Nano-accuracy measurement technology of optical-surface profiles

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ABSTRACT

Recently, metrology in the fields of synchrotron- and X-ray optics entered the nano-accuracy and sub-50 nrad rms range. In addition to developing novel surface profilers, now dedicated specific measurement technologies play very important roles in reducing errors in measurements. All facts, producing an error of about 10 nrad rms, must be treated very carefully. A temperature stability of 0.01-0.02°C (P-V) over 24 hours is one of most important parameters in ensuring nano-accuracy. The Elcomat 3000/8 autocollimator has large saw-tooth error of 269 nrad rms, which must be suppressed. A fixed reading location setting method shuns the saw-tooth impact, so that it is possible to reach sub-50 nrad rms accuracy in measuring a precise plane mirror. A dense measurement method, combined with finding a peak-valley center to remove saw-tooth effectively promotes accuracy for sphere test. In this paper, we detail a graphic method of combining multiple FW/BW scans in selecting stable files that can reduce the error by10-15 nrad rms.The alignment of precise parallelism between the autocollimator's axis and the direction of the slide's movement are introduced, and some nano-accuracy tests are introduced.

Keywords: surface profiler, profilometer, nano-accuracy, precise measurement

1. INTRODUCTION

For measurement with nanometer and nanoradian accuracy (for simplicity we use "nano") are required in many high technology areas: viz., synchrotron radiation (SR) optics, extreme ultra-violet lithography (EUVL), X-ray telescopes, and X-ray free electron lasers (XFEL). Recently, the metrology in the fields of synchrotron optics and X-ray optics has stepped up into the level of sub-50 nrad rms accuracy [1-9]. In addition to precise profiler development, specific technologies must be applied to reduce errors in the tests. Any error of ~10 nrad rms must be considered for removal. A lot of negligible facts for 100-300 nrad rms measurements become serious for sub-50 nrad rms tests. Long-term thermal stability of 0.01-0.02C (P-V) becomes indispensable. An extremely accurate (50 nrad P-V error over the entire range of the test) and an ultra-stable autocollimator (AC) are expected. Removing the saw-tooth error (0.269 nrad rms) of the existing Elcomat 3000/8 is under investigation. Furthermore, a sub-50 nrad rms test for curved mirrors is necessary.

2. TEMPERATURE STABILITY AND PROFILER STABILITY

Temperature stability is one of most important facts to ensure the nano-accuracy of the test. We consider that 0.01-0.02°C (P-V) thermal stability in 24 hours is necessary to assure this metrology.

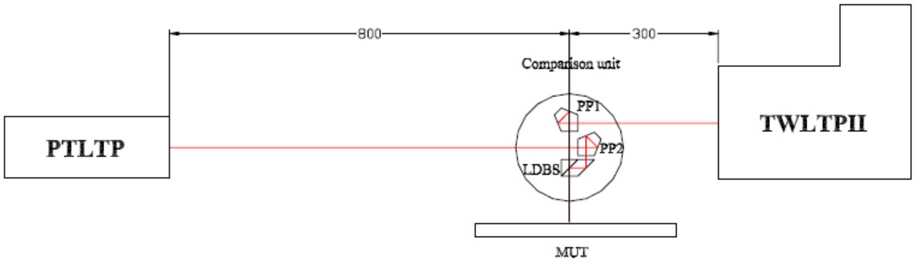

Fig. 1 Configuration of the simultaneous comparison test between penta-prism LTP (PTLTP) and TWLTPII

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To compare the stability and estimate the requirement for temperature stability quantitatively for assuring nano-accuracy, we introduce an excellent test for comparing stability comprised of four LTP profilers with a temperature variation of 0.5ºC [10]. Both the penta-prism LTP (PTLTP), and the Taiwan LTPII (TWLTPII) send out beams (Fig. 1). After their reflection on the MUT, each of which is split into two beams aimed towards to PPLTP and TWLTPII separately. So four beam spots impinge upon two CCDs of PPLTP and TWLTPII. They can be considered as comparison tests of the stability of the four LTPs. It is clear that the PPLTP has better stability than TWLTPII (as determined by their essential characteristics and structure); the variation in temperature (Fig. 2) dominated the errors in stability errors (Fig. 3). So, assuring a stable temperature is essential. The PPLTP's stability is about 0.9 µrad rms when temperature deviates by 0.5ºC. If the temperature deviation is 0.05ºC, the estimated stability could be about 90 nrad rms. When using an improved NOM, the best stability scan for the NSLSII-NOM can be 42 nrad rms over 16 hours (Fig. 4).

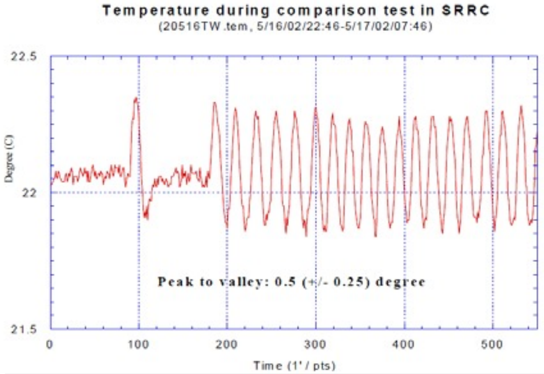

Fig. 2 Temperature oscillations during the stability scan

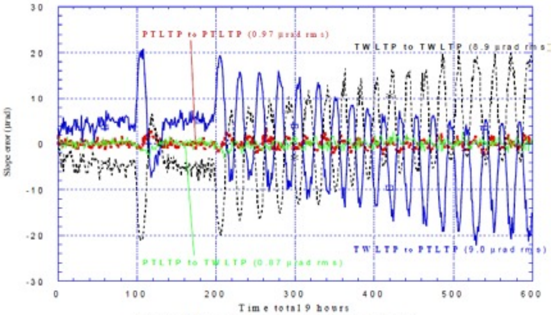

Fig. 3 Stability comparison on TWLTP and PTLTP

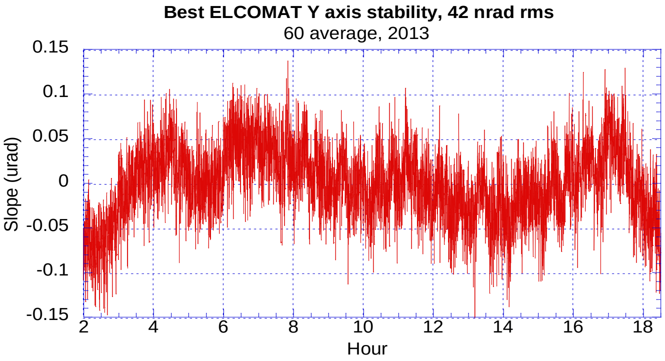

Fig.4 Best stability scan for BNL-NOM: 42 nrad rms over16 hours,

3. APPLYING GRAPHICAL METHOD OF USING MULTIPLE FW/BW SCANS IN SELECTING STABLE FILES TO PROMOTE THE ACCURACY OF MEASUREMENTS

In the nano-accuracy stability test, the profiler's stability curve is not fully complying with the environmental temperature curve. Thermal distortion hysteresis, internal heat sources (for example, the light source, the CCD and its controller), along with the mechanical relaxation of the profile and mirror support still may degrade accuracy at the level of tens of nrads, which could be serious for sub-50 nrad rms measurements. For the reasons described above, we require 0.01-0.02°C (P-V) stability in 24 hours for nano-accuracy in metrology (previously we required 0.04°C (P-V) stability in 15 hours).

We apply a graphic method of using multiple FW/BW scans in selecting stable files to further promote the accuracy of our measurements. It can reject files with unstable scans so to obtain much accurate results of testing. This approach involves making multiple sequence scans, with a forward scan (FW) and immediately afterwards a backward scan (BW) in each scan. We compare the FW/BW scans for checking instability in over a short period (minutes), and compare multiple scans for checking long periods (hourly) instability, and then select the most stable files (those with the smallest deviations among all scans) in both short- and long-scans. The large vertical shift will cause a related large oscillation in a period of one scan.

We used multiple scans on the NOM as a sample to demonstrate this method graphically: 120 sequential FW/BW scans were taken on a 150 mm plane mirror with a step of 0.5 mm; each FW/BW scan took 40 minutes, so that the total testing time was 80 hours. The temperature deviation was about 0.05°C (P-V). If the stability is perfect, the FW/BW curves will overlap and be about parallel. We can identify the difference between the FW and the BW by eye with a sensitivity of 50 nrad (P-V) or less, so that the FW/BW error in residual stability error could be estimated roughly in 15 nrad rms. Figure 5 shows the large instability of 200 nrad P-V (roughly estimated by eye on the figure) between FW/BW for first scan (ScY1), a smaller instability of 100 nrad for the 20th scan (second line), and the further reduced instability of 60-70 nrad for the 120th scan (fifth line), and the smallest (50 nrad or less) instability at the 60th scan (third line). The vertical shifts of the scans reflect long period instability (Fig, 6). The shift in range of the total number of scans is 2000 nrad. For selecting the best set of scans, we must choose scans with small vertical shifts, combined with small FW/BW oscillations. The dark area around 60th scan is what we expected (Fig. 7). From the graphics we identified the best files, the 43-77th scans, for averaging. These 35 scans have a 300 nrad (P-V) vertical shift with 30-50 nrad P-V oscillation in FW/BW. Using these selected scans, we can reduce the error further. There are 3 zones in 120 scans: the worst (scan 3-17, the worst 1st and 2nd scans have been removed), the moderate (96-120th scans), and the best (43-77th scan).

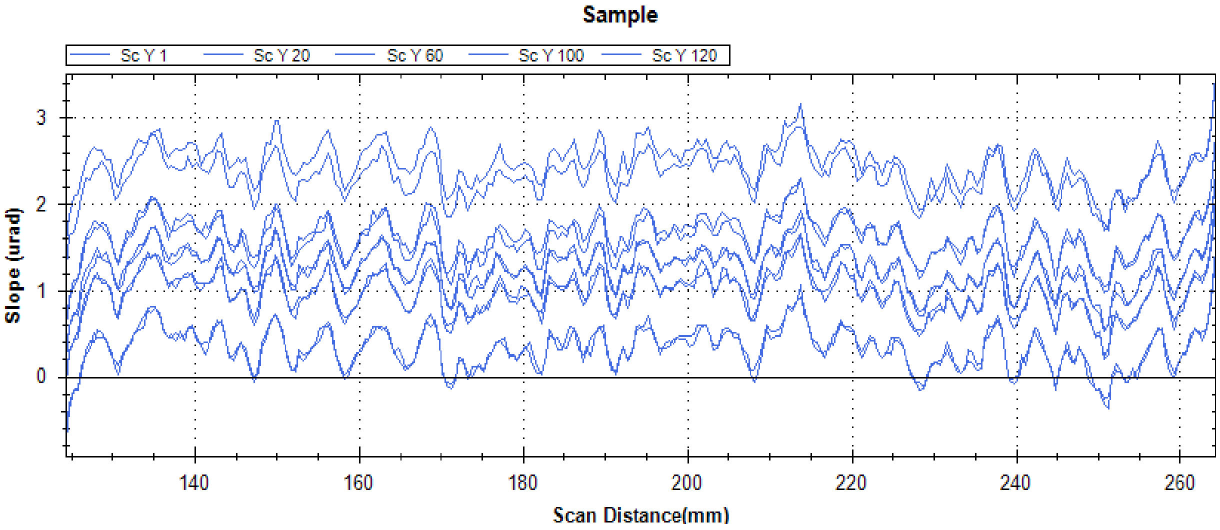

Fig. 5 The variation of a single FW/BW scan. The difference between the FW scan and BW is evident to the eye in the range of sensitivity of 50 nrad (P-V) or less. The 60th scan is the best.

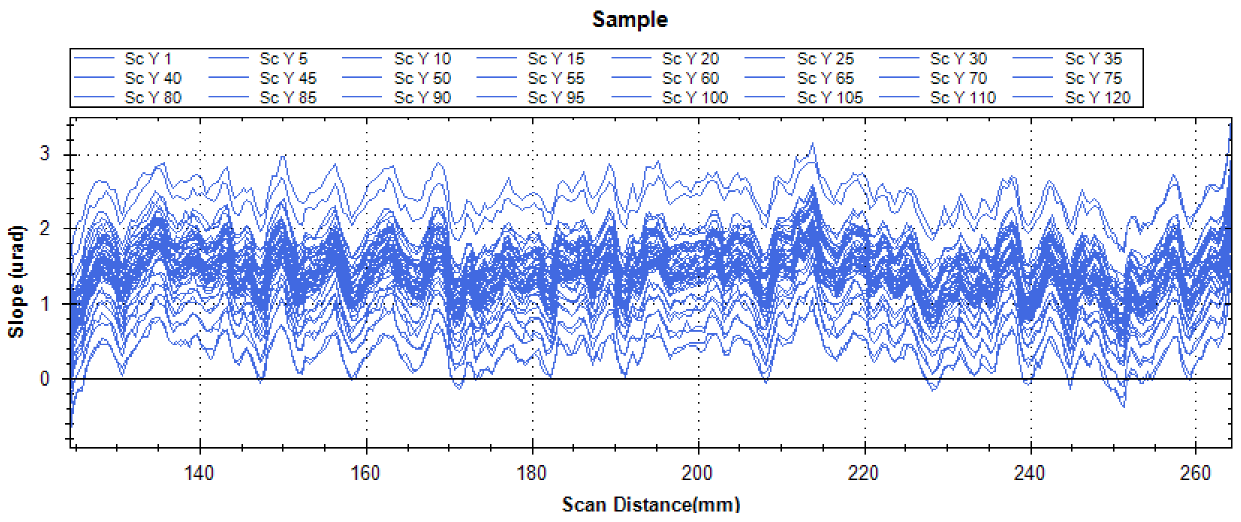

Fig. 6 Multiple scans display vertical shifts (long-period instability). We must choose scans with small vertical shifts combined with small FW/BW oscillations for selecting best scan set. The dark area around 60th scan is what we expected

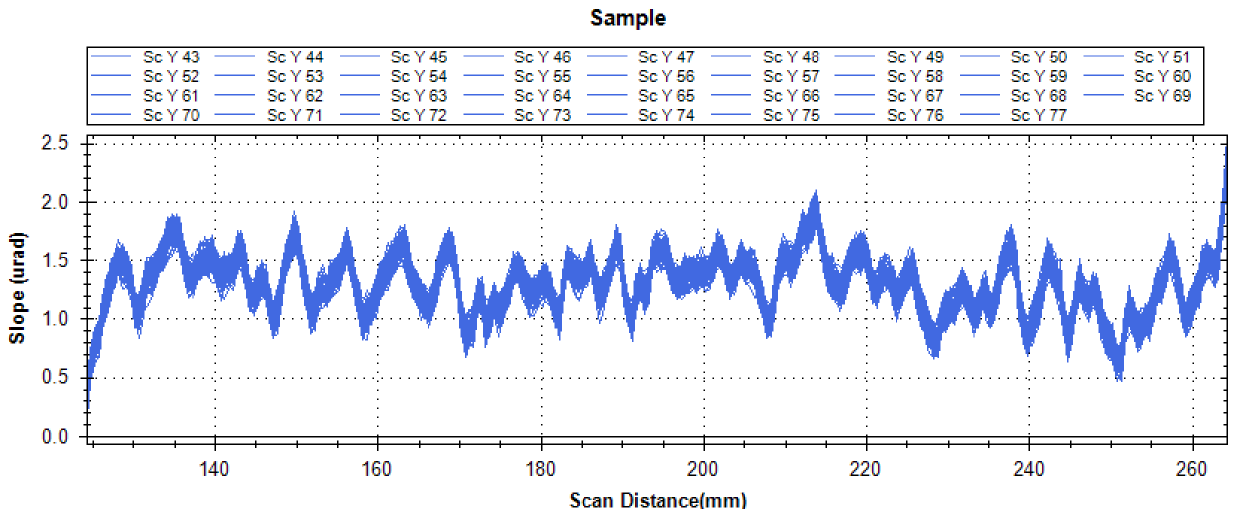

Fig. 7 Finally selected scans, having small variation in both FW/BW scans and different scans. These individual scans are in an envelope of 300 nrad (P-V), and each FW/BW scan has only a 30-40 nrad (P-V) shift

To obtain a quantitative improvement, we calibrated the difference between the FW/BW scans in the cases of a single scan and 15 scans (table 1) in 3 zones:

Table 1: Different error in slope of multiple FW/BW scans (nrad rms)

	In worst zone	In best zone	In moderate zone
Single scan	179 (1st scan, worst)	67.5 (70th scan)	66.7 (120th scan)
15 scans average	31.4 (scan 3-17)	17.0 (scan 53-67)	26.0 (scan 96-120)

It is very clear that the 9-14.4 nrad rms improvement (in 15 scans) can be achieved with this method.

4. THE SAW-TOOTH ERROR OF THE AUTOCOLLIMATOR MUST BE REDUCED

4.1 The saw-tooth error in the NOM system

The Elcomat 3000/8 applies a cross-reticle of an 8-line, high-resolution CCD detector, and a control system to obtain highest possible cross-position reading. ACs usually are designed and specified for use at relatively large or unrestricted apertures. However, with a very small test aperture and in a high accuracy test, the saw-tooth deviation becomes evident. It is a systematic deviation that degrades the measurement's accuracy.

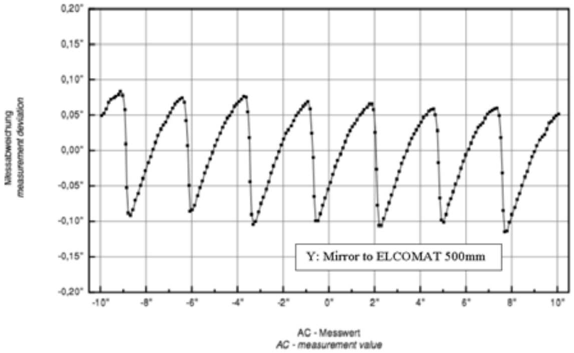

Fig. 8 Realistic Saw-tooth error of the Elcomat 3000/8. It is calibrated by using the PTB's the primary angle-reference standard, the Heidenhain WMT220 angle comparator. The coordinate X is **the** WMT220 angle reading**,** the coordinate Y is difference between WMT220 and the Elcomat

Figure 8 is an example of the saw-tooth-like oscillating pattern of the NSLS II's Elcomat SN 998. The saw-tooth's period, approximately 2.74" (13.28 µrad) in the direction of the Y axis of the Elcomat, is associated with the 7 µm- pixel pitch of the CCD detector. We undertook a calibration using the PTB's primary angle-reference standard, the Heidenhain WMT220 angle comparator, that has an uncertainty of u=0.001 arcsec (4.85 nrad). For this calibration, we employed a 2.5 mm-aperture beam, and a 100% reflectivity mirror with a 0.1" test step. The mirror was set on the rotational center of the WMT220 at fixed distance of 500-mm. The real saw-tooth deviation in Fig. 8 is the difference between the angle readings from the Elcomat and the WMT220; it is not the error in the slope of the mirror.

The severe distortion of the reticle's image on the detector, caused by diffraction and interference (aggravated by our using a small AC aperture), causes deviations in calculating the position-data, and finally results in a saw-tooth-like effect.

Its peak-to-valley error is about 0.165" = 800 nrad (2.5 mm aperture). The root-mean-square error is 269 nrad, a number large enough to negate a sub-50 nrad rms measurement. The period of saw-tooth deviation is about 2.74". The angle of its slowly rising section is 2.34" (11.34 µrad), while that of its quickly falling section is 0.4" (1.94 µrad).

4.2 The specific reading-location method to enhance the accuracy of measurements on a precise plane mirror

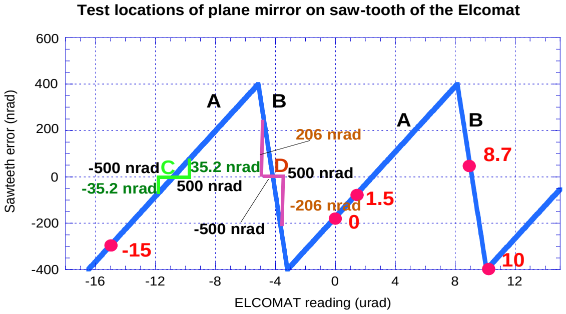

Fig. 9 A series of tests on plane mirror were done with Elcomat reading at different locations (-15, 0, 1.5, 8.7, 10). The differences among 0, 1.5 and -15 urad are <40 nrad rms, the differences between two groups of (0, 1.5, -15) and (8.7, 10) are in the range of 60-100 nrad rms (see table 1 for details). The green lines scales are magnified for clarity. Conclusion: The plane-mirror test should locate the Elcomat reading at the slowly rising section of the saw-tooth curve

We here use the approximately simulated saw-teeth curve (Fig. 9). The angle period of saw-teeth errors is about 2.74", including a 2.34" slowly rising section, and a 0.4" quickly falling section.

In a precise plane-mirror test, the slope variation in the Elcomat reading is very small (1-2 µrad P-V).

If the Elcomat reading is arranged at different location in the saw-tooth, the tested error will be very different. For example, if the reading is on the slowly rising section of the saw-teeth, due to the saw-tooth deviation, the +0.5 µreal-slope variation will be read as 0.5 μrad + 800 nrad * 0.1" / 2.34" = 0.5 μrad + 34.2 nrad (in green lines); at -0.5 μrad, the real-slope variation will be read as –0.5 μrad -34.2 nrad. So, the entire deviation will be 17.1 nrad rms. In contrast, if the Elcomat reading is located on the quickly falling section of the saw-teeth, the ±0.5 real slope will be read as ±0.5 μrad -/+800 nrad * 0.1" /0.4" = ±0.5 μrad -/+200 nrad (in pink lines). Hence, the entire deviation will be 100 nrad rms, a very large deviation (100 nrad rms) that will destroy sub-50 nrad accuracy.

According to the above analysis, we must use a specific reading-location method: Tilt MUT a little to shift the Elcomat reading to the center of the slowly rising section of the saw-teeth.

We compared a series of tests on mirror #1 (silicon, plane, length 150mm, uncoated, beam spot 2.5 mm) at different Elcomat reading locations (Table 2). Every test comprises 60 scans on average, and 60 reading averages at each point.

Table 2: The differences in five tested files (the first-order polynomial has been removed

File location	-15u - 1.5u*	-15u – 0u NORev#	-15u - **8.7u**	1.5u - 0 u NORev	1.5u - **8.7u**	0 u NORev - 8.7u
Error nrad rms	39.7	38.4	**79.1**	28.8	**98.5**	**99.7**
File location	**8.7u** -**10u**	1.5u - **10u**	-15 –**10u**	0u NORev - **10u**		
Error nrad rms	44	67.6	58.3	66.9		

* "-15u – 1.5u" means the difference of the files located at –15urad and +1.5urad of the Elcomat readings. The locations are displayed on Fig. 9. Good locations: "-15u", "0u" and "1.5u". Bad locations: "8.7u", and "10u"

"NORev" means mirror is not reversed; otherwise the mirror is reversed by 180° .

The tests (-15u, 0u, 1.5u) located on a slowly rising section of the saw-tooth show a good repeatability of <40 nrad rms. The accuracy of the test is poor when the Elcomat reading was taken on a quickly falling section of the saw-teeth (8.7u, 10u). The differences between any test file on the rising section (-15 u, 0u, 1.5u) and any test file on falling section (8.7u, 10u) always are large (100 nrad rms). These tests show that a specific reading location is preferred for measuring plane mirror in sub-50 nrad rms accuracy

4.3 Small saw-tooth profiler development

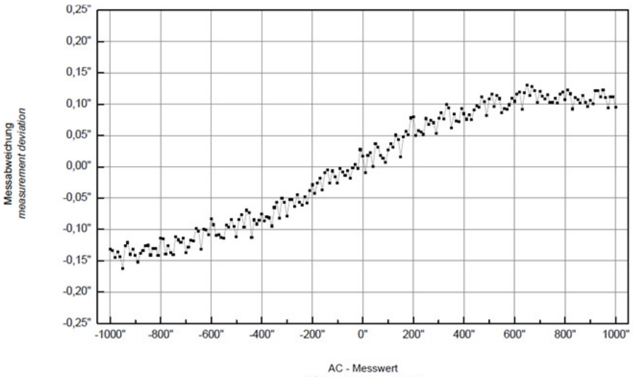

Fig. 10 Saw-tooth error test of new Elcomat 3000/10 in X-axis, calibrated at the PTB. The saw-tooth error is only 0.01" (50 nrad, P-V)

If we can remove the saw-tooth error from its source of AC (producing the error), it will be much more effective. Moller Weld Optical (MWO) made an effort in trying to reduce saw-tooth by using a 10-lines cross on our newly ordered Elcomat 3000/10. We find that the saw-tooth error in X axis is reduced (Fig. 10, tested by the PTB) significantly though the Y-direction had not improved much. In this case, the saw-tooth P-V value in the X-axis is about 0.03" (150 nrad) compared to our Elcomat 3000/8 value of 0.15" (800 nrad) (Fig. 8). Finally, we decided to use it, because we can set the X direction of the Elcomat 3000/10 at the test direction, so rendering the Y-axis reading useless. In this way, we need not use the troublesome dense measurement and the P-V center method to remove saw-tooth error. More experiments are necessary to verify this fact.

5. ALIGNMENT TECHNOLOGY

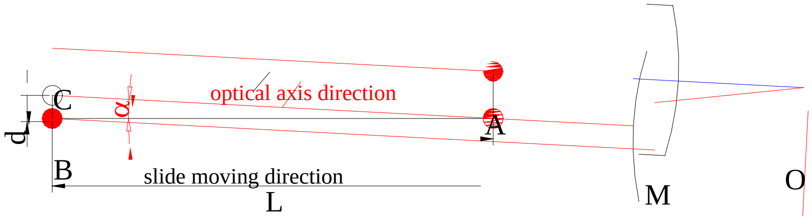

Fig. 11 Non-parallelism between optical axis and slide moving direction causes using different beams (OA and OMB) of AC, so error is generated

The parallelism alignment between AC axis and slide moving direction is a very important issue for sub-50 nrad rms tests.
If the direction of AC axis and that of the slide movement are not parallel, during the test the aperture will move in the slide- moving direction from A to B with a lateral displacement, d (Fig. 11) relative to AC axis. It means the testing beams at the scanning start point A is using the beam OA, but at the end point B the testing beam is using different beam OMB of collimated light of AC. The α is the misalignment angle between the carriage's moving direction and the optical axis. Because of the systematic error of the AC, the difference between two beams could be a several tens nrad rms error in distorting the measurement's accuracy.
Theoretically, we can make this alignment by moving the carriage, and looking directly at the lateral displacement of the beam spot of fixed AC, and then tilt the AC to make this displacement near to zero. However, it is hard to use the Elcomat output beam for precise alignment because the small beam of the Elcomat/8 is weak, blurred, and blinking. APS applied a small strong collimated laser-beam for alignment [11]. ALS sets up a 1 mm pinhole on the axis of the AC to create a small beam and uses a CCD camera attached on a carriage to assess the lateral displacement of the blurred beam spot in different distances [12]. Moller Weld Optical (MWO) developed New Aperture Centering Device (ACenD) to help the alignment of the Elcomat 3000/8 with an accuracy of 0.01-0.1 mm over a long distance [1].

At the time of BNL-NOM development in 2013, we applied small collimated laser beam with CCD for the alignment [8]. We used a three-step precise alignment method. A collimated pencil beam of diode laser easily is used, and aligned parallel to the air-bearing direction because it is visible, clear, small, and hence, well-shaped for precisely detecting position. Then, theoretically the Elcomat could be adjusted to parallel to laser beam by locating the laser beam's image at the center of the Elcomat. However, the laser beam's spot cannot be read by the Elcomat because it recognizes only its own 8-lines cross-reticle image reflected from a mirror. So, the laser's direction must be transferred to a perpendicular mirror; then, the mirror can be used for finally aligning the Elcomat .

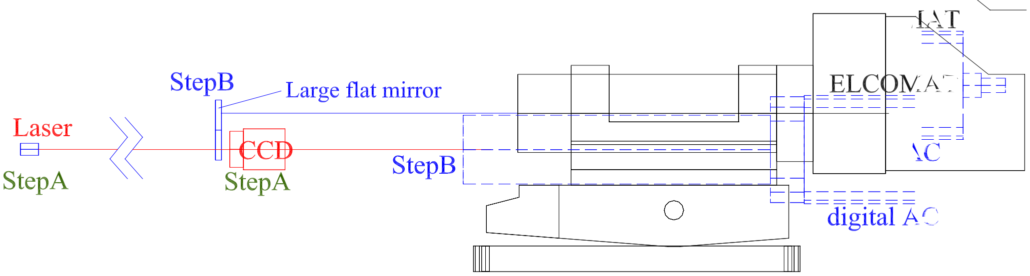

Fig. 12 Simplified alignment method: step A, set a laser to be parallel to air-bearing slide by use of a CCD position monitor; Step B, take off the CCD and set a digital AC in parallel to the laser beam by focusing its beam to the center of the AC. Then a large mirror is set in perpendicular to digital AC. After taking off digital AC the Elcomat is adjusted in perpendicular to the mirror either. In this way, laser beam, air-bearing slide and Elcomat are in parallel each other

After 3 years, we tested its alignment error: the displacement is 0.6 mm in an 800 mm moving- distance. Now, we use a simplified aligning method by employing a pencil-beam and a large mirror as follows: keep using a pencil laser beam as alignment source, and using CCD as precise displacement monitor (same as in the previous method) to align the laser beam parallel to direction of movement. After aligning the laser beam, the CCD camera is removed, and a digital AC is used to accept the laser beam (Fig. 12). Tilt the digital AC and let the laser's image focus on the center of the digital AC (its reading "0"), so the digital AC is aligned precisely parallel to the direction of the laser beam. A visual AC is simple and accurate for this application, but is not suggested because of the need for assuring the safety of the eye.

To transfer the digital AC direction (it is parallel to the laser's direction and that of the slide's moving direction now) to the direction of the Elcomat axis, a large and precise plane mirror is set to do this job. The first, we aligned the mirror's direction perpendicular to the digital AC by focusing its reflected image at the center of the digital AC; then the digital AC is removed; Second, we use this mirror to align the Elcomat by locating the image of its reflected beam at the center of the Elcomat. It is clear that if the same mirror reflects two beams from two ACs (digital AC and Elcomat) to be focused to the centers of ACs individually, then the two optical axes of the ACs are parallel.

Following is the estimated accuracy of this alignment method:

a) The CCD monitor reading error could be 5 μm, or about 1" (1 μm/200 mm)
b) The error in digital AC alignment with laser beam could be 2"
c) The error in mirror setting with the digital AC could be 1.5"
d) The Elcomat alignment with the mirror could be < 1"
e) The error produced by mirror's flatness is negligible

So the accuracy of aligning of this method can be estimated as 5" (< 0.03 mm in a distance of 1000 mm). This is suitable for testing sub-50 nrad rms accuracy

6. THE DEVELOPMENT OF A NANO-ACCURACY SURFACE PROFILER

Developing a nano-accuracy surface profiler is the essential for sub-50 nrad rms accuracy test. The optical systematic error must be removed. One of most important ways is to change the design of the systematic scheme of the profiler to be able to subtract the systematic during the test by calibrated data file (the NOM is impossible to subtract calibrated error). To be able to subtract the error properly, the optical path in the AC (or the optical head) during the test must be the same optical path in the AC during the calibration. This means that the new profiler should be developed. The scheme design of a scanning optical head with non-tilted reference is a preferred choice [15].

As described above, the saw-tooth error of the Elcomat also must be removed, though the demonstrated method in suppressing the saw-tooth for plane mirror tests can reach sub-50 nrad rms accuracy. But it is troublesome for testing sphere mirrors and it is questionable for aspherical mirror tests [16]. For the saw-tooth problem, the best way is to remove the Elcomat saw-tooth error completely, or to develop a new AC (or optical head) as soon as possible.

We will discuss and detail the development of a nano-accuracy surface profiler in another paper.

7. CONCLUSION

Sub-50 nrad rms measurements, especially for spheres and aspherical surfaces, is a major task for metrology of synchrotron optics and X-ray optics. To reach sub-50 nrad rms accuracy, special measurement technology and methods have to be adopted. A stable temperature of 0.01-0.02°C (P-V) in 24 hours is one of most important facts to ensure the test's accuracy. The Elcomat 3000/8 has a large saw-tooth error of 269 nrad rms when using a 2.5 mm aperture beam-spot, which must be suppressed or eliminated. Using an enlarged aperture can suppress the saw-tooth error significantly, but it also suppresses the real error in the higher spatial-frequency range. So, it is not a preferred solution for our nano-accuracy test. A method for setting a fixed reading location shuns the saw-tooth impact, so it is possible to reach sub-50 nrad rms accuracy in measuring a precise plane mirror. A dense measurement method, combined with finding peak-valley center to remove saw-tooth effectively promotes the sphere test's accuracy. A graphic method of multiple FW/BW scans in selecting stable files can reduce the error by10 nrad rms. Precise parallel alignment between AC axis and the direction of slide movement is an essential requirement for nano-accuracy tests. Significant enhancement in accuracy also rely upon improvements of measurement method and measurement instruments. The NSP [15] significantly reduces systematic error and possibly removes residual error by incorporating an ultra-precise calibration correction table. Hence, it is one of the hopeful developments for nano-accuracy measurements.

8. ACKNOWLEDGMENTS

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