MONTE-CARLO UNCERTAINTY EVALUATION OF TRANSFER STANDARDS FOR ATOMIC FORCE MICROSCOPY

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Atomic force microscopes (AFMs) are frequently used to measure surface features and parameters. The traceable calibration of images obtained is a pre-requisite for establishing the uncertainty associated with such a measurement and to be used in quality assurance processes. For this purpose, the typical procedures for the calibration of these instruments use transfer standards, which typically consist on gratings produced using optical lithography with x-y-z dimensions traceable to a national laboratory [1 - 3]. In this way, the traceability chain for AFM instruments is the following: meter – laser interferometry – MAFM (metrologic AFM with displacements measured by means of laser interferometry) – transfer standard – AFM.

In this work, we will estimate the uncertainty of a typical transfer standard for AFM calibration using a Monte-Carlo technique. This procedure appears very useful specially when model equations are complicated and the sensitivity coefficients are difficult to obtain. Uncertainty budget and model equations (xy and z) for the calculations are obtained from bibliographic data [4], where the gratting calibration was made using a MAFM. Next we describe equations, standard uncertainty and type of distribution for each term:

$$L_{xy} = l_{xy} \frac{\lambda}{4n\cos\theta_{xya}\cos\theta_{xym}\cos\theta_{xyt}} + L_{xyAbbe} + L_{xydp} + L_{xymf} \qquad \text{(x-y axis)}$$

$$L_{z} = l_{z} \frac{\lambda\cos\theta_{zt}}{4n\cos\theta_{zm}} + L_{zAbbe} + L_{zdp} + L_{zmf} + L_{zct} \qquad \text{(z axis)}$$

where:

l_{xy} is the distance in the *x* or *y* axis ($u_{lx} = 6.1\cdot10^{-9}$ m; $u_{ly} = 10^{-8}$ m; probability distribution: normal).

l_z is the distance in the *z* axis ($u_{lz} = 9.2\cdot10^{-10}$ m; probability distribution: normal)

n is the refractive index ($u_n = 7.8\cdot10^{-6}$; probability distribution: normal)

λ is the laser wavelength ($u_l = 10^{-15}$ m; probability distribution: normal)

$\cos\theta_a$ is the angle between the measurement axis and the displacement axis ($u_{\cos\theta a} = 10^{-10}$; probability distribution: rectangular)

$\cos\theta_m$ is the angle between the incident laser beam and the mirror normal ($u_{\cos\theta m} = 2\cdot10^{-6}$; probability distribution: rectangular)

$\cos\theta_t$ is the tilt angle of the simple relative to the *x* measurement axis ($u_{\cos\theta xt} = 1.3\cdot10^{-6}$; $u_{\cos\theta yt} = 2.6\cdot10^{-6}$; $u_{\cos\theta zt} = 2.5\cdot10^{-6}$; probability distribution: rectangular)

L_{Abbe} is the correction factor of Abbe offset ($u_{xLAbbe} = 1.3\cdot10^{-9}$ m; $u_{yLAbbe} = 1.1\cdot10^{-11}$ m; $u_{zLAbbe} = 1.3\cdot10^{-10}$ m; probability distribution: rectangular)

L_{dp} is the correction factor for the dead path length in the interferometer ($u_{xLdp} = 9 \cdot 10^{-11}$ m; $u_{yLdp} = 1.5 \cdot 10^{-10}$ m; $u_{zLdp} = 1.4 \cdot 10^{-10}$ m; probability distribution: rectangular)

L_{mf} is the correction factor for thermal expansion in the metrology frame ($u_{xLmf} = 1.7 \cdot 10^{-11}$ m; $u_{yLmf} = 2.2 \cdot 10^{-10}$ m; $u_{zLmf} = 1.9 \cdot 10^{-10}$ m; probability distribution: rectangular)

L_{ct} is the correction factor of the cross-talk movement of the AFM tip ($u_{Lct} = 4.3 \cdot 10^{-11}$ m; probability distribution: rectangular)

Monte-Carlo evaluation was performed for 100000 random values generated according the above mentioned input distributions. Output values obtained for the three measurement axes are the following:

$L_x = 189$ nm U (L_x) = 12 nm (95 % confidence)

$L_y = 189$ nm U (L_y) = 20 nm (95 % confidence)

$L_z = 79.1$ nm U(L_z) = 1.8 nm (95 % confidence)

All of them are in agreement with those achieved in the bibliography [4]. This fact demonstrates the good fitting of the output uncertainty to a normal distribution and the accomplishment of the Central Limit Theorem. An example of one output distribution is depicted in Figure 1. The application of Monte-Carlo technique for uncertainty evaluation in nanometrology opens the possibilities to quantify more complicated model equations that can take into account the dimensions of the tip or the Van der Waals forces between tip and sample.

References:

[1] R. Leach, J. Haycocks, K. Jackson, A. Lewis, S. Oldfield, and A. Yacoot, Nanotechnology, **12** (2001) R1-R6.
[2] WGDM-7: Preliminary comparison on nanometrology. Final Report of Nano 4: 1D gratings (2000) 7.
[3] WGDM-7: Preliminary comparison on nanometrology. Final Report of Nano 2: Step height standards (2003) 3.
[4] J. Haycocks and K. Jackson, Precision Engineering, **29** (2005) 168-175.

Figure 1: Uncertainty distribution of L_z obtained using Monte-Carlo evaluation