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# OPTICAL METHODTS FOR CALIBRATION OF GRATINGS

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*Vă prezentăm un set-up optoelectronic pentru caracterizarea metrologică a codoarelor optice. Practic, set-up –ul este un interferometru traceabil de masurat deplasări cu rezoluţie şi acuratete de ordinul nanometrilor. Astfel, reţeaua de 24 de micrometri măsurată cu ajutorul interferometrului traceabil poate fi acum acceptată ca instrument metrologic pentru calibrarea instrumentelor sensibile la scara nanometrică.*

*We present a complete optoelectronical set-up for optical encoder metrological characterization. Basically the set up is an interferometric one able to measure length, in a traceable manner, with nanometer resolution and accuracy. The 24 micrometer gratings can be now accepted as metrological tools for calibrating sensitive instruments at nanometric scale.*

**Keywords:** accuracy, calibration, optical encoder, interferometry, microscopy

## 1. Introduction

Nanotechnology is the investigation, application and production of materials or devices with a dimension or production tolerance of less than 100 nm. This size range covers precision engineering at the top end (100 nm) and atomic physics and chemistry at the bottom end (0.1 nm). Nanometrology is concerned with measurement of thin films, surface roughness, shape, position, volume, etc., associated with one body, which can be large as well as small. Tolerances and clearances between objects and accuracy and precision of instruments is another preoccupation of nanometrology.

Dimensional nanometrology is considered a part of metrology that is concerned with measurement and calibration of dimensional quantities of components *with at least one critical dimension or functional feature* below 100 nm for which the uncertainty is required to be on the order of nanometers or better.

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Measurements referring to a standard are called *traceable*. The term *traceability* is used in length metrology to refer to an unbroken chain of measurement comparisons relating the measurements of an instrument to the standard definition of the meter. Traceability can be used to certify the accuracy of an instrument relative to the standard.

Commercial length measuring interferometers usually have sub-nanometer resolution but their *accuracy* strongly depends on local conditions (e.g. mechanical stability, temperature, air turbulence, humidity, or their own intrinsic unstable parameters like wavelength, beam pointing, nonlinearity in fringe counting, etc.).

A novel paradigm in nanometrology asks for in situ measurements as opposed to measurements of the sample moved out from its original place and consequently, altered. For this reason the calibration process is of uttermost importance. In this paper we present an optical setup able to measure in the micrometer range with nanometer resolution and tens of nanometers accuracy end also to measurement of the optical encoders; generally, the optical encoders are gratings [1-3].

## 2. Experimental set-up

The optical encoder was firstly analyzed using commercial devices, such as: optical microscope, contact profilometer, atomic force microscopes. The resulting (RMS) error was in the range of 40 nm.

Next, we built an opto-electronic setup able to measure in the micrometer range with nanometer resolution.

Fig.1 shows the setup with the line detection system and a commercial Twyman-Green interferometer (e.g. SIOS interferometer) to calibrate the grating.

The SIOS interferometer is a commercial traceable instrument for distance measurement. It uses a stabilized He-Ne laser (@ 633.961 nm) and the measuring arm is composed of the measuring head and a reflector placed on the moving part. For our experiments we used about 5 mm displacement range and interferometer resolution about 1.2 nm.

The retro-reflector is fixed on a travel stage (e.g. a microscope XY translation table from PRIOR) which stands on a vibration isolated optical table together with the grating and the whole setup. In order to perform high resolution/and accuracy measurements the seismic noise is the first that needs to be reduced bellow the intended measuring range, using vibration isolation.

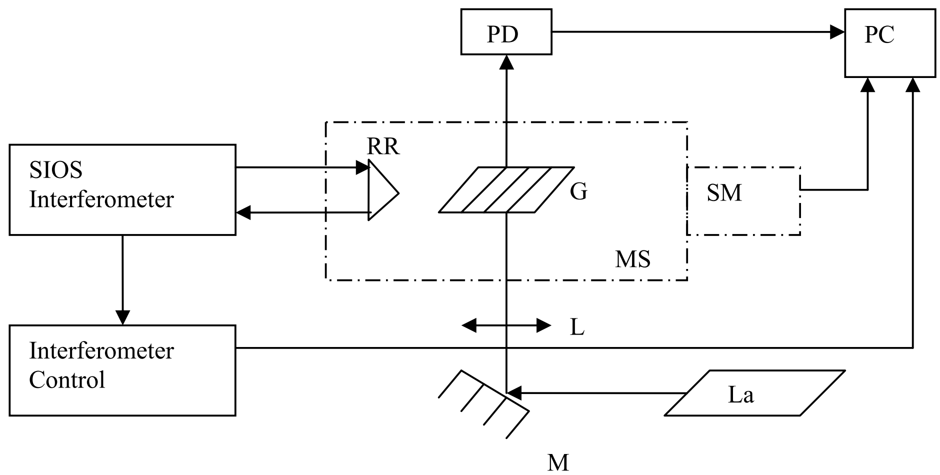



Fig. 1. The setup for measuring a 24 micrometers pitch grating:
La - HeNe laser; M- mirror; L - Lens; G-grating; MS - travel stage; RR - retro reflectors; SIOS interferometer; PD - photodetectors; PC – computer.

A lens is focusing the laser beam on the grating in order to reduce the beam diameter bellow the size of the pitch of the grating. All devices are connected to a computer and the measurement is realized in real time with a fast data acquisition system. The equivalent movement of 24 grating lines was commanded to the travel stage and the displacement value as indicated by the SIOS interferometer was recorded at the same time.

### 3. Measurements and results:

Several types of gratings were tested regarding both profile and material or line density (e.g. 24 µm chrome on glass, 10 µm chrome on silicon, 48 µm chrome on glass and metallic copper). We conducted independent measurements with four devices: Axio Imager Zeiss optical microscope, Ambios interferential microscope (e.g. using white light interferometry principle), XP2 Ambios contact profilometer and atomic force microscope (AFM type QUESANT Q-SCOPE™ 350.

They all display nanometer or even sub-nanometer (e.g. AFM) resolution. Comparison with a laser interferometer allows for traceable measurements because this is the *de facto* standard meter as stated by the international definition of the length unit.
For practical reasons, a Ronchi grating, realized by chrome deposition onto glass and having the nominal pitch of 24 µm, was chosen.

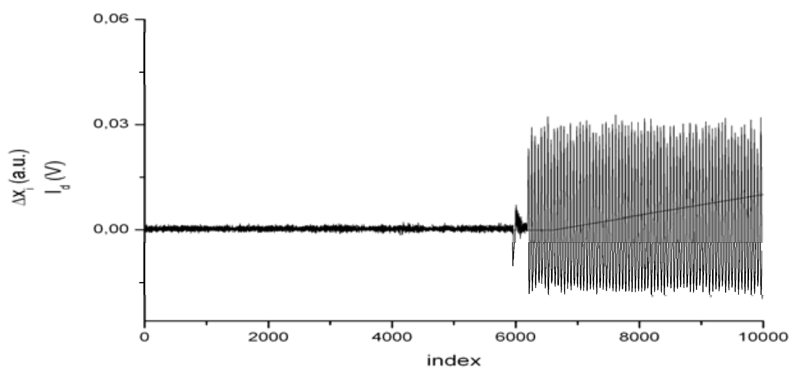



Fig. 2. The acquisition noise when the travel stage is at rest and in motion (for the SIOS interferometer and the photo-detector).

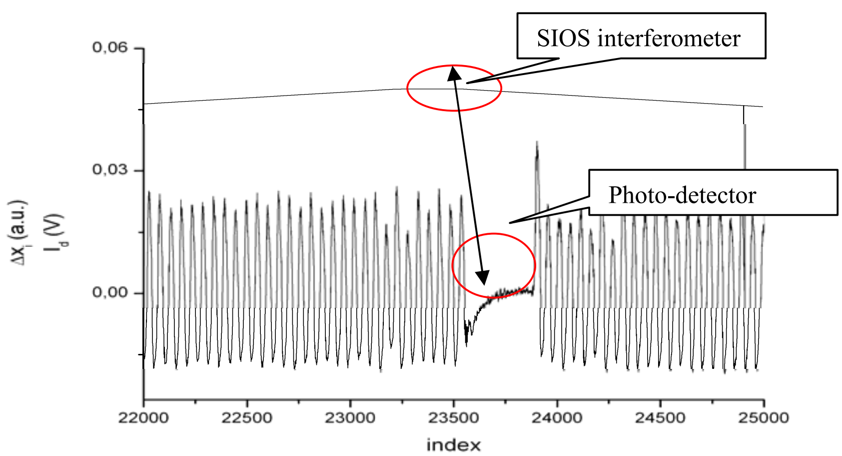



Fig.3. Correspondence between static zones recorded with the SIOS interferometer and the photo-detector.

We are interested in comparing the uncertainty (expressed as the root mean square) for the commercial devices and for the home made interferometric setup.

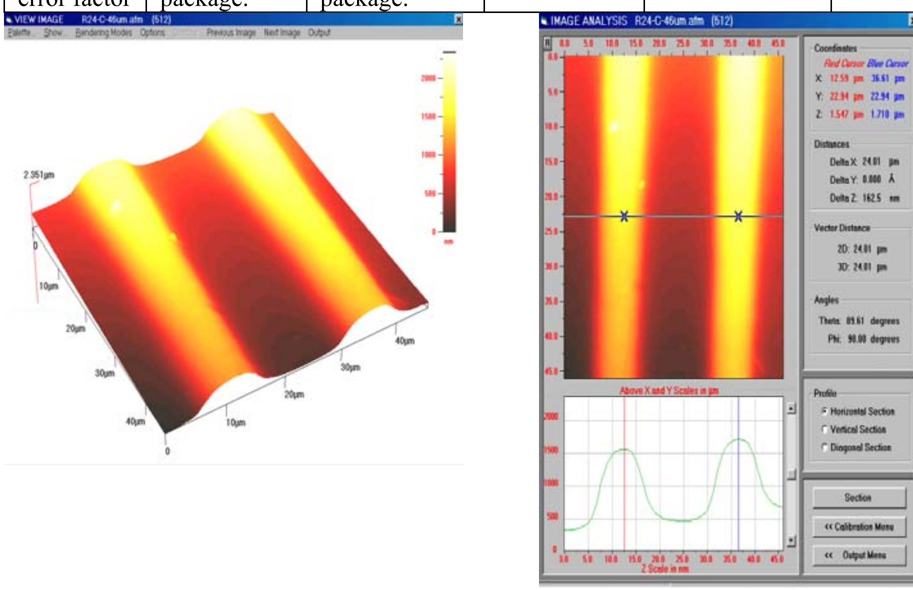
The measurement of grating pitch is realized by correlation between the SIOS interferometer and photodetector outputs (Fig. 2). More data can be obtained for a forward/backward displacement, when the SIOS interferometer output increases linearly and the photodetector output shows the returning points (e.g. the saddle-like shape, common to oscillatory motion) [5]. This is shown in Fig. 3.

As the grating moves repeatedly forward and backward with constant velocity there is a delay at the returning points. Consequently, the program extracts the zones where the travel stage together with the grating is static. This is done by considering as static the sequences of measurements in which the maximum absolute difference between any two measurements is less than the noise multiplied by a certain factor. Adjacent static zones are then stitched together.

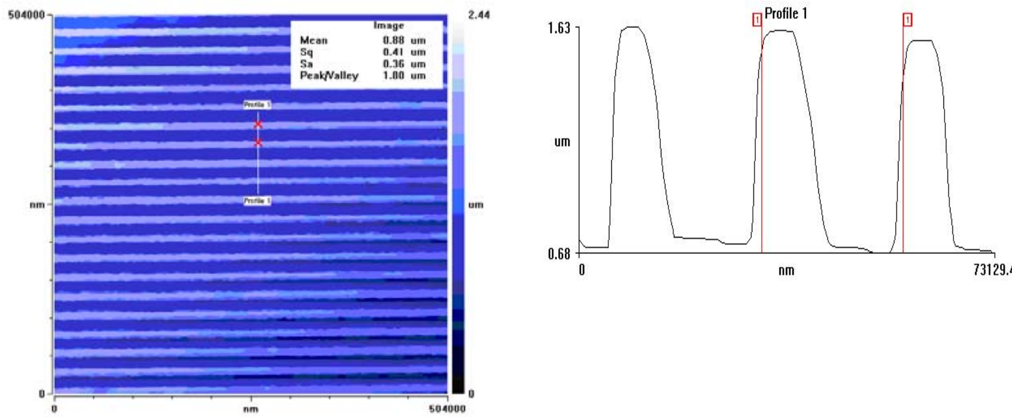
*Table 1*

**Results obtained with commercial devices and with the traceable setup**

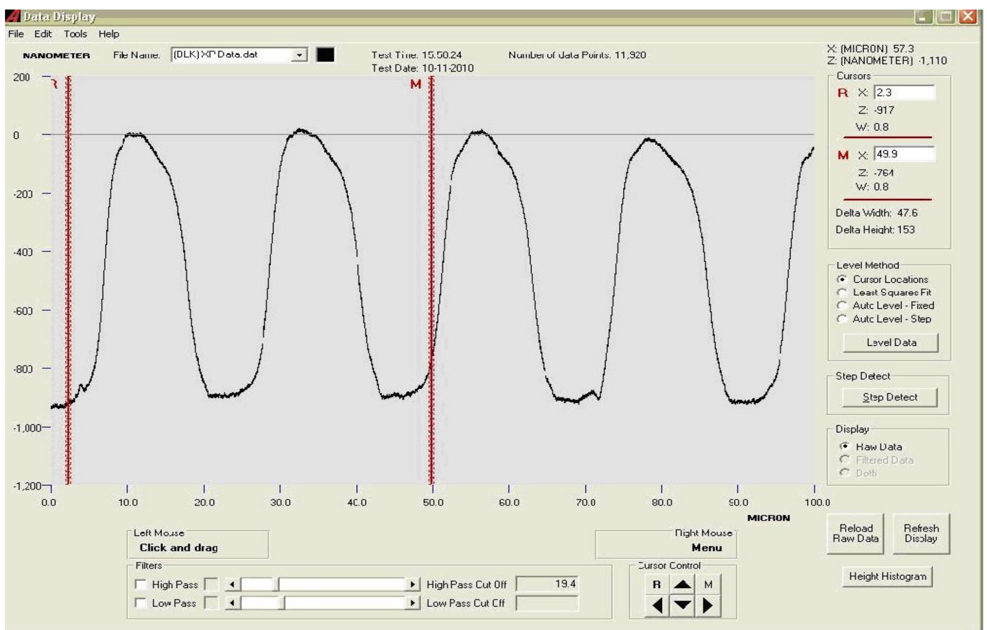
| Instrument | Optical Microscope | The profilometer | AFM | Interferometer Microscope | Interferometer |
|---|---|---|---|---|---|
| Type | Axio Imager from Zeiss | Ambios sXP2 | Quesant Q-SCOPE™ 350 | Ambios -WLI Xi 100 | SIOS |
| (p±σ) nm | 24 000 ±39 | 24 000±32 | 24 000±10 | 24 000± 26 | 24000±21 |
| σ (nm) | 39 | 32 | 10 | 26 | 21 |
| p= pitch of grating σ= the error factor | 60 measure-ments for a 25 lines package. | 60 measurements for a 25 lines package. | 60 measure-ments | 60 measurements | 7 sets for 1500 samples |




*(a)* Atomic Force Microscope (Quesant Q-SCOPE™ 350) measurements.




*(b)* White Light Interferometer (Xi 100) measurements.




*(c)* Contact profilometer (XP2 Ambios) measurements.

Fig.4. Results obtained with commercial devices: (*a*) AFM, (*b*) WLI and (*c*) contact profilometer.

## 3. Conclusions

The experience gained when realizing these precision measurements allows us to conclude the following:

- Commercial devices have a high sensibility (e.g. resolution) but their precision depends on many factors, and a stable environment is the most important of all. Inherent mechanical vibrations of the building, air conditioning and presence of the people in the laboratory induce perturbations to the measurements. Another factor is given by the principle and construction of the device, as we observed differences in the line profile (e.g. from rectangular to rounded profiles). Not all devices react in the same manner to a step-like object. It is expected to obtain more round edges the grater the diameter of the stylus (e.g. for contact profilometer). The appropriate curvature radius for the tip of the stylus must be chosen when making a specific measurement. For example, a 2.5 µm tip was used for the 24 µm grating, which would be useless in measuring a 3 µm grating. Moreover, there are differences in night and day time measurements, regarding seismic noise;

- The calibration of the commercial devices is valid for a limited period of time, so it must be realized daily. At this level of sensitivity the device easily and quickly loses calibration;
- Numerical results may differ from a device to another, even with 100%, when measuring nanometer scale objects;
- High inclinations of the surfaces may result in an impossible measurement with the WLI. This device is suited for height step measurements;
- The most sensitive device (AFM) is also the most imprecise one on the nanometer scale;
- The shape – profile – of the object to be measured (Fig. 4) is of high importance for a direct measurement;
- The higher the number of lines integrated into the measurement, the more precise (on average) the measurement; thus the AFM which has a very small viewing field introduces the largest errors as it does not mediate on more lines of the grating.

A comparative study between commercial devices and a home-made interferometer setup was realized in this manuscript. The main conclusion is that measurements reporting nanometer accuracy are difficult to be considered correct.

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