

Analysis of the Vistec LMS IPRO3 performance and accuracy enhancement techniques

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ABSTRACT

Following the international technology roadmap for semiconductors the image placement precision for the 65nm technology node has to be 7nm. In order to be measurement capable, the measurement error of a 2D coordinate measurement system has to be close to 2nm. For those products, we are using the latest Vistec registration metrology tool, the LMS IPRO3. In this publication we focus on the tool performance analysis and compare different methodologies. Beside the well-established ones, we are demonstrating the statistical method of the analysis of variance (ANOVA) as a powerful tool to quantify different measurement error contributors. Here we deal with short-term, long-term, orientation-dependent and tool matching errors. For comparison reasons we also present some results based on LMS IPRO2 and LMS IPRO1 measurements. Whereas the short-term repeatability and long-term reproducibility are more or less given by the tool set up and physical facts, the orientation dependant part is a result of a software correction algorithm. We finally analyse that kind of residual tool systematics and test some improvement strategies.

Keywords: Registration metrology, grid calibration, coordinate measurement, ANOVA, random factor models, reproducibility, matching, photo lithographic masks, accuracy enhancement

1. INTRODUCTION

In the current mask makers world the most advanced reticles are manufactured in a photo-lithographic way. The customer's electrical circuit layout is split into several layers, which are written on separate resist coated blanks. After developing the photo-resist the masks can finally be patterned by different kinds of etch process steps. Keeping in mind that recent complex circuits involve up to 40 different reticles (layers), which has to be aligned to each other properly in the wafer fab, one can imagine that establishing a stable coordinate system is one of the most important tasks. Moreover, the so called *double patterning* strategy is recently discussed in the industry as a potential candidate to further shrink the pattern size, which would bring registration in an even brighter spotlight.^{1,2} As a mask shop having customers who might mix reticles from different mask suppliers one also has to focus on providing an Euclidean coordinate system as the most common used one.

As a consequence, we are heavily committed to establish the best possible Euclidean coordinate system in our mask shop in measuring coordinates with the most advanced tool in the market, the Vistec LMS IPRO3, and applying elaborate coordinate correction algorithms in order to meet this target. This ensures best layer-to-layer overlay for our customers.

In the following the registration calibration procedure, which was also performed on the LMS IPRO3 setup, is briefly discussed. In the next section we first discuss different experiments on how to calculate the coordinate measurement error with a special emphasis on the ANOVA methodology. By doing that, we try to provide some

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deeper inside into the meaning of the different statistical values. Secondly, we describe the tool matching error with exactly the same ANOVA method and summarize the *golden tool* approach for having multiple tools on one site or across several mask shops.

In the last section we investigate types of residual systematic measurement errors, which in principle could be reduced by additional measurement data post-processing. One candidate is the remaining grid distortion, which is visible in the overlay of a 0 degree and a 90 degree measurement. The current Vistec's polynomial correction algorithm might have problems to compensate some nasty distortions with high spatial frequencies. We test a linear and a thin plate spline (TPS) approach to identify these kinds of grid imperfections. Other error components are summarized, such as errors induced by reticle variations and reticle-holding frames*.

2. REGISTRATION CALIBRATION

Before starting the measurement analysis the LMS IPRO3 had to undergo a calibration procedure, to insure that the measured length is linked to the *official meter* and to establish an Euclidean metric. The first could be done in a very straightforward way by executing the Vistec's built-in distance calibration to a length artifact, which is available from several official calibration institutes. In our case we have been using a NIST substandard. In that way the scale of one interferometer axis is properly scaled. But that's only half the battle. The most difficult part is to determine and to minimize the point-to-point bias of the measured 2D coordinate system to the Euclidean metric. Basically we are dealing with the mapping function of the recorded interferometer *tic-marks* coordinate system to a Euclidean one. The imperfect stage coordinate system is mainly caused by the interferometer mirror body topography and the changing index of refraction of air, through which the interferometer laser is traveling.

Although Vistec provided a 2D coordinate system artifact, which was certified in the accredited measurement laboratory of Vistec Electron Beam GmbH, Jena (Germany), the gauge precision of 10nm was not good enough for our requirements. Instead we applied the commonly used method of self-calibration,³ which is a mathematically rigorous method to calibrate the stage to itself. In fact different methods have been developed in the past,⁴⁻⁶ but all of them use the fact that all kind of grid distortions could be detected by one of the following two ways:

- 2-pivot point methodology, using at least two measurement sets, with different rotation centers⁷
- 1-pivot point and translation methodology⁸

As recommended by Vistec, we implement the first method using a 6 inch and a 5 inch reticle. This method is also known as the *combined correction*. It should be mentioned, that it is worth using a 5 inch plate with a very small border exclusion. This avoids S-bow like residual distortions after the correction. In Figure 1 we compare the correction results for two different 5 inch reticles and present the current grid difference to the artifact.

3. REGISTRATION MEASUREMENT ERROR

Basically, one could be interested in absolute coordinates or relative ones. In this section, we only focus on relative coordinates which correspond to the mask coordinate system. The absolute to the relative coordinate system is linked by a translation (*total approximate origin*) and a rotation (*residual theta*). Both parameters are calculated within the tool's alignment procedure.

Usually the total measurement error is thought as a composition of different sources:

- Short-term repeatability. Direct comparison of multiple successive measurements. Assumed as stochastic noise, denoted by σ_{short} .
- Long-term reproducibility. Comparison of measurements taken on different days, including mask loading and unloading cycles. Corresponding distribution function unknown, given by concrete tool drift behavior. Effect characterized by σ_{long} .

*Ceramic frames are used to hold the reticle in a reproducible manner during measurements and handling cycles.

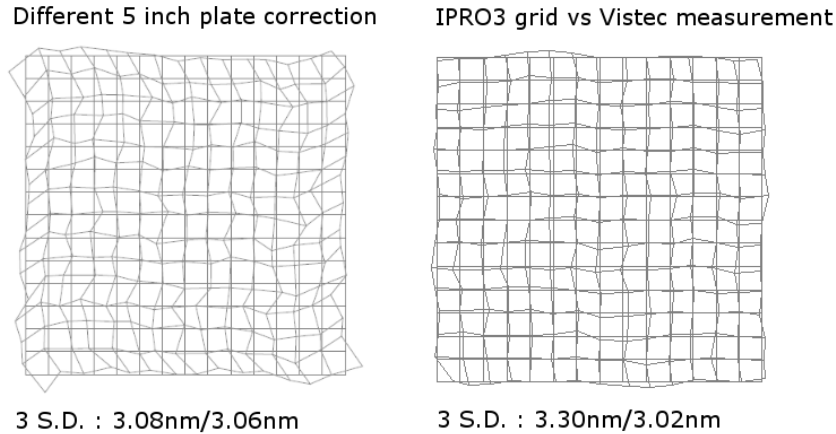


Figure 1. Left picture: Current LMS IPRO3 grid (reference) compared to prior correction (distorted one). The two combined corrections differ in the used 5 inch reticle. For the old correction a 5 inch plate with 13mm border exclusion was used, whereas for the new correction one with 4mm exclusion. Clear S-bow like distortion is visible. Right picture: Current LMS IPRO3 grid (reference) compared to the Vistec, Jena measurement.

- Isotropy. Coordinate system deviation from Euclidean metric, due to imperfect stage correction, ceramic frame and reticle variations, denoted by σ_{iso} .

Note that these main three error classes have different impacts on the product quality and on the derived tool capability. For example, the isotropic component is rather irrelevant for the measured 3-sigma registration value. Once the reticle writing tools are tuned to a dedicated registration tool coordinate system, whatever it is and how good it is, the measured mask is as good as the measurements tool stability. The only important things are short and long-term stability in order to achieve low 3-sigma registration results. On the other side, there is no high precision 2D artifact in the world and the wafer fabs might mix reticles from different mask shops. At that point the Euclidean coordinate becomes important, in order to guarantee the customer a best layer-to-layer overlay, no matter what reticle vendor he might choose. This point seems for us a really important one and is therefore included in our total measurement error calculation and tool capability definitions.

For each error source one has a certain experiment in mind how to identify it. In the following subsections, we compare different approaches how to determine the single measurement error components and how to derive the total measurement error. Further on we suggest a method how to determine the measurement capability of a complete tool park, where matching imperfections have to be taken into account. As a general notation we use the following expression for a coordinate measurement (see Appendix A)

$$Y_{k,ij}^n = \mu_k^n + d_{k,i}^n + \varepsilon_{k,ij}^n \quad (1)$$

Short-term repeatability could be calculated out of $\varepsilon_{k,ij}$, whereas long term drift and isotropy imperfections are related to $d_{k,i}$.

3.1. Direct isotropy check

As a first guess for the total measurement error you could simply:

- Measure reticle 3 times in 0 degree orientation,
- measure the same positions 3 times in 90 degree orientation,

- choose registration evaluation in DEVA software,
- load average of 0 degree measurement as reference,
- overlay the averaged, software back rotated, 90 degree measurement
- take the calculated *Max 3S.D.* values (3-sigma) as the result ($3\sigma'$).

This number is sometimes called the LMS IPRO accuracy. Whereas the isotropic error is well represented in that number, short and long term statistics are not. For LMS IPRO tool generations with dominated isotropy-related errors, that might be a valid choice. But what is the interpretation of σ' ? How is it related to a hypothetical stage error? Neglecting the stochastic noise, the following equation helps to answer this question

$$\begin{aligned}\sigma_x'^2 &= \text{var}_n (d_{x,0}^n - d_{y,1}^n) \\ &= \text{var}_n (d_{x,0}^n) + \text{var}_n (d_{y,1}^n) - 2 \text{cov}_n (d_{x,0}^n d_{y,1}^n)\end{aligned}\quad (2)$$

Assuming that the isotropic error d is Gaussian distributed with strength σ_{iso} over the reticle and the stage errors are completely uncorrelated, σ' would be $\sqrt{2}\sigma_{iso}$. On the other hand, if the d 's are negatively correlated, σ' tends to zero. An indication for a four-fold rotational symmetry (e.g. S-bow like distortion). And finally the worst case. For positively correlated data, σ' gets close to $2\sigma_{iso}$, visible as e.g. ortho-like distortions. Obviously σ' tends to overestimate σ_{iso} . On the other side σ_{short} and σ_{long} are underrepresented, thus things might compensate.

3.2. Vistec's built-in approach

The second rather heuristic approach is Vistec's confidence limit methodology, which is also used for the LMS IPRO tool acceptance tests. The procedure looks like:[†]

- Measure the reticle 10 times in 0 degree orientation,
- repeat this experiment for 90, 180 and 270 degree, respectively,
- load all measurement files into DEVA software, using the *stats per point* modus,
- group them as so-called packages
- evaluate with *confidence limit* option
- take maximum 3-sigma as the final result ($3\sigma''$)

In contrast to the latter definition, we are evaluating the statistics of each measurement point separately, instead of directly looking to the variance of all measurement point deviations. Expressed in terms of Equation 1, we get

$$3\sigma_x'' = \frac{1}{2} \max_n \left[|d_{x,0}^n - d_{y,1}^n| + 3\sqrt{\text{var}_j (\varepsilon_{x,0j}^n)} + 3\sqrt{\text{var}_j (\varepsilon_{y,1j}^n)} \right] \quad (3)$$

In case of short-term noise is independent of the measurement location and orientation, we get

$$3\sigma_x'' = 3\sigma_{short} + \frac{1}{2} \max_n |d_{x,0}^n - d_{y,1}^n| \quad (4)$$

One can easily extend that equation for 4 different orientations ($i=0, \dots, 3$), instead of 2 ($i=0,1$). For 4 orientations the final expression for the total measurement error is $\sigma'' = \sigma_{short} + \frac{1}{3}\sigma_{iso}$. Please note that the range of a stochastic variable approximates only 6σ for high i (e.g., for normally distributed random variables i should reach at least 200). For $I = 4$ we approximately get a factor 2 instead of 6. Thus in σ'' the isotropic error term is slightly too small. On the other side the maximum over all locations is taken.

[†]In the following procedure σ_{iso} is determined. Instead of measuring different rotations, one can measure on different days in order to get an estimator for σ_{long}

ANOVA based error budgets, multi point alignment							Vistec's approach	
Experiment	$3\sigma_{short}$	$3\sigma_{long}$	$3\sigma_{iso}$	$3\sigma_{grid}$	$3\sigma_{match}$	3σ	$3\sigma''_{long}$	$3\sigma''_{iso}$
IPRO1 [†]	1.34	0.88	-	1.70	-	-	1.66	-
IPRO2 [*]	1.17	1.25	-	1.70	1.20	2.41	-	-
IPRO2 [†]	1.27	0.83	-	1.70	1.20	2.27	1.69	-
IPRO3 [*]	1.00	0.85	1.99	-	-	2.38	-	-
IPRO3 [†]	0.66	0.58	1.52	-	-	1.75	0.73	1.19
IPRO3 [†]	0.61	0.76	1.52	-	-	1.81	0.84	1.14
IPRO3 [‡]	0.64	0.69	1.52	-	-	1.79	-	-

Table 1. Comparison of error budget estimations, based on the ANOVA (left part) and Vistec's (right two columns) approach. (*) Last year measurements ($I_{iso} = 3, I_{long} = 3, J = 10, N = 200$), (†) recent measurements ($I_{iso} = 4, I_{long} = 3, J = 10, N = 8 \times 8$), (‡) taking 10 days including one footprint correction ($I_{long} = 10, J = 3, N = 8 \times 8$). LMS IPRO3 performance was significantly improved. For comparison reasons we took for Vistec's evaluation the mean values instead of the maximum. Results comparable for σ_{long} , different for σ_{iso} due to larger group bias, which is more punished by the ANOVA methodology.

3.3. Analysis of variance (ANOVA)

We are proposing a different scheme, based on the well-known ANOVA approach (to be precise, ANOVA with random factors).⁹ The required measurement set is the same as in the Vistec approach and we are also calculating the local statistics for each measurement point first, taking the total group mean as the reference. But the evaluation is a bit different. We directly get the right variance estimators, which are $\text{var}(d_i) = \sigma_{iso}^2$ and $\text{var}(\varepsilon_{ij}) = \sigma_{short}^2$ (or σ_{long}^2 for I days). For the total measurement error we add all components quadratically, hypothesizing that all contributors are independent, and get

$$\sigma^2 = \sigma_{short}^2 + \sigma_{long}^2 + \sigma_{iso}^2 \quad (5)$$

Calculation details are given in the Appendix A.

3.4. Qualifying multiple tools

In the last sections we analyzed the determination of a single tool's measurement error consisting of measurement noise, tool drift and imperfections caused by the self-calibration procedure. Having multiple registrations tools on site, there might be reasons for not self-calibrating each single tool. In these cases tool matching may play a more important role. The best tool would be considered as the *golden tool* and thus serve as a reference for the other *matched tools*. As a consequence, the total measurement error is described differently than in Equation 5

$$\sigma^2 = \sigma_{short}^2 + \sigma_{long}^2 + \sigma_{match}^2 + \sigma_{grid}^2 \quad (6)$$

The grid accuracy σ_{grid} is determined by the *golden tool* measurement and could be estimated by

$$\sigma_{grid}^2 = \frac{\sigma_{short}^2}{J} + \sigma_{long}^2 + \sigma_{iso}^2 \quad (7)$$

All variances on the right side are derived from the *golden tool* measurements. J indicates the number of repetitions, used for measuring the reference grid. Technically, the reference measurement will be transferred to all *matched tools* using Vistec's footprint correction. Slight mismatches could also be directly applied to the *matched tools* footprint.

Measurement results are summarized in Table 1. In case of compensating first order distortions (scale/ortho) the result gets about 10% better (see Table 2).

4. ACCURACY ENHANCEMENT TECHNIQUES

Improving the tools total performance could be tackled either by hardware improvements or by identifying systematic errors. In that section we restrict the discussion on the residual systematic errors.

ANOVA based error budgets, scale/ortho removed						
Experiment	$3\sigma_{short}$	$3\sigma_{long}$	$3\sigma_{iso}$	$3\sigma_{grid}$	$3\sigma_{match}$	3σ
I _{PRO1} [†]	1.29	0.62	-	1.42	-	-
I _{PRO2} [†]	1.18	0.84	-	1.42	1.19	2.35
I _{PRO3} [†]	0.62	0.52	1.28	-	-	1.51
I _{PRO3} [†]	0.59	0.52	1.25	-	-	1.48
I _{PRO3} [‡]	0.62	0.56	1.27	-	-	1.52

Table 2. Same set of measurement, than in Table 1. But all first order distortions are eliminated. Results improve approximately by 10%.

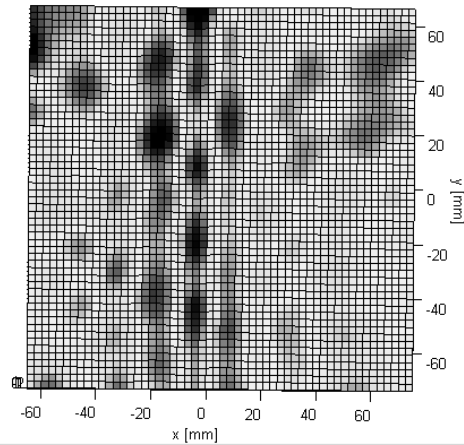


Figure 2. Identification of the residual isotropic error signature by using a thin plate spline (TPS) algorithm (only y-distortions plotted). There is a vertical residual distortion clearly visible.

4.1. System's self-calibration residuals

System's self-calibration algorithm is based on the assumption, that the stage to Euclidean coordinate system mapping is dominated by smooth functions and could be fitted by polynomials up to 8th order. In some cases it might happen, that some sharp local grid distortions remain and are still visible after the standard grid correction. If those distortions are permanent in time, they might be compensated by applying a suitable local grid correction.

After the most recent LMS I_{PRO3} correction we indeed identified some residual signature (see Figure 2). Actually applying the inverse signature can improve the isotropic distortion more or less effectively. In Figure 3 we present some examples. In all cases the isotropic error could be reduced.

4.2. Plate thickness variation compensation

All reticles which are loaded into the LMS I_{PRO3} are transferred to ceramic frames, in which they are supported by three ruby balls. Due to gravitational forces the plates sag. Especially the surface stretching and compression is corrected by the built-in bending correction. But what happens if the bending correction assumes a slightly different plate thickness? Could that contribute to the mask specific measurement error budget? We simulate the effect for a 100 μ m thinner plate and get an isotropic error of about half a nanometer (see Picture 4).

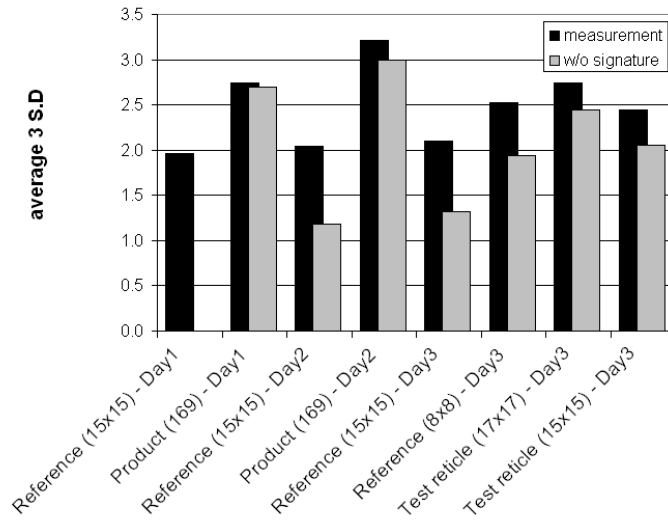


Figure 3. Isotropic measurement error reduction by applying the tools grid distortion residuals to a couple of measurements. The signature was determined by the "Reference (15x15)-Day 1" measurement. Even after 3 days, the result gets significantly better. For products and other test reticles, the result was less pronounced.

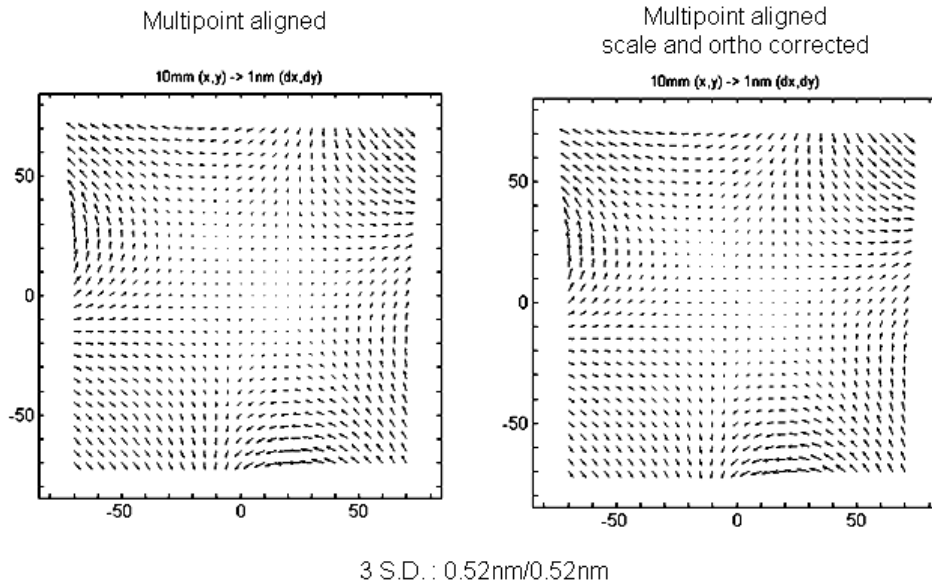


Figure 4. Isotropic error estimation for a hypothetical wrong bending correction. Plate thickness of 6.25mm instead of 6.35mm was assumed. In this picture the 0 degree measurement was overlapped by the 90 degree one.

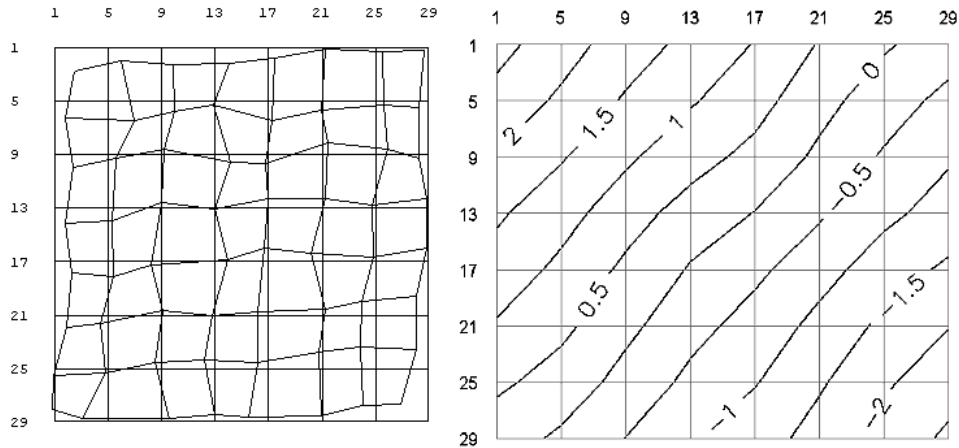


Figure 5. Difference plots for measurements on the same plate, but measured in different ceramic frames. Right figure: Laser auto focus (LAF) position difference. Relative horizontal LAF positions presented as a contour plot. Numbers in μm . Plate is diagonal tilted (peak to valley: $5.3 \mu\text{m}$). Left figure: Corresponding registration difference. Ortho error in tilted direction visible (3 S.D.: $x=2.09\text{nm}$, $y=2.14\text{nm}$, $\text{ortho}=0.018\mu\text{rad}$)

Frame	3 S.D. x [nm]	3 S.D. y [nm]	x scale [ppm]	y scale [ppm]	ortho [μrad]	x tilt [nm/mm]	y tilt [nm/mm]	LAF range [μm]
30081	1.84	2.23	0.0042	-0.0131	-0.0111	30.8	29.5	8.5
30082	1.22	2.29	-0.0009	-0.0145	0.0046	3.2	28.9	4.5
30083	1.68	1.73	0.0046	-0.0080	-0.0093	17.2	21.4	5.5
30084	2.09	2.14	-0.0072	-0.0098	0.0178	-20.8	16.5	5.3
30085	1.45	1.65	-0.0002	-0.0094	-0.0026	-0.7	14.3	2.1
30086	1.74	2.06	0.0016	-0.0091	0.0153	-0.8	17.6	2.6

Table 3. Comparison of measurement in special frame number 30080 to the above listed ones. X and y reticle tilted numbers are also differences to frame 30080 tilt.

4.3. Frame specific correction

There is a magazine for up to 8 reticles in the LMS IPRO climate chamber. All of them are placed in special ceramic frames. How could different frames induce additional systematics to the measurement? In fact we observed a different tilt on some frames. In Figure 5 we compare the horizontal tilt of two frames with the corresponding registration overlay and see some correlations between the tilt and ortho orientation. Obviously this could not be caused by a geometric effect. Looking on a tilted plate we see a seeming shrinkage of $h^2/(2L)$. In Picture 5 we observed a tilt h of about $5.3\mu\text{m}$ over a distance of $L = 198\text{mm}$. That corresponds to a geometric shrinkage of approximately 0.7\AA . Thus, this could not be the root cause of the measured ortho of $0.018\mu\text{rad}$. In order to minimize such effects we recommend to use the Vistec's frame specific correction.

5. SUMMARY AND CONCLUSIONS

We analyzed the LMS IPRO3 performance by using different statistical methods. Focusing on the ANOVA method, we estimate the total measurement error by 1.8nm . The ANOVA method could also be applied to determine the matching error between two registration tools. As a clean statistical method we recommend using that methodology for estimating the coordinate measurement error.

The LMS IPRO3 performance was significantly improved by Vistec in 2006 by further suppressing the influence of the barometric air pressure changes.

Finally we demonstrate that there are still tiny systematics in the isotropy error which cannot be corrected by the actual self-calibration algorithm. By compensating these residuals we could improve the systems accuracy.

But even for a perfect system correction on SPC or other test reticles, we see the influence of different plates and different ceramic frames on the measurement error, which has to be addressed for future tool generations. So far we can partially minimize them by applying a frame specific correction.

APPENDIX A. ANALYSIS OF VARIANCE FOR REGISTRATION MEASUREMENT TOOLS

We denote the measurement on position n , measurement repetition j in i -th measurement set as

$$Y_{k,ij}^n = \mu_k^n + d_{k,i}^n + \varepsilon_{k,ij}^n \quad (8)$$

- $Y_{k,ij}^n$: measured coordinate
- μ_k^n : true coordinate value
- $d_{k,i}^n$: random factor (long-term or isotropy-induced)
- $\varepsilon_{k,ij}^n$: stochastic error
- $n = 1 \dots N$: measurement position label. N is number of measured coordinates.
- $k = \{x, y\}$: x or y coordinate label
- $i = 1 \dots I$: package label, like days or orientation
- $j = 1 \dots J$: measurement repetition

Dropping the position and coordinate index, we could estimate the variances

$$\text{var}(\varepsilon_{ij}) = \sigma_{short}^2 \quad (9)$$

$$\text{var}(d_i) = \sigma_d^2 \quad (10)$$

with

$$\sum_{i,j} (Y_{ij} - \bar{Y})^2 = J \underbrace{\sum_i (\bar{Y}_i - \bar{Y})^2}_{SQZ} + \underbrace{\sum_{i,j} (Y_{ij} - \bar{Y}_i)^2}_{SQI} \quad (11)$$

and

$$E\left(\frac{1}{I(J-1)} SQI\right) = \sigma_{short}^2 \quad (12)$$

$$E\left(\frac{1}{I-1} SQZ\right) = \sigma_{short}^2 + J\sigma_d^2 \quad (13)$$

as

$$\begin{aligned} \hat{\sigma}_{short}^2 &= \frac{SQI}{I(J-1)} \\ \hat{\sigma}_d^2 &= \frac{1}{J} \left[\frac{SQZ}{I-1} - \hat{\sigma}_{short}^2 \right]. \end{aligned} \quad (14)$$

Thereby, $E(x)$ denotes the expectation of the random variable x and $\hat{\sigma}$ the experimental determined variance in contrast to the theoretical one. Be aware, that σ_{short}^2 is in fact the mean of the single group variances $\sigma_{i,short}^2$.

For an experiment without knowing the repetition and group, the derived variances represents best estimators for short term and group variances.

For the final result we take the average variances over all measurement positions and report the maximum of x and y orientation. In cases of the appearance of negative σ_d^2 values, we set those number to zero.

Further notation for operators acting on a single parameter index:

$$\begin{aligned}\text{var}_i(x_{ij}) &= \frac{1}{I-1} \sum_i (x_{ij} - \bar{x}_{\cdot,j})^2 \\ \bar{x}_{\cdot,j} &= \frac{1}{I} \sum_i x_{ij}\end{aligned}$$

The reader who is familiar with standard GR&R methods, that is, with variance components, ought to know the formulas in this appendix.

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