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The turbulent history of interferometric methods of precision positioning

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Since the earliest developments 150 years ago, advances in light sources, optics, and data processing have firmly established interferometry as an indispensable tool for measurement of distance, displacement, and angle. While it can be sensibly argued that ever-increasing demands on precision have driven advances in interferometric positioning, here we follow the path to the current state of the art with a different driving force in mind: the presence of air in the beam paths, and the innovations required to deal with refractive index changes and air turbulence.

Free-space, laser-based Interferometers have evolved from a simple Michelson geometry with fringe counting to complex, multi-axis instruments that have sub-nanometer noise levels for monitoring stage motions of several meters per second (Figure 1). These systems readily satisfy the Abbe principle, are directly traceable to the unit of length, and when placed in a vacuum, have unparalleled performance [1]. However, in more common applications where the measurement beams pass through the atmosphere, refractive index variations and turbulence are dominant sources of uncertainty.

An alternative to line-of-sight interferometers is encoders that work together with diffraction gratings to monitor both in-plane and out-of-plane motions of stages (Figure 2). Encoders have the enchanting property of much shorter beam paths through air than free-space systems—a practical necessity for modern high-end semiconductor photolithography machines. Adapting multi-axis encoder technology to the performance demands of photolithography leverages the high-speed electronics and low noise characteristic of heterodyne free-space interferometry in new geometries [2].

A third approach considered here is multi-axis precision positioning for short-range measurements using multiplexed fiber optic interferometry (Figure 3). An example system includes up to 64 passive sensors operated from a common, multi-wavelength source/detection system [3]. The noise performance is 0.02 nm Hz-1/2 over a 3.5mm ± 0.6mm measurement range. These levels of precision once again test the limits of what can be accomplished in the presence of air. In this instance, the solution is to dedicate one or more measurement channels to the task of determining the refractive index of the local atmosphere using stable etalons of traceable, fixed length.

Figure 1: Free-space precision stage motion measurement system.

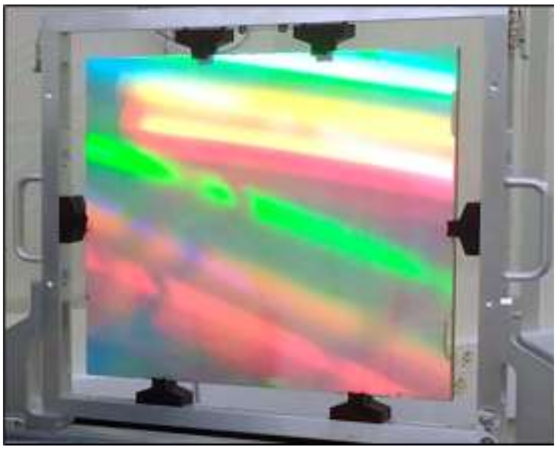

Figure 2: Large 2D grating for encoder-based stage motion control.

Figure 3: Passive sensor for multi-axis, fiber-based position measurement.

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2. V. Badami, J. Liesener and P. de Groot "Encoders graduating to extreme precision," *Mikroniek* 59 (2), 26-31 (2019).
3. V. Badami and E. Abruña, "Absolutely: small sensor, big performance," *Mikroniek* (1), 5-9 (2018).