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CALIBRATION OF A VERTICAL-SCAN LONG TRACE PROFILER AT MSFC*

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Calibration of a vertical-scan long trace profiler at MSFC

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ABSTRACT

The long trace profiler (LTP) is the instrument of choice for the surface figure measurement of grazing incidence mirrors. The modification of conventional LTP, the vertical-scan LTP, capable of measuring the surface figure of replicated shell mirrors is now in operation at Marshall Space Flight Center. A few sources of systematic error for vertical-scan LTP are discussed. Status of systematic error reduction is reported.

Keywords: long trace profiler, calibration, accuracy, systematic error

1. INTRODUCTION

The long trace profiler (LTP) is an instrument widely used for measuring the surface figure of grazing incidence mirrors. Used for x-ray applications, these mirrors tend to be very long (up to 1 m in length). In case of the replicated optics designed for x-ray astronomy applications, the mirrors have shape of cylindrical shell and their tangential profile is hyperbolic or parabolic. Performance prediction of the replicated optic requires precise metrology of outer surface of the mandrel to be used for manufacturing the shell mirror and the inner surface of the resulting shell. Since the whole optical system of the conventional LTP is mounted and moved on massive horizontal slide it is impossible to use it for profile measurements of the inner surface of the shell mirror. This problem was overcome in one of the modifications of the LTP, the vertical long trace profiler (VLTP). The optical system of the VLTP is kept stationary, while a scan arm can be mounted and moved inside of the shell mirror. This VLTP was developed by P. Takacs et al[1, 2] under phase II SBIR and is currently in operation at Marshall Space Flight Center (MSFC).

The accuracy of the VLTP depends on its operation, precision of its elements and thermal and vibrational stability of surrounding environment[3]. Here we report the current status of systematic error reduction for the VLTP installed at MSFC. An error due to changes in optical system of the VLTP from thermal effects was reduced by installing an enclosure around the VLTP. Accuracy of the VLTP was improved by increasing the beam separation distance. Preliminary results on correction of errors due to imperfection of the VLTP stages are also presented.

2. VLTP OPERATION

The VLTP is based on principle of the pencil-beam interferometer[4, 5]. A schematic of the optical system and the VLTP are shown in figures 1a and 1b. Light from a polarized He-Ne laser is collimated and sent into beamsplitter creating two parallel, coherent beams directed into Porro prisms. The spacing between the beams is adjustable by lateral translation of the Porro prism. Then the beams are split again into two sets, one set exits the optical head downward toward the reference mirror, while the other one exits horizontally and passes through pair of penta prisms to hit the surface under the test (SUT). The two penta prisms are installed at vertical stage, one stands on the base of the vertical stage and the other is mounted on a scan head. During slope measurements the scan head assembled at the end of the scan arm (see figure 1b) moves in up or down direction, so the slope of the sample at different positions on the vertical stripe of the sample can be measured. The penta prisms assure that pair of the beams directed into sample is always parallel to the optical table. The beams reflect from sample back into penta prism system and together with pair of the beams reflected from reference mirror are directed into Fourier Transform (FT) lens, which produces two interference patterns at the detector. The detector is a linear array with two sets of 1024 pixels arranged in two parallel rows separated by about 1 mm. Each pixel is 25 μm wide and 2.5 mm high. The beam reflected from the SUT moves along the length of array as the slope of the surface changes.

The interference pattern contains cosine component whose phase depends on the phase difference between two beams. The position of the cosine minimum depends on the slope of the sample surface. To determine the relative slope the software looks for change in relative positions of the intensity patterns minima. This minimum is found by fitting a parabola to few points of cosine, which represents the intensity profile on the detector array. The slope profile of the SUT calculated from

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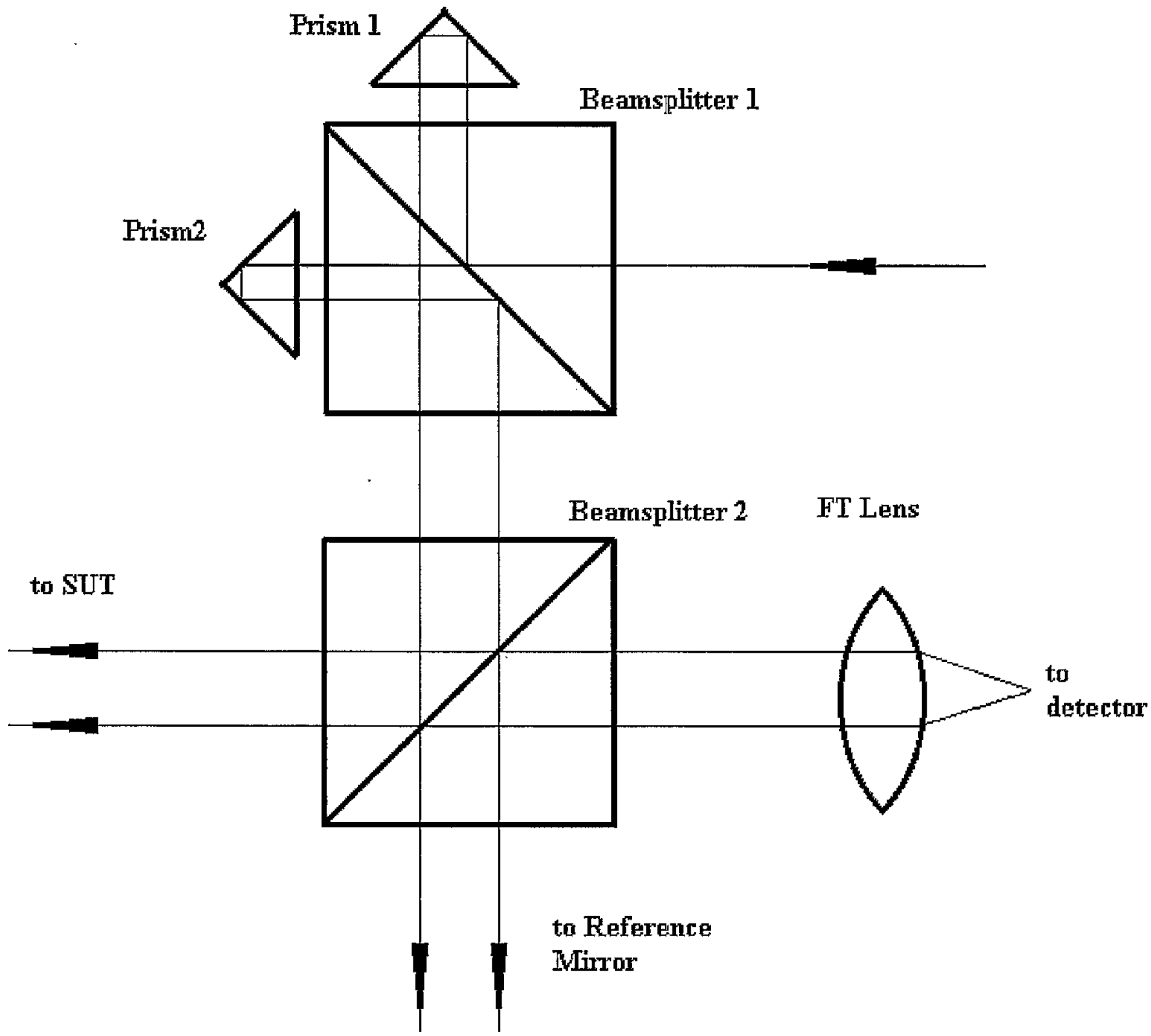

Figure 1a. Schematic of optical system of the VLTP. A laser beam is split in two beams by beamsplitter 1 and pair of prisms. One beam set from beamsplitter 2 goes to the SUT. Another set exits the beamsplitter 2 towards Reference Mirror. Sets of beams reflected from the SUT and the reference mirror are directed to beamsplitter 2 and then into the lens and detector array. Dove prism (not shown) can be introduced into test beam in order to rotate the pair of beams by 90 degrees.

these data can be than transferred into a height profile. To eliminate the slope error due to beam pointing instability in the laser, the slope of the sample under test is determined by subtracting the measured slope of the reference mirror, which remains stationary during the scan, from measured slope of the sample mirror.

3. SYSTEMATIC ERROR REDUCTION

3.1. Thermal enclosure

In order to estimate the systematic error due to changes in optical system from thermal effects, vibrations or mechanical stress relief from unstable mounting or elasticity in components of the VLTP a stability scan is usually collected prior to any

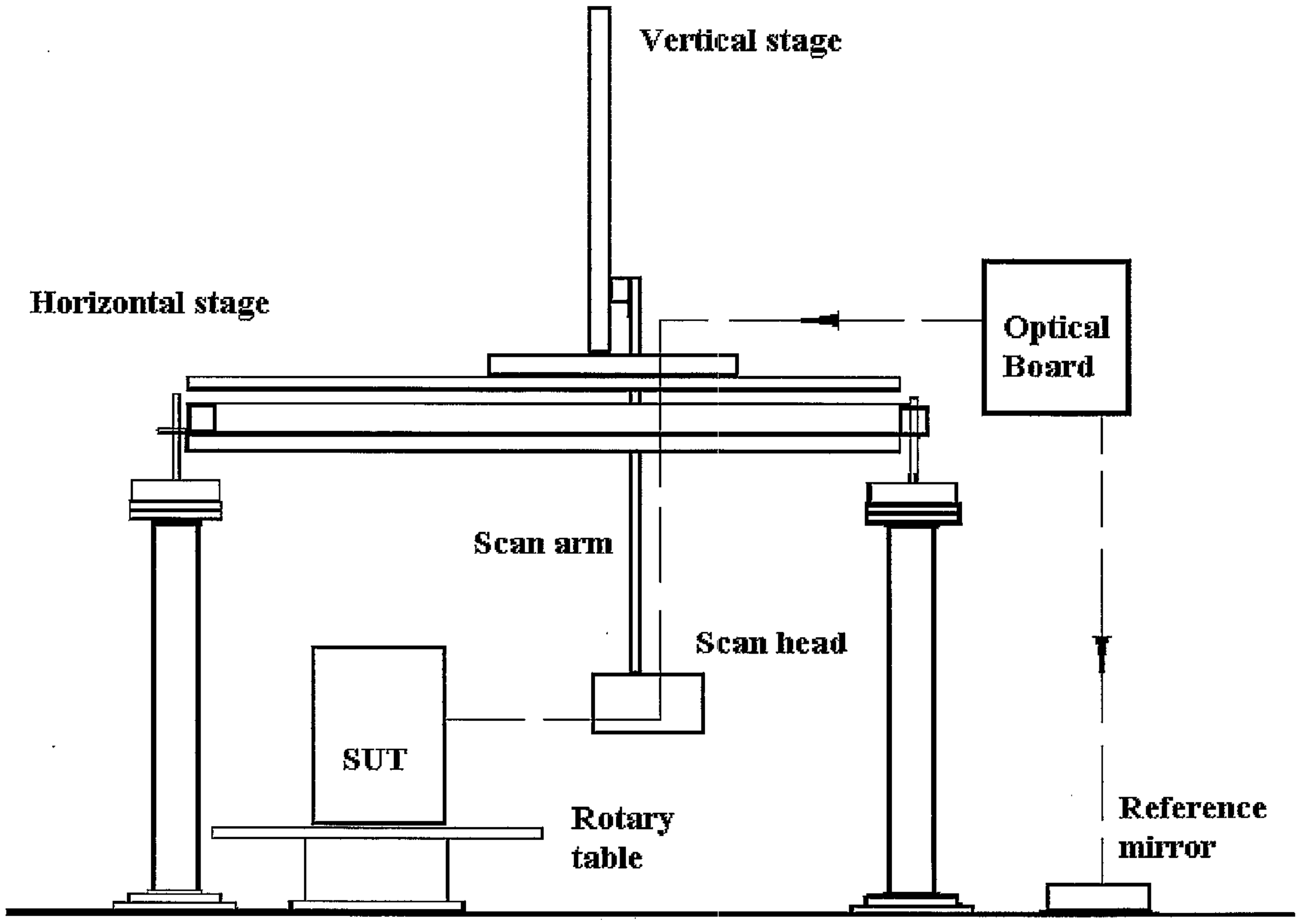

Figure 1b. Schematic of the VLTP. Laser beam from optical board goes to the SUT through a pair of penta prisms (not shown). Beams reflected from the SUT return to optical board and focused on the detector in order to produce two fringe patterns, one for the test beam and another for the reference beam.

slope measurement. During the stability scan the VLTP, with scan head stationary, measures the slope between the same two points on the SUT as function of time.

The position of the cosine component of the interference pattern and, hence, the calculated slope of the sample surface

Table 1. Ratio between the peak-to-valley value of the flat and stability scans as function of the beam separation. The error in determining of the ratio is estimated to be ± 0.2

Distance between beams, mm	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
P-V of flat scan to P-V of stability scan	3.7	2.9	1.8	1.55	1.4	1.3	1.25	1.3	1.2	1.5

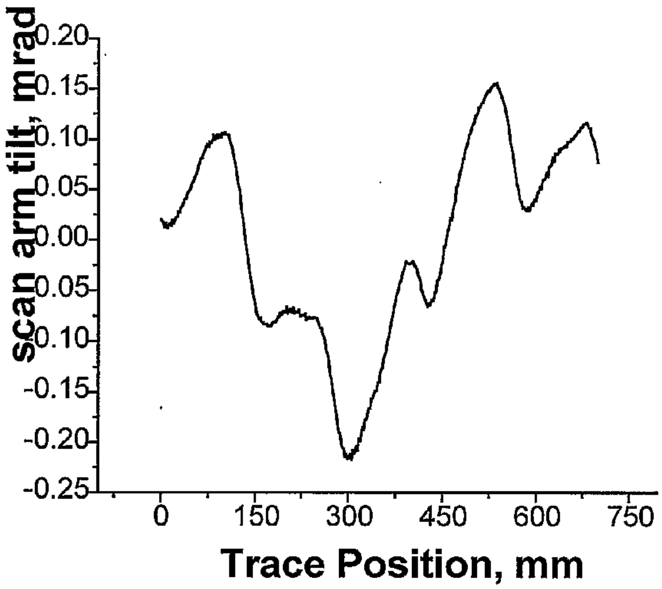

Figure 2: The scan arm tilt as a function of the vertical position of the scan head.

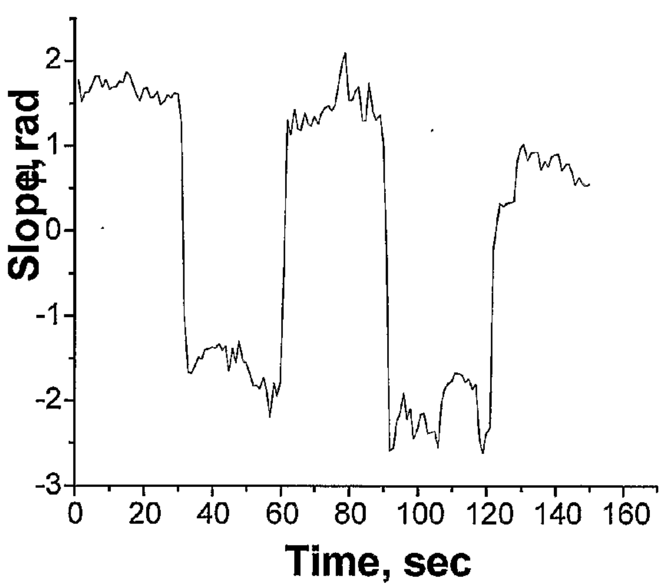

Figure 3. Example of the stability scan collected in order to measure the specific slope change. The scan arm was displaced by –256 μm, +209 μm, -221 μm and +159 μm at 30, 60, 90 and 120 seconds respectively.

depends on dimensional changes in different parts of the VLTP due to thermal stress relief. To minimize this effect, thermal enclosure around the VLTP was installed. Temperature fluctuates 2 °F and 0.5 °F with period of about half an hour outside and inside of the thermal enclosure, respectively.

In order to examine the effect of thermal changes on profile measurements, 5-minute stability scans were made before and after the thermal enclosure installation. The AXAF test flat, the height profile of which has the peak-to-valley value of less than 15 nm over vertical test stripe as measured by ZYGO interferometer, was used as a sample. The peak to valley values for stability scans transferred into height profiles varied from 0.1 to 0.2 μm and from 0.02 to 0.06 μm before and after enclosure installation, respectively. All subsequent measurements presented in this paper were done with the thermal enclosure installed.

3.2. Beam separation distance

The distance between two beams is set to be about 1mm (a diameter of the laser beam) in order to affirm the largest possible spatial frequency measuring range. However, in this case the interference profile minimum is poorly defined and it introduces an error in determining of the cosine minimum. Increasing the distance between two laser beams results in better contrast of the interference pattern minimum. In order to investigate the dependence of the profile measurement accuracy on the distance between two beams, we made ten series of profile scans of the vertical stripe of the AXAF flat mirror. The separation distance was changed by adjusting the Porro prism position and measured at output of optical board. For each separation distance three 200 mm scans were made. 5-minute stability scans were made before and after each scan series, and transferred into height profiles. In order to remove the stability issues from consideration, the peak-to-valley values for height profiles of test flat were compared to averaged peak-to-valley values of the stability scans. The results of these measurements are summarized in Table 1. The ratio between the peak-to-valley value of the flat and stability scans decreases with increase of the distance between two beams from 1.0 mm to 1.5 mm. Then this ratio becomes almost a constant, therefore 1.5 mm beam separation distance was set for remaining measurements. The peak-to-valley value of the height profile of the vertical stripe of the AXAF test flat measured at separation distance 1.5 mm was found to be 55 ± 5 nm.

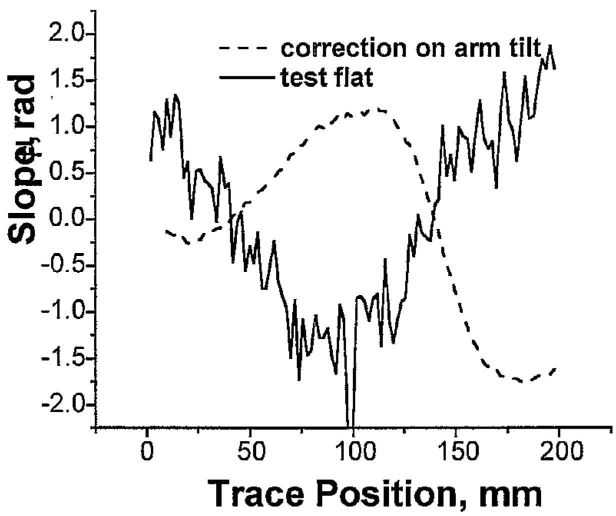

Figure 4a. The slope profile of the test flat measured with the VLTP. The correction function represents the slope change due to the scan arm tilt.

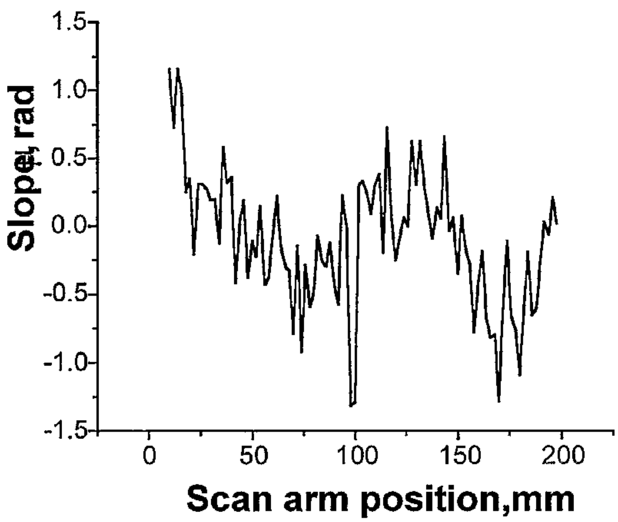

Figure 4b. The slope profile of the test flat corrected on the slope change due to the scan arm tilt.

3.3. Tilt of scan arm

One of the possible sources of the systematic error is displacement of the laser beam as a function of the probe scan height. This systematic error is similar to retrace error in regular interferometers. The cause of laser beam displacement is angular motion of the scan arm as the vertical stage carriage moves up or down. It leads to lateral motion and rotation of the penta prizm installed at scan arm. In ideal case, when there are no abberations in optical components (the penta prizms and FT lens), phase shift of returning beams should remain the same. The abberations could produce phase shifts in the returning beams and cause the fringes on the detector to move.

To measure the scan arm tilt as a function of the vertical position of the scan head, we attached a small flat mirror to the end of the scan head facing the lower penta prism. This mirror moves together with the probe head and tilts by the same angle as the scan arm. The beam incident on the mirror is always parallel to the optical table due to pair of penta prisms, but the beam reflected from the mirror contains the arm tilt angle. Three scans each 700 mm long were made and the slope profiles were averaged. The averaged slope profile is shown in figure 2. The slope change is 0.374 mrad over 700 mm scan length, which translates into 0.43 mm lateral motion of the scan head (the length of the scan arm is 1.15 m).

To confirm that the scan arm tilt produces a deviation of the fringe pattern, we removed the captive mirror and set the AXAF flat mirror to reflect the beam back into the penta prizm. A micrometer actuator was mounted to push the back side of the scan arm toward the flat mirror. Series of stability scans were collected. During these stability scans the scan arm was pushed and released by micrometer pin with fixed steps, and the respective slope changes were measured. An example of the stability scan is shown in figure 3. For displacement range from 50 to 400 μm the slope change was found to be linear with displacement and the specific slope change was measured to be 14.0 ±1.0 nrad per micron of lateral motion of the scan arm. In order to make correction on the slope change due to the scan arm tilt, measurements of the arm tilt and slope profile of the AXAF flat mirror were repeated for lower 200-mm vertical range of the VLTP. The scan arm tilt was converted into lateral motion of the scan head and the specific slope change was used to plot the slope change due to the scan arm tilt as a function of the scan head position. Measurement results for the slope profile of the AXAF flat mirror as well as the slope correction function are shown in figure 4a. Slope profile of the AXAF test flat corrected on the slope change due to the scan arm tilt is presented in figure 4b. The peak-to-valley value for corresponding height profile of the vertical stripe for the AXAF test flat was found to be 20 nm. Such a technique can be used for calibration of the whole vertical range of the VLTP. However, this method has to be verified by measurements of other calibrated surfaces.

3.4. Detector Clocking Error

Another possible source of the systematic error is angular misalignment of the detector. The pair of beams reflected from the SUT produces an interference pattern at the plane of the detector. During the vertical stripe scan of the SUT, the interference pattern is supposed to move along the longer axis of the detector array as the slope of the SUT changes. A change in position of the interference pattern is directly proportional to change in the slope of the SUT. A tilt between the axis of the detector and the path of the interference pattern at the detector plane results in cosine error in determination of the interference pattern position. Moreover, twist in scan arm of the VLTP leads to rotation of the lower penta prism and, hence, to error in slope determination due to shifting of the interference pattern in direction perpendicular to the interference pattern path.

In order to align the detector with the interference pattern path we measured the figure of the convex surface with radius of curvature about 20 meters at different angular positions of the detector. When the trace of the interference pattern is aligned with the longest axis of the detector, the path of the interference pattern produced by pair of beams reflected from the surface with constant curvature would have minimum and the sag of the figure profile should have a maximal value. Sets of three 200-mm scans were collected and then averaged for each angular position of the detector. Original angular position of the detector was set to be a zero angle. Sags of averaged figure profiles measured at different angular positions of detector are shown in Table 2. Maximal sag occurred at –2 degrees angle of the detector, therefore this detector angle was set for remaining measurements.

Table 2. The sag of the convex mirror as function of the detector clocking angle.

Clocking angle, deg	1	0.5	0	-0.5	-1	-2	-3	-3.5
Sag P-V, μm	63.687	63.717	63.725	63.735	63.741	63.750	63.740	63.722

3.5. Cylindrical Sag Error

The VLTP measures slope in vertical stripe of the SUT. For figure measurements of cylindrical x-ray optic elements, such as x-ray shells and mandrels, it is important to have the stripe be parallel to the axis of symmetry for an optical element. In the case when the stripe is tilted regarding the SUT axis of symmetry, the cylindrical sag error will be introduced. In order to reduce this error, the vertical part of the incoming beam has to be aligned to be parallel with axis of rotation for the table supporting the optical element.

To align axis of rotary table of the VLTP with vertical part of the incoming beam we installed a flat mirror on the rotary table. The lower penta prism was removed from the scan head, so the incoming beam is reflected from the mirror in direction of top penta prism. The distance between incoming and out going beam at the top penta prism was minimized by tilting of the horizontal stage of the VLTP. The angle between the axis of rotary table of the VLTP and vertical part of the incoming beam is estimated to be less than 0.2 mrad. This alignment was made for the scan head positioned exactly above the center of the rotary table of the VLTP. The scan head is placed in this position during the profile measurements of the inner surface of the x-ray shell mirrors. However, twist in horizontal stage might introduce an additional tilt to the vertical part of the incoming beam at different positions of the scan head across the range of the horizontal stage. Such a situation can take place during profile measurements on outer surfaces of mandrels when the scan head is set about 40 cm from the center of the rotary table. To measure the twist of the horizontal stage a small flat mirror was attached at the bottom of the scan head. With the lower penta prism removed a Dove prism was placed into the beam path to rotate the beam pair by 90 degrees to sense the twist of the horizontal stage. In order to let the VLTP measure the twist of the horizontal stage a stability scan was set up with 5-second time intervals between data frames. During the stability scan the horizontal stage was manually moved between distinguished positions between data frames, thereby acquiring twist of the horizontal stage as function of its position. The twist was measured to be 1.30 ± 0.05 mrad. In order to reduce the error introduced by this twist, the horizontal stage was shimmed. Twist of the horizontal stage measured after shimming was found to be 0.12 ± 0.02 mrad. It is estimated that the cylindrical sag error in height profile measurement of 100 mm diameter and 300-mm long mandrel due to the twist in the horizontal stage and the vertical stage tilt would be lees than 15 nm.

SUMMARY

In order to achieve high-accuracy measurements of absolute surface height with the VLTP, the systematic error reduction is very important. Use of thermal enclosure around the VLTP lowered the error in determination of the surface height due to vibrational and thermal instability of surrounding environment. Achieving better contrast of the interference pattern also improved accuracy of the VLTP. The detector clocking error and the cylindrical sag error were reduced as well.

It was shown that the change in the scan arm tilt during a vertical scan produces a deviation of the fringe pattern. The slope change due to the fringe pattern deviation is linear with scan arm displacement and the specific slope change can be used to correct the error introduced by the scan arm tilt. However, this technique has to be verified by profile measurements of other calibrated surfaces and we intend to do that in future.

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