1.4. Metrology error sources and their control

In this section we define each of the major metrology error sources and discuss the means for controlling them. The error sources that we will be concerned with are: encoder errors, Abbe error, interpolation error, velocity error, detector shot noise error, encoder obstruction error, and “other” errors.

1.4.1 Encoder errors

Encoder errors, i.e. errors in the positions of the rulings on the encoder, are the most fundamental errors that we have to contend with. Clearly, these are systematic errors and could, at least in principle, be measured and corrected for. These type of correction is quite feasible for errors with low spatial frequency, but becomes unmanageable at high spatial frequencies where the error table becomes very large and where initialization becomes critical.

Our approach to the fabrication of encoders has been to make them as accurately as possible and to particularly avoid error sources with high spatial frequencies. Factors that invariably contribute to encoder errors are mechanical motions during fabrication, and the passage of time during the fabrication process. Mechanical motions lead to vibrations and small angular displacements that translate into Abbe errors, and the passage of time leads to varying environmental factors that affect encoder accuracy—such as temperature and atmospheric pressure. Following is a list of encoder fabrication techniques together with notes on their pros and cons in terms of accuracy.

FABRICATION TECHNIQUE	PROS	CONS
Step & repeat lithography	Standard practice; well-understood; machines are available to make large encoders (≥ 400mm dimensions)	Inevitable stitching errors (because the metric of the projected image patches can never precisely match the metric of the stage motion)
Direct laser-write lithography	Lithography machines are available that provide excellent accuracy and absence of high-spatial-frequency errors (e.g. the CORE and ALTA machines made by Etec.).	The highest quality machines can only cover up to 175mm × 175mm; lower quality machines have quite large high-spatial-frequency errors. All machines have a scale factor error, typically a few parts in 10^6.
Holography	Simultaneous and rapid exposure of the entire encoder go a long way to eliminate errors due to mechanical motions and long fabrication times.	Prohibitively expensive to make large encoders; requires two orthogonal exposures; requires large optics of very high quality.[1]
E-beam lithography	Capable of very high spatial resolution, but this is not really a requirement for XY encoders with resolution at the nanometer level.	Not readily adaptable for the fabrication of large encoders.

We routinely measure encoder errors by comparing encoder measurements to those made with a laser interferometer, while taking care to minimize Abbe errors in either metrology system. Figure 8 shows error plots obtained with a variety of encoders. During these measurements, every effort is made to minimize atmospheric turbulence in the vicinity of the laser interferometer; the stage is moved slowly, and the stage and entire metrology system in enclosed in a plastic tent to reduce air currents and acoustic pick-up.

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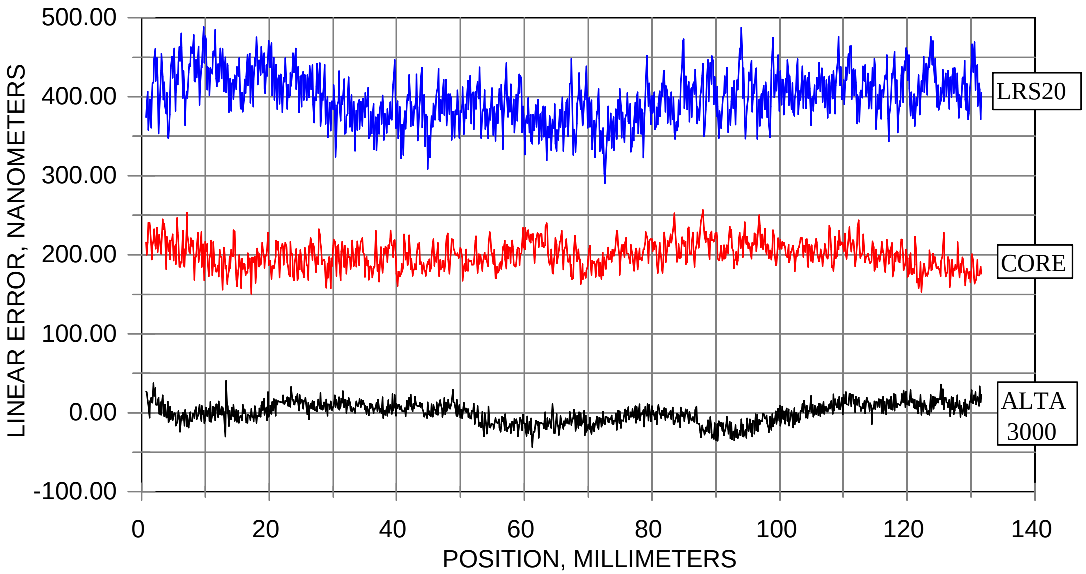
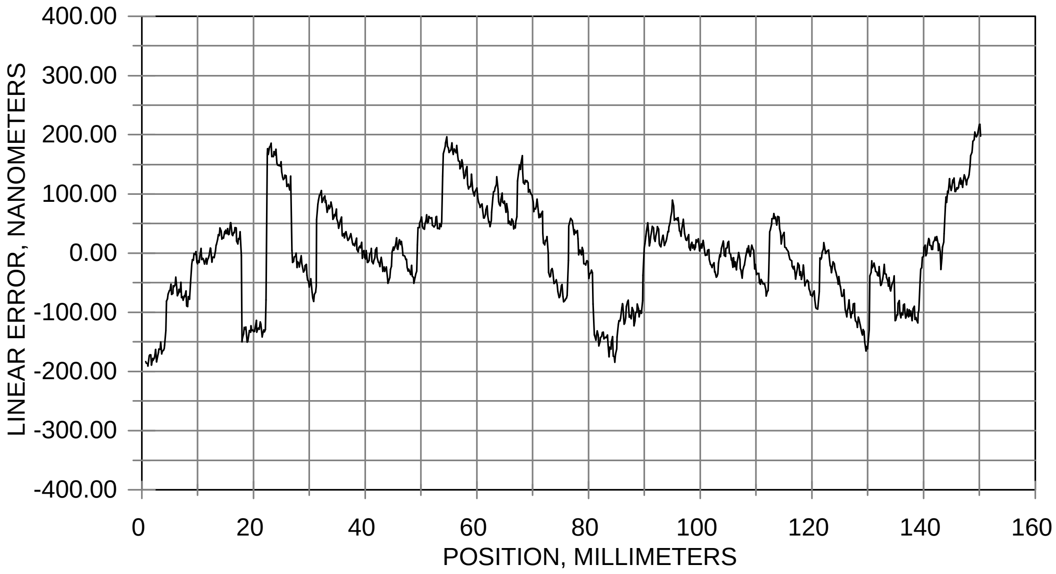
[1] We have developed a techniques for making long (> 100cm) holographic encoders without the need for large optics, but are not able to extend this technique to 2 dimensions. (To be published.) Please see appendix A for more details.



ALTA 3000 vs. CORE vs. LRS200
GRID CALIBRATION 6/16/98



IMPROVED STEP & REPEAT

Figure 8. Error Plots for Various Encoders

The top plot shows error curves for grids made with three different direct-write techniques. The bottom plot is the best effort yet that we've seen for a step and repeat process. Clearly the ALTA 3000 offers the best overall accuracy. Unfortunately, it is limited to a plate size of 175mm. The step and repeat grid has the worst accuracy of the lot, but it is capable of handling up to 400mm plates.

Figure 9 shows measurements made with both an XY encoder and a laser interferometer on a nominally stationary stage in a normal laboratory environment (with no plastic tent). The effects of low-frequency air turbulence on the interferometer measurement is quite clear, while the encoder measurement makes it possible to see the small and slow displacement of the stage—probably due to thermal effects. While the laser interferometer is more accurate that the encoder (particularly in terms of systematic errors), the encoder measurements are more repeatable. Our ultimate goal is to capture the accuracy of a well-stabilized laser interferometer in a robust encoder on a fused silica substrate, and to thus combine the inherent accuracy of the laser with the inherent stability of the encoder.

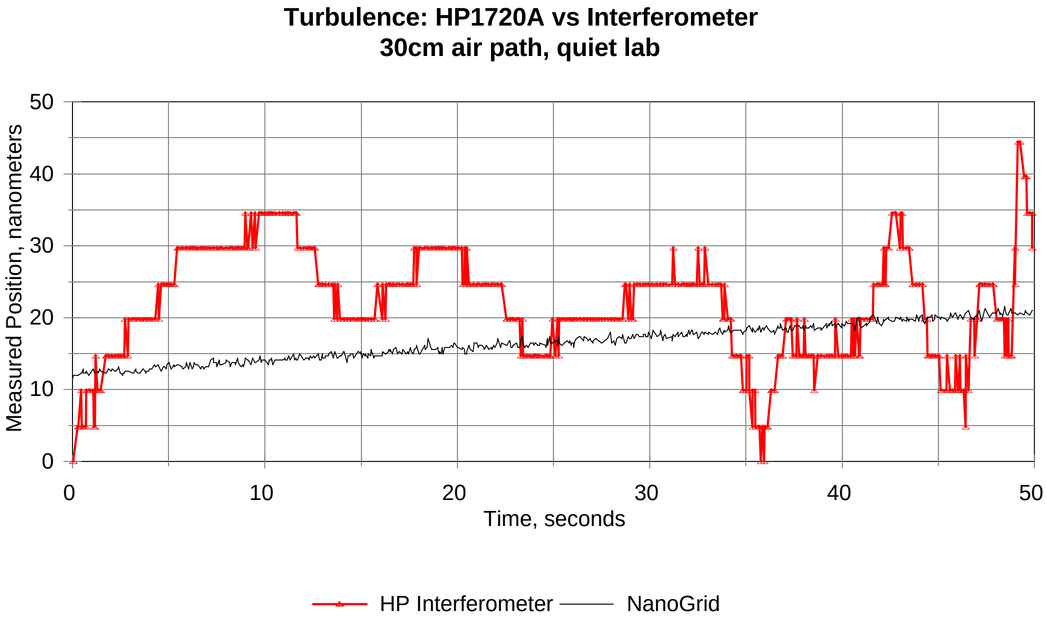


Figure 9 Stationary stage; effects of turbulence on position measurement

Normal quiet laboratory environment. Residual air turbulence causes a 40nm peak-to-peak random error in the laser interferometer measurement, while the NanoGrid measurement is essentially unaffected. Note how the slow displacement (probably thermal in origin) can be seen in the NanoGrid measurement, but not in that of the laser interferometer.

1.4.2 Abbe error

Abbe error occurs when (a) there is a physical separation between the point of measurement and the point of action (we define the *point of action* as the point at which we desire the measurement), and (b) there is a rotation of the moving frame of reference relative to the stationary frame of reference. For the present discussion, we will assume that the rotation is about the Z-axis, and that the desired measurements are of the X and Y displacements of the moving frame of reference (e.g. the frame containing the wafer, the XY encoder, and the stage that carries them) relative to a point of action located in the fixed frame of reference (e.g. the tip of an atomic force microscope). Figure 10 illustrates the situation. The point of action is at P, and the point of measurement is at P′. If the moving frame of reference rotates about the Z-axis by an angle $\Delta\theta$, as shown, there is no X or Y displacement of the point P, but there will displacements Δx and Δy at P′:

$$\Delta x = y\Delta\theta \text{ and } \Delta y = x\Delta\theta, \qquad (9)$$

where x and y are the coordinates of the point of measurement, P′, relative to the point of action, P.

Note that if we are concerned only with displacement in the y-direction (vertical) then the Abbe error can be reduced to zero by making sure that P and P′ lie on a line that is parallel to the y-axis.

Abbe errors are insidious because they can be either repeatable or non-repeatable. If they are repeatable, then they can easily be misinterpreted as encoder errors—and if they are non-repeatable, they can be misinterpreted as turbulence (or other non-systematic) errors. Repeatable Abbe errors are commonly caused by small imperfections in the ways of an air-bearing stage, while stages with circulating bearings generally cause non-repeatable Abbe errors. An advantage offered by an XY-encoder metrology system is the ability to locate the point of measurement very close to the point of action. The ultimate reduction of Abbe error would be a metrology system in which the wafer whose position was to be measured had an XY-encoder on it rear surface, being viewed through a transparent fused silica stage with the point of measurement directly below the point of action.

To get an idea of the magnitudes involved in Abbe errors, consider a 1 mm lateral (x) offset between the point of measurement and the point of action. A 0.1 milliradian rotation (i.e. 1mm in 10m) about the z-axis would then cause an Abbe error in a y-measurement of $1\text{mm} \times 0.0001\text{rad} = 0.1\mu\text{m}$, or 100nm. As we shall see later, actual measurement errors of this magnitude are frequently due to Abbe error.

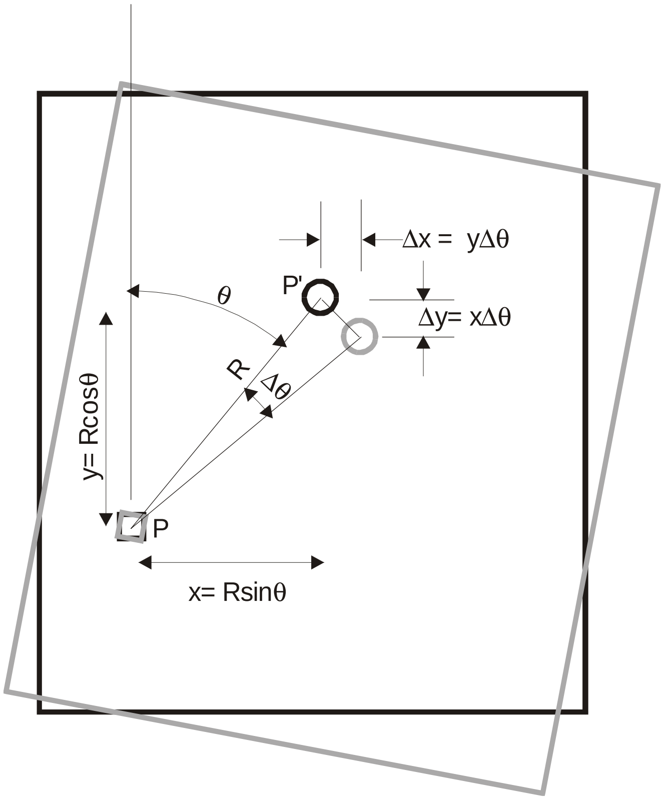


Figure 10 Abbe Error

P is the point of action (where the measurement is desired) and P¢ is the point of measurement. The black and gray portions of the figure show the stage before and after the stage has been rotated about the Z-axis at P by Dq (rotation about another point would be equivalent to rotation about P plus a common Cartesian displacement). The changes in the measurement at P¢ due to the rotation about P is the Abbe error. Clearly, the Abbe error is minimized by keeping the point of measurement as close as possible to the point of action.

1.4.3 Interpolation error

As we saw in equations 4, 5, 6, and 7, the measurement of position (modulo d) is inferred from measurements of R, S and T—predicated on the assumption that the values of I_1 and I_2 in equations 4a, 4b, and 4c were all equal. In fact, due to mismatches in the gains and offsets of the detectors and amplifiers that create these signals, this assumption is never fulfilled. We have termed the resulting errors *interpolation errors,* and have found that by keeping the gains and offsets them matched to within 0.1% (which we can just do using standard electronics components), we are able to keep the interpolation error below 10nm peak-to-peak.

The form of the interpolation error depends on its origin. Gain mismatches between R, S, and T signals cause a sinusoidal a interpolation error with a period of d/4, and offset mismatches produce an interpolation error with a period of d/2. If there is leakage of zero-order diffracted light onto the detector, there tends to be an interpolation error with a period of d. Errors in the gains and/or offsets of the quadrature phase signals X and Y cause similar interpolation errors.

1.4.4 Velocity error

Velocity error is a direct result of the finite *data lag*, or time lag between the occurrence of a position value and the corresponding output signal. If the stage is moving in the x-direction with a velocity v_x, and if there is a data lag τ, then when the stage position is reported, the position measurement of x will be in error by:

$$\Delta x_{VELOCITY} = v_x \tau. \qquad (10)$$

For a 10µsec sec value of τ and a stage speed of 100mm/sec, the velocity error is 1µm.

Fortunately, the velocity error is easy to correct for and this is routinely done. If, however, the data lag is variable, then the velocity cannot be corrected for and there may be significant errors if measurements are made when the stage is moving in different directions or at different velocities.

1.4.5 Shot noise error

For a given nominally constant optical power falling on a detector, there is a corresponding *shot noise* associated with the randomness in the number of photons detected within any specified time interval. When, on the average, N photons are detected within a specific time interval, there is an rms variability $\delta N_{RMS} = \sqrt{N}$, in the number of photons detected in a single measurement. This is a fundamental noise source, and the associated noise can only be reduced by increasing the light level or the measurement duration (bandwidth reduction). A well-designed sensor system is generally *shot-noise limited*, meaning that all of the controllable noise sources have been reduced to a level below that of the shot noise.

4.6 Grid-obstruction error

Large defects or debris on the grid surface can cause a measurement error. In the worst case, the debris can completely occlude the output laser spot, thus causing the sensor to lose count. This is referred to as a *global error* in that all subsequent measurements will be of by the number of counts missed during occlusion. In a less severe mode, debris can occlude a small portion of the illuminating spot, thus causing the phase of the fringe pattern to be shifted. These are known as *local errors* in that subsequent measurements return to the non-occluded value.

For lithography applications, this error is dealt with by ensuring that the grid is made with no defects and that it is clean upon installation. The lithography process itself requires ultra-clean operation, so the risk of post-installation contamination is small. For other applications, however, this may not be the case. For instance, in memory repair, debris is generated as part of the repair process. While every effort is made to keep this debris from the vicinity of the grid, there is still the risk that the grid can become contaminated. The sensor design must take this into account.

The OPTRA sensor has been redesigned to minimize the effects of contamination. The primary design change has been to increase the number if fringes being sensed and thereby average out the contamination induced errors. In the vicinity of contamination, the fringe pattern undergoes a phase shift that is not proportional to stage position, thus creating a measurement error.   By sensing fringes outside of the vicinity of the contamination, we are able to average out the contamination induced phase error.