement range: **up to 20 nm**
- Target measurement uncertainty: **0.6 nm**
AFM scanner calibration aspects

Scanner errors:
- Non-linear response to actuation voltage
- Geometrical distortions
- Cross-talk

Calibration required:
- Sensitivity (x,y,z)
- Non-linearity (x,y,z)
- Squareness (xy, yz, zx)
Classical calibration approach

- Delicate structures, susceptible to contamination and damage
- Expensive to fabricate and calibrate
- Fixed height/pitch, multiple standards needed for full scanner volume
- Limited availability small heights/pitches
- Cross-talk effects

ISO 5436 step height standard

1D pitch standard
Virtual height standard concept

- Versatile
- Small heights accessible
- High precision surface not required
- Robust
- Fixed contact point; independent of probe radius and shape
- No lateral scanning; avoids cross-talk
Virtual height standard implementation

- Single crystal stack piezo
- Natural piezo sensitivity; intrinsically stable
- Nominal sensitivity: 1 nm/V
- Waveform generator without additional amplifier
- Small footprint
Traceability: Picodrift interferometer

- Double-ended heterodyne interferometer
- Optically balanced paths
- Spatially separated frequencies
- In-situ air refractometer
Picodrift complete setup

1. Traceable: beat node measurement against primary standard
2. Stability: laser locked to stable ULE cavity, environment parameters monitored
3. Measurement:
   - beam preparation
   - beam delivery
   - interferometer
   - detection
   - processing

Diagram:
- ECDL
- I-HeNe
- DDS
- EOM
- LP
- PID
- AOM
- interferometer
- reference
- sample
- FPGA
- DDS
- reference
- sample
- Processing

Equation:
\[ w = 2\pi (f_1 - f_2) \]
\[ \cos \omega \]
\[ \sin \omega \]

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Virtual height standard calibration

Mirror
Retroreflector
Piezo
Virtual height standard calibration results

Virtual standard piezo calibration

\[ y = 1.0882x \]
\[ 1 - R^2 = 1.1 \times 10^{-8} \]
Virtual standard calibration uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>Relative error of order $10^{-6}$, negligible</td>
</tr>
<tr>
<td>Alignment</td>
<td>Relative error of order $10^{-7}$, negligible</td>
</tr>
<tr>
<td>Resolution</td>
<td>1 pm</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>2 pm</td>
</tr>
<tr>
<td>Noise</td>
<td>5 pm</td>
</tr>
<tr>
<td>Stability (ageing)</td>
<td>1% per year</td>
</tr>
<tr>
<td>Environment</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Target value for total calibration uncertainty: **0.3 nm**
AFM z-axis calibration with virtual height standard

- AFM: 10 lines/s
- Virtual standard: 20 Hz square wave
- Z-axis calibration factor from virtual standard: 0.926
- With physical artefact: 0.94
Virtual ISO 5436 calibration

- AFM: 10 lines/s
- Virtual standard: 30 Hz square wave
- Z-axis calibration factor from ISO 5436 analysis: 0.922
Virtual lateral standard concept

- **Shear piezo** of the same material as virtual height standard
- Use **correlation** between two AFM images to calculate **lateral sensitivity and non-linearity**
Virtual lateral standard calibration

- Square mirror to aid alignment
- Displacement doubling
- Maximum non-linearity: 2 pm
AFM lateral scale calibration with virtual standard

- Interlacing minimizes effects from tip and sample instabilities, noise and drift
AFM lateral scale calibration with virtual standard

- Calibration coefficient: $0.9005 \pm 0.0026$
- Non-linearity determined from correlation between vertical image lines

![Graph showing non-linearity 400 nm range](image)

Non-linearity 400 nm range

- Uncorrected
- Corrected

Horizontal position / nm

Non-linearity / nm
Summary

- The **aim4np project** aims to bring nanometrology to production environments with a **robot-mounted AFM**
- **Virtual standards** based on single crystal stack piezo actuators have been developed for on-site AFM calibration, providing great versatility and robustness without sacrificing accuracy
- The virtual standards have been **traceably calibrated to sub-nm accuracy** using the special **Picodrift interferometer**
The project consortium aim4np acknowledges funding from the EU commission under its FP7 NMP Programme.
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