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SUB-μRAD ANGULAR STABILITY MEASUREMENTS BY USE OF LONG-TRACE-PROFILER-BASED SYSTEMS*

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Abstract

High accuracy angle measurement at the sub-μrad level requires extremely high instrument stability. In order to reach sub-μrad stability (0.1 arc second or less) over long time periods, it is necessary to maintain the test object and almost all of the optical components in the measuring instrument in very steady positions. However, mechanical force relaxation, thermal expansion, and asymmetric structures produce angular and linear displacements in the system, resulting in angular measurement error. A Long-Trace-Profiler (LTP)-based stable equipment is used to test precision angular stability with sub-μrad resolution. Long term stability over 15 hours has been measured on different kind of mechanical structures. Temperature monitoring during the tests is extremely important. Some test results showing the effects of thermal variations are presented, which indicate that temperature stability on the order of 0.1°C is absolutely necessary for repeatable sub-μrad measurements. The optical method, using optics with an even number of reflecting surfaces (for example, a right angle prism, pentaprism, or rhomboid prism) to reduce the influence of existing angular displacement, is introduced and the comparison measurement is presented. An optical fiber transfer line is able to reduce the laser angular shift from about 10 μrad to a level of 0.3 μrad rms. Careful system configuration, design and operation are very important for the sub-μrad angle stability.

Keyword: anglular stability, sub-μrad, precise measurement, long trace profiler, LTP, temperature stability

1. Introduction

High-precision angle measurement instruments such as autocollimators, theodolites, goniometers, and the Long Trace Profiler (LTP)[1, 2] have accuracies in the 0.2 to 1 arc second (1 to 5 μrad) range. Separate from instrument precision, the practical absolute measurment accuracy depends on operator experience, environmental conditions, mounting stability, and many other factors. For measurements over a long time period, the stability of the instrument and its supports is a very serious problem. Generally, instrument specification does not include long turn stability, and users must test for it themselves if it is necessary. In order to reach μrad or sub-μrad measurement precision, it is better to know the influences of different factors independently, and then to improve. Due to the reasons described in the following, we made the effort to test sub-μrad stability over long time periods.

First, the LTP is an angle-sensitive instrument with the capability of achieving μrad measurement accuracy with carefult operation. However, under certain conditions we can easily find that the test result is not very reliable and repeatable. Instability usually occurs immediately after the operator adjusts the interference fringes for symmetry after they have drifted too much. A stability scan made immediately following a fringe adjustment usually shows a drift of several μrad in both the test and reference channels. The reference subtraction does not completely correct the entire error signal, particularly over a long test period. In order to improve LTP stability and accuracy, sub-μrad measurement stability is necessary.

Second, the LTP could be used in principle to test absolute flatness on a large surfaces with high accuracy. However, if one is going to measure a 500 mm long surface with an accuracy of λ/10 or better, the stability and repeatability of the LTP should be less than 0.5 μrad (peak-to-valley, or about 0.125 μrad rms) over the entire scanning length. Furthermore, a large flat surface requires a 2-dimensional test, so a one hour or longer scanning time will be required, resulting in the requirement of sub-μrad stability over this time period.

Third, if the LTP is going to perform as a precise angle monitoring system, sub-μrad stability is also needed over long time periods.

The stability of a measurement result mainly depends on two aspects: the internal nature of the instrument, and the outer measurement environment, particularly the temperature stability. If the instrument configured and constructed is very stable by nature, it could decrease the requirements on temperature stability for a given accuracy level. Conversely, if one operates this stable instrument in a very stable environment, for example, ± 0.1 °C, this stable instrument will contribute to a much higher test accuracy. However, this paper is only going to present some measurements which could be useful for setting up precise experiments. We present several test results on laser angular drift, relaxation of mechanical mounts, thermal influence, and so on. Most of these tests were done over 15 hour time periods, where we can see the sub-μrad drift very clearly. An LTP-based system is used as a test tool. The details of its construction are beyond scope of this paper.

2. Laser beam drift test

In order to make a sub-μrad angular measurement, the source beam should have sub-μrad angular stability. The He-Ne laser is used in the LTP because of its small frequency shift and stable intensity output. According to the specification of the He-Ne laser presented by manufacturer[3], its angular drift is < 30 μrad after 15 minutes. However, 30 μrad is a significant amount of angle error for a sub-μrad measurement if it is not dealt with carefully. We tested it in this way. A He-Ne laser cylinder was placed on a V-block freely at a distance of 1.8 meters from the detector. The laser beam was directed to the LTP detector and a stability scan was made. If the laser pointing direction shifts, the beam spot on the detector will move. By calibrating the detector position scale factor, the angular drift in the laser beam can be measured. We assume that the V-block will not create a large angle drift and can be neglected for rough estimating test. Fig. 1 shows the laser direction drift starting at the time when the laser was just switched on. In the first hour, the laser direction varied significantly, but there was a smaller drift of about 10 μrad shift over the next 5 to 6 hours. Fig. 2 presents the laser beam drift in a equalibrium condition: the laser was stabilized for several days in a stable environment. The anglular drift is less as 6 μrad (p-v) over 15 hours. However, this drift magnitude will still destroy the test accuracy.

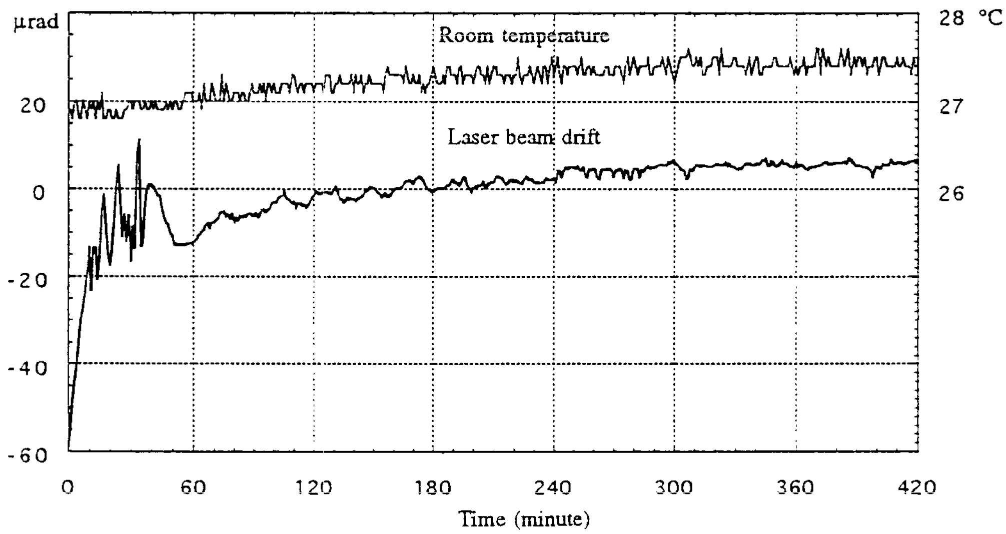

Fig. 1 He-Ne laser beam drift stating at just turning on laser

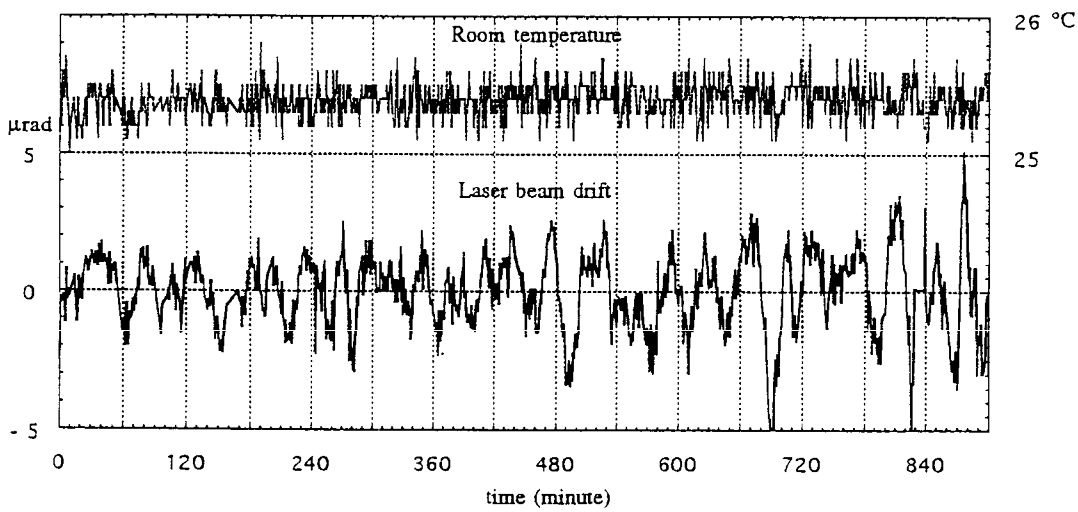

Fig. 2. He-Ne laser beam drift at stabilizing status

Irick uses a second reference mirror to monitor beam pointing error from a laser diode source. This error signal can then be subtracted from test beam data[4]. The adoption of a optical fiber introduced by Takacs reduces laser beam angular drift to the sub-μrad level. The He-Ne laser is coupled to a single-mode, polarization-preserving optical fiber by a focusing lens, and the optical fiber collects the beam and transfers it to the other end of the fiber, where it is then collimated by another GRIN lens cemented to the end of the fiber. In this situation the direction of the output beam is only determined by the relative lateral position between the fiber and the collimation lens, which is fixed. All the beam collected by input end of the fiber, no matter its direction shift, will always be transferred to the output end center after multiple reflections in the fiber. In practice, the total beam shift incorporating the fiber angular drift can be less than 0.3 - 0.4 μrad rms within 15 hours, which is described in the next paragraph.

3. Stability measuring tool, LTP-based equipment (LTPBE)

In order to measure sub-μrad angular stability of the mechanical structure, optics, and thermal impact on objects to be used in stable testing instruments, the first thing is to seek a tool with sub-μrad resolution and sub-μrad stability. The LTP can easily recognize a slope variation of less than 0.1 μrad (0.02 arc sec) with very high resolution [5]. The LTP uses a two-pencil-beam interference technique to determine the local surface slope angle. In order to achieve better position resolution on the detector than the 25 μm pixel spacing, the partial intensity curve is fitted at the minimum in the fringe pattern with a 2^{nd} order polynomial curve, and the minimum position is calculated with high precision from the fit coefficients. In this way it is easy to resolve distances of 0.1 to 0.2 μm on the detector, which translates into angles on the surface of 0.04 to 0.08 μrad with a FT lens focal length of 1250 mm. Practical examples of the achievable resolution of the LTP in mirrors tested at ELETTRA are presented in Fig. 3. Fig. 3a is the slope curve of a stability scan and Fig. 3b is the slope profile of a plane mirror of 200 mm long. From these curves we see that the LTP has a high angular resolution despite the extremely high f/number of the collimated laser probe beam.

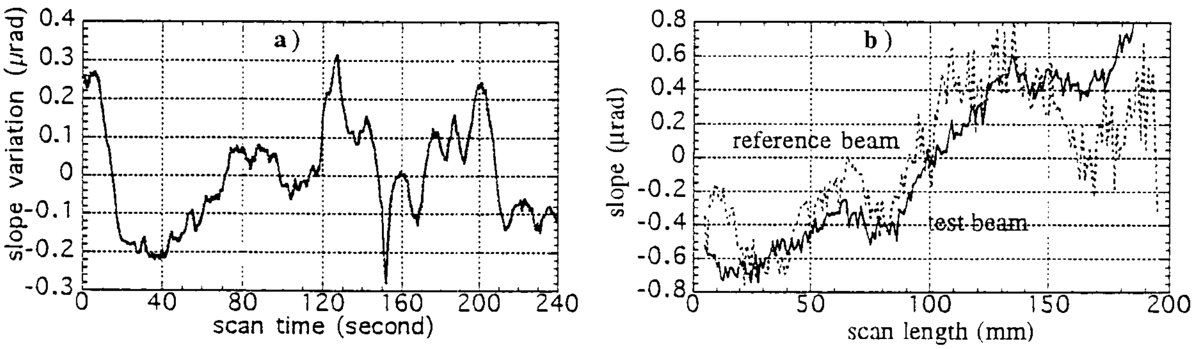

Fig. 3. Practical profiles indicate the LTP has a resolution better than 0.1 μrad
a) the stability scan made in ELECTTRA
b) the measurement on a plane mirror of the ESCA beam line at ELETTRA

The standard LTP optical system does not have sufficient long-term stability to be considered for use as a stable instrument for long term sub-μrad stability measurements, because it can only achieve about 1 μrad rms in a ±0.1 °C environment over 15 hours, and it must apply the reference beam correction. Reference beam subtraction mainly corrects optical path difference variations between the two pencil beams, created by mechanical relaxation and thermal expansion of the equal-optical path system (EOPS)[6], and will not be able to subtract the entire errors produced after EOPS. The better way is to make very stable probe beams even without the need of reference subtraction. Then we can measure two factors together at the same condition on two beams (reference and test beam) of the LTP for the comparison purpose.

To achieve long-term stability, we developed an LTP-based equipment (LTPBE) as a test tool which maintains the high sensitivity of the LTP and improves its stability. We fixed the EOPS of the LTP and clamped the optical fiber rigidly into a sealed cube, incorporating with the use of low expansion material. LTPBE must be stabilized for days without adjustment before measurement. In order to test the exact stability of this tool itself, we put the Fourier Transform (FT) lens just behind the EOPS to focus the beam onto the detector directly. In this way, the real stability of this tool can be tested without being influenced by other unstable factors. We used FT lens, detector, and software of the LTP to detect its angular stability. We made five stability scans, each of 15 hours. The average slope stability is 0.41 μrad rms (0.16, 0.46, 0.48, 0.54 μrad rms individually) with no reference beam subtraction applied (Fig. 4). The room was kept with a temperature oscillation of estimating about ± 0.4 °C (unfortunately, we had not monitored the temperature at this time). This test result also indicates the slope error produced by individual factor of laser beam drift, fiber head fixing, or optical system fixing must be less than

0.4 μrad rms. We mention the LTPBE in this paper is for explaining that the measurement results by use of this tool, presented in this and next paragraphs, are reliable.

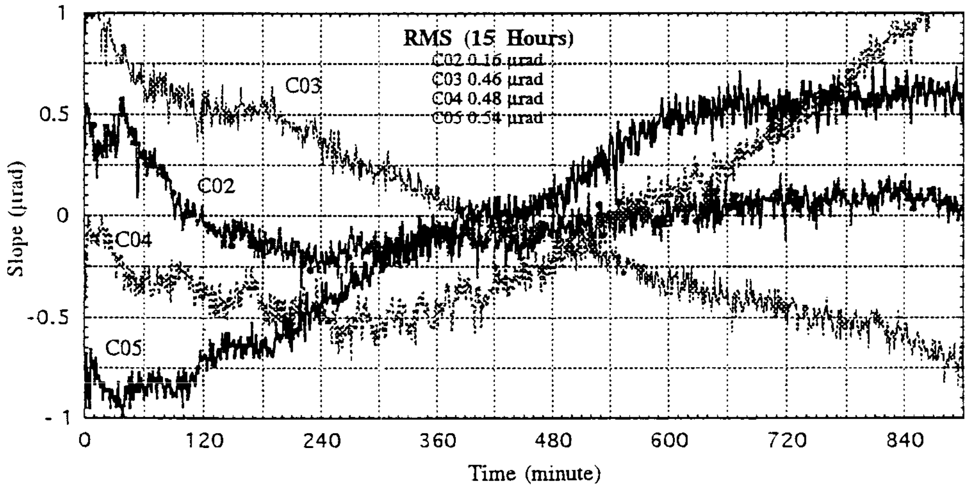

Fig. 4. 15 hours stability measurements of the LTP- based equipment

4. Mechanical stability measurement

Mechanical stability is one of the key factors for the instrument stability. The mechanical mounts and the adjustable units are the most commonly used parts in precision instruments, which may produce angular errors in the order of μrad. For example, the instability of fixing mounts of reference mirror and mirror under test will contribute directly to the slope error of the test result, which cannot be corrected by subtracting the reference data. The mechanical stability mainly depends on material and structure stability, thermal expansion, and relaxation. A well designed mechanical mount will reduce the requirements on temperature control.

4.1. Mechanical relaxation measurement of two different kinds of mounts

In order to obtain sub-μrad test results, the mechanical relaxation value and shifting period should be known. A no reference subtraction LTPBE is suitable for this test. Of course, at this moment a polarization beam splitter should be added to the LTPBE like that in the LTP. The whole system can maintain a stability of 0.3-0.5 μrad rms in the temperature of ±0.1 °C, or about 1-1.5 μrad rms in the temperature of one to two degrees over 15 hours. These results are for the test beam only with no reference correction applied.

Following are descriptions of the mechanical stages that were measured. Two tilt stages were tested at the same time by use of two beams (test and reference) of the LTPBE. The first stage is a flexure mount produced by Newport Corp., which uses leaf springs to maintain the position. The second tilt stage produced by J. A. Noll Co. consists of two adjusting screws, one ball and one retaining wire spring. In order to isolate the thermal stability from mechanical relaxation we kept the mounts and LTPBE near each other inside a rough cardboard shield, where they were stabilized for an entire day. Then the shield was opened in order to tilt the two stages about 5000 μrad and then to return to the original position by looking at the fringe movement on the screen. The shield was closed immediately after the adjustment. This adjustment was done within 15 seconds and should not interfere with the temperature. After the adjustment a stability scan was begun immediately, as well as the temperature recording. Fig. 5 shows test results over 15 hours with a stable temperature of ± 0.1 °C. It is very clear the mechanical relaxation will last for about 3 hours with a value of 1.5 μrad (p-v). From this test it seems that the flexure mount is slightly better. Of course, the error value will vary depending on the particular situation like spring force, machining quality and so on.

4.2. Measurement of single screw pressing structure

Prism and round or rectangular optics can be simply fixed by single screw by pressing them against a plate (Fig. 6). Generally, the angular position is not very stable for this fixture because it is not sure if it is contacted very well. Fig. 6 shows 15 hours test result while a mirror just pressed to the table by a single screw. There is significant mechanical relaxation on the order of 80 μrad over four hours. However, this relaxation value is random, it could be larger or smaller depending on the contact situation. This method of fixturing should not be considered in applications requiring high instrument stability.

These are a few test examples to show the importance of sub-μrad measurement. The real error being contributed in the particular case should be tested individually.

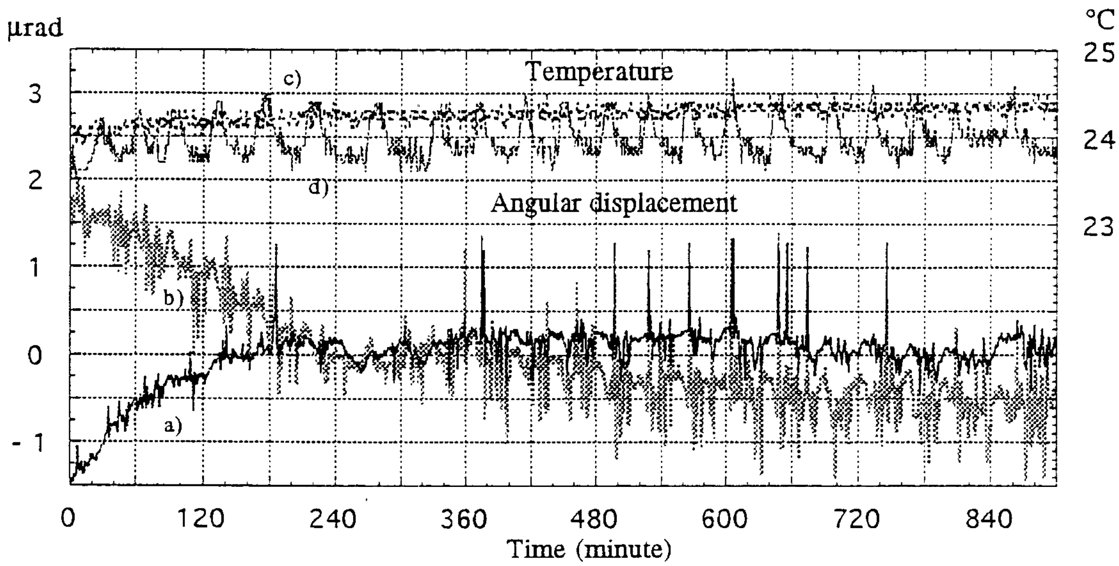

Fig. 5. Relaxation measurements of two tilt stages after tilting-returning adjustment
a) New Port Co. flexure tilt stage b) J. A. NOLL Co. ball spring mount
c) CH1: sensor in cardboard box d) CH2: room temperature, outside the box

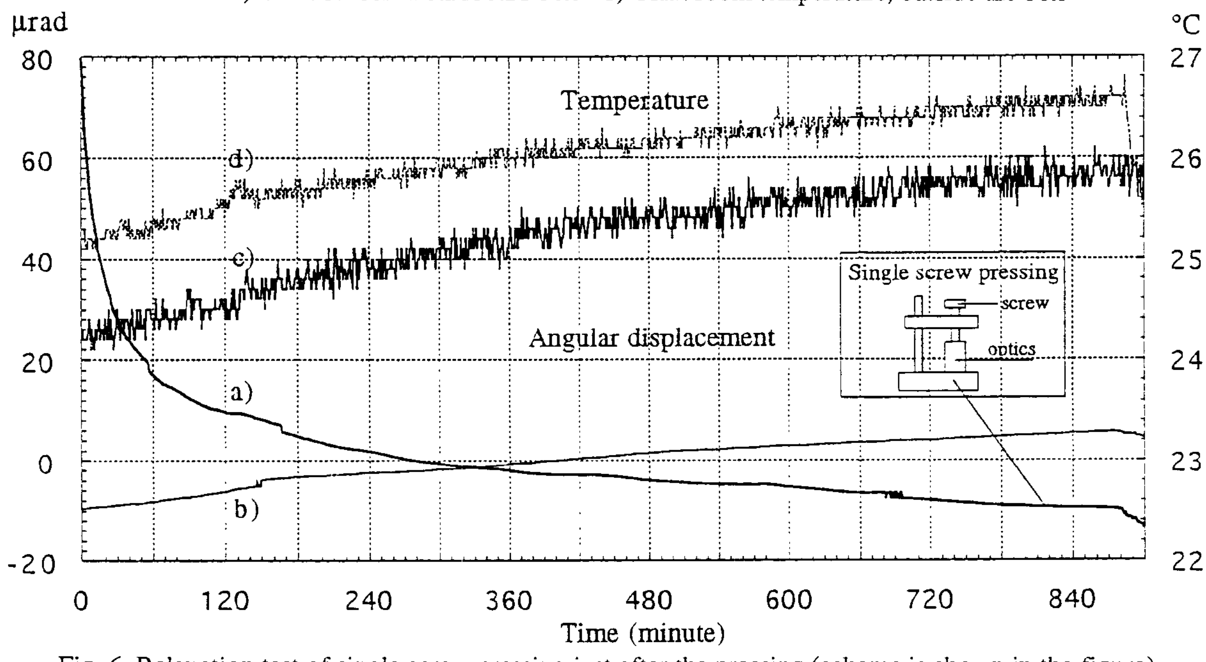

Fig. 6. Relaxation test of single screw pressing just after the pressing (scheme is shown in the figure)
a) single screw pressing b) New Port Co. flexure stage not being in touch for days
c) CH1: temperature in cardboard box d) CH2: room temperature

5. Thermal influence

Thermal stability is a very important consideration for sub-μrad measuring instruments as well as for the LTP. The LTP requires temperature stability in the order of ± 0.1° C. Of course, to identify the measurement error created by thermal influence, for example, expansion, refraction index of optical material and so on, in specific cases is a complicated task. In the following we will present some examples.

5.1 Temperature measurement:

According to operating experience with the LTP, some test results were very reliable, but some were not. The main reason is unexpected environmental temperature changes if the instrument has not been touched for hours. For example, at ELETTRA before installing the temperature-control room, test results with the LTP in summer of the LTP were not repeatable because of large temperature variations in midday. Even though there was a room temperature control system, it did not work well on certain days, which caused stability problems. At BNL when we made stability scans over several days, large errors occurred on certain days. We recognized the cause as a faulty temperature control system which lowered the temperature during working hours and raised it at night. In the optical metrology laboratory of SRRC in Taiwan, the temperature can be controlled within ± 0.05°C or better, so the slope error over 15 hours can be much better[8]. For sub-µrad precision measurement, a computer controlled temperature monitor system is absolutely necessary to record the temperature at all times during the measurement. The sensitivity of the instrument should be 0.05-0.01 ° C. We adopts OMB-MULTI SCAN 1200 high speed isolated measurement system produced by Omega Technology Company to do the test. The sensitivity is 0.1 °C.

5.2. Measurement of sub-µrad shift responding to small temperature fluctuations

A stability scan combined with a precise temperature measurement at the same time was done in the following set up: the LTPBE was set on a small optical board, with one mirror reflecting the reference beam also fixed on the same board. The mirror reflecting the test beam was fixed on a mechanical linear stage which was put on a large optical board. The reference mirror and the LTPBE were shielded in the same cardboard enclosure. However, the stage was exposed to the room environment. At two locations the temperatures were tested. CH1 is located inside the cardboard box and CH2 is set on the slide outside the cardboard box.

Fig.7 shows 10.7 hour stability curves extracted from a 48 hour stability scan with the temperature variation of ±0.1 - 0.2°C. It shows a 1 µrad rms stability error over the entire 2-days period without reference correction. The test result shows the thermal influence very clearly. The room temperature control system switches the heater or cooler on and off in order to keep the room temperature uniform. This creates a small temperature fluctuation of 0.6 °C (p-v) with a cycle of about 28 minutes. This slow oscillation temperature affects the measurement equipment, resulting in a slope error of 0.5 µrad slope error (p-v) with the same cycle period as that of the temperature. The value of the slope error depends mainly on the mechanical structure of mirror mounts. Another interesting fact is that the cardboard shield is very effective at reducing slope curve fluctuations. There was less temperature fluctuation on CH1 because it was covered by the cardboard. The two mirrors were mounted on identical Newport Corp. flexure mounts.

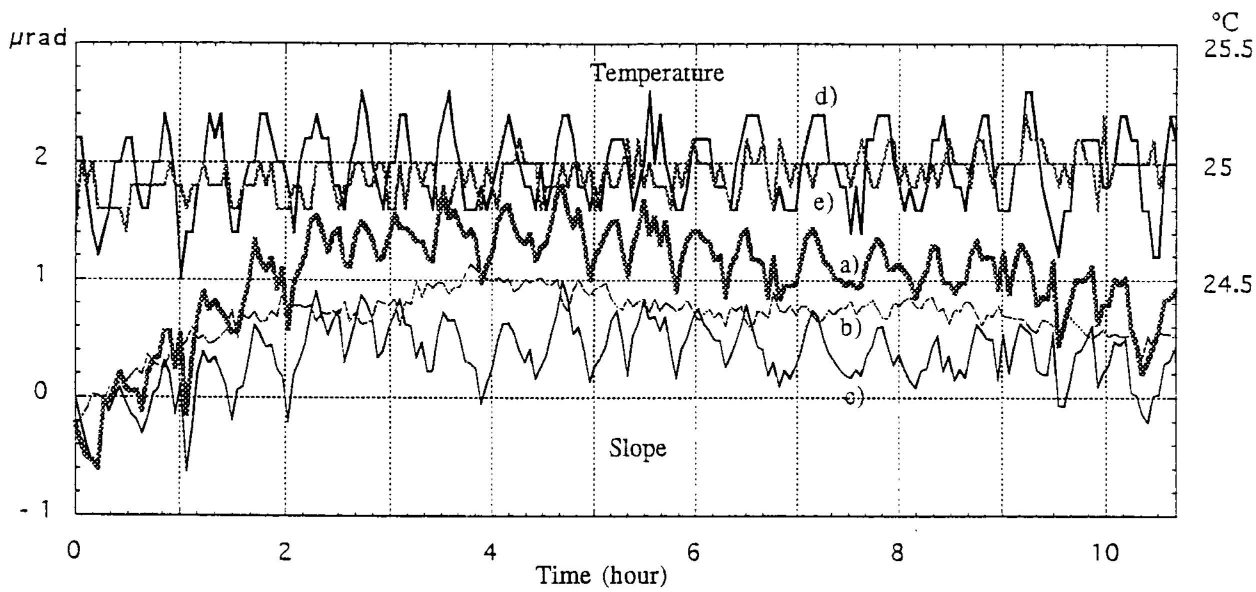

Fig. 7. Measurement of sub-µrad shift responding to less temperature fluctuation (quoted from 48 hours file)
a) test beam with mirror mount outside cardboard box; b) reference beam with mirror mount inside box;
c) after subtracting reference beam data; d) room temperature; e) temperature inside the cardboard box

5.3. Test result of sudden temperature shift

In order to examine the influence of temperature on slope error, we tested the angular shift during a sudden temperature change. Fig. 8 shows the 7 hours thermal character of a flexure mount and a single screw pressing fixture at a time when the temperature climbed 2 degrees. The whole set was equillibrated for one day before the test. At the beginning the temperature was stable and the two beams were quiet. When the temperature climbed, the two beams moved in different directions by different amounts. The total angular shift of the flexure mount was about 11 μrad (p-v) responding to the 1.6 °C temperature change. We noticed from the test result that the single screw pressing mount had a smaller angular drift. It was re-pressed in random apart from the one of Fig. 6. Single screw pressing could be different every time. In this situation, if we subract one from another (reference correction option) the error will be wrong even worse.

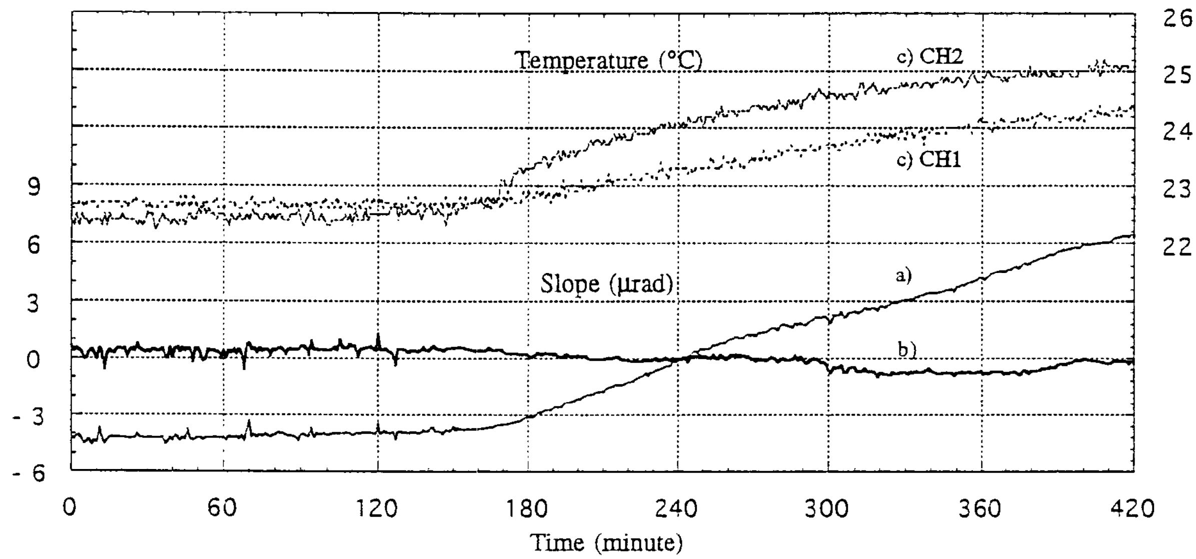

Fig. 8. Slope drifts during the sudden temperature variation
a) flexure mount of New Port Co. b) single screw pressing
c) CH1 and CH2: temperature inside and outside the shield

5.4. Requirement to the temperature stability

The environment is the most sensitive factor in produceing slope errors and has to be controlled very well. From the test results presented above (Fig. 5, 6, 7 and 8) we can estimate the sub-μrad angular shift produced by temperature fluctuation in the LTP, which is about 0.5 μrad (p-v) each 0.1 °C for low frequency temperature variations. The slope values created by moderate frequency (tens minutes) temperature variation is less, but if one is going to make a sub-μrad test it is necessary to pay attension on it. As mentioned above, if this error is not able to be subtracted from reference beam data of the LTP, it will produce significant slope error in the sub-μrad measurement. So the temperature stability of the environment should be in ± 0.1 °C or better.

6. Measurement of the reduction of stability error by use of specific optical components

In order to reduce the angular shift produced by mechanical and thermal factors, one method is to make these angular variations insensitive to the test result. Far example, the application of a scanning penta prism to the LTP reduces the accuracy requirement of the slide significantly, so that a mechanical linear stage can be used[6].

This is an optical method to decouple mechanical stage precision from the measurement. In principle, if an input beam is reflected by two surfaces with fixed angle, α, between them, the output beam will have a constant angle β with the input beam as:

$$\beta = 2\,\alpha$$

It means if the incident beam direction is kept fixed, the output beam direction will not change even if the two surfaces are rotated together. The right angle prism, a pentaprism, and a rhomboid prism reflect the beam at fixed angles of 180°, 90° and 0° respectively. If the plane reference mirror of the LTP is replaced by a right angle prism to reflect the beam back to the LTP, the angular drift of its mount, no matter if it is caused by thermal or mechanical displacement, will not influence the test result. Fig. 10 is a comparison between making use of a right angle prism and a plane mirror to reflect the test and reference beams. As a matter of fact, in this way the test beam slope expresses the combined stability of the LTPBE and mirror support, but the reference beam slope only expresses the stability of the LTPBE. We can apply them related to a particular situation when it is necessary.

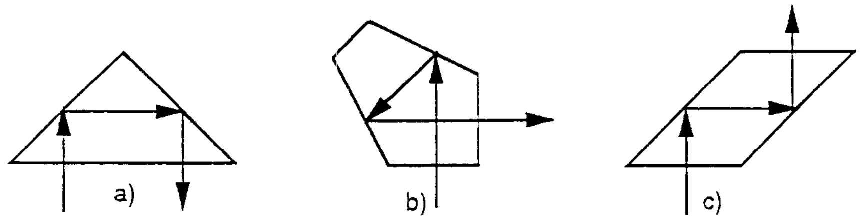

Fig. 9. Example of double reflection prisms. If the prism rotates the output beam direction will keep unchanging
a) right angle prism turns beam 180° b) penta prism turns beam 90°
c) rhomboid prism turns beam 0°

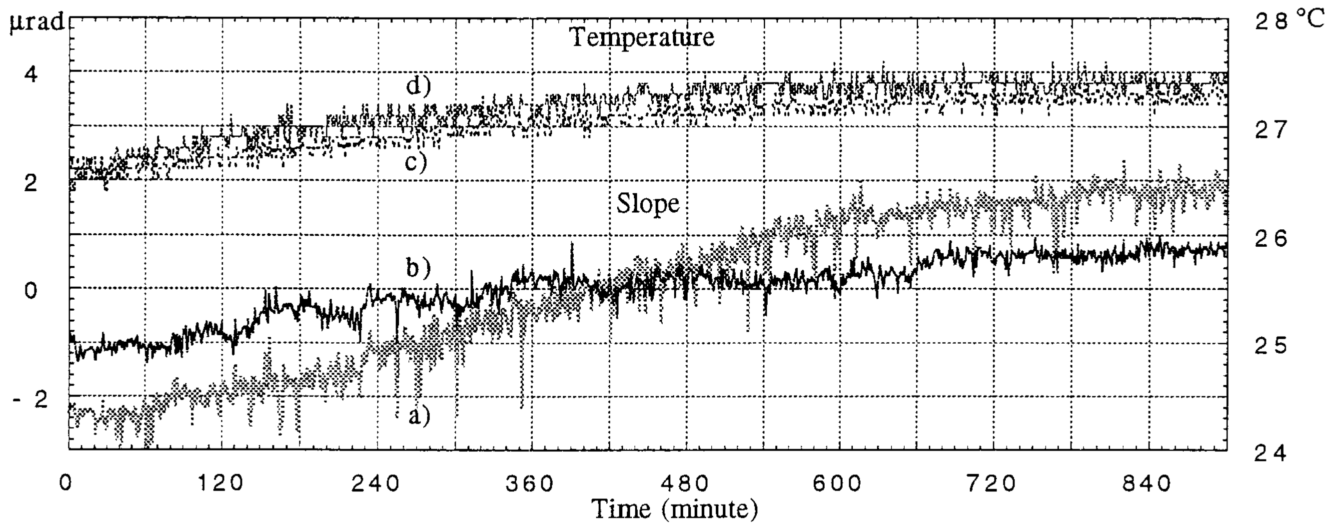

Fig. 10. Stability comparison between beams reflected by right angle prism and by mirror
a) reflected by mirror b) reflected by right angle prism
c) temperature close to mirror and prism d) room temperature

7. Conclusion

Precision angular measurement requires stable equipment, angular shift test of 1 μrad accuracy requires sub-μrad stability instruments. A precise flatness measurement needs sub-μrad stability over a long time period. Long term angle monitoring also needs significantly stable instrument. In order to achieve sub-μrad stability, a more stable test tool is necessary, and LTP-based equipment is suitable for this purpose. A He-Ne laser coupled with an optical fiber can provide output stability of 0.3 μrad in angular drift despite the He-Ne beam drift of several μrad. The temperature recording of ± 0.1 ° C sensitivity must apply at the same time when the entire sub-μrad measurement is made in order to assess the reliability of the test data. Mechanical relaxation should be tested before a unit is used for the sub-μrad equipment. Relaxation of several μrad may occur and it will take about 3 hours to be in equilibrium after mechanical adjustment. Different mechanical units have different relaxation characteristics. An equilibrium period should be considered for sub-μrad test. Temperature drift is a fatal factor in sub-μrad testing. A fluctuation of 0.1 °C can produce 0.5 μrad (p-v) angular error according to the measurements, so temperature stability of ± 0.1 ° C is absolutely necessary for sub-μrad test. Optical methods are very helpful in reducing the stringent requests placed on the mechanics and should be implemented when possible.

Acknowledgment

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