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Vol. 8(19), pp. 997-1004, 23 May, 2013
DOI: 10.5897/IJPS2013.3810
ISSN 1992-1950 © 2013 Academic Journals
http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Dimensional stability of mirror materials for opto-mechanical reference system

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Accepted 24 April, 2013

Sensors, IR beams and lasers used in many opto-mechanical systems have stringent alignment retention requirements for use over an extended temperature range. Thermal effects are the primary cause for alignment drift during operation. Thermal expansion and contraction of materials can result in dimensional instability of mirror surfaces. This paper focuses on the importance of dimensional stability of mirror materials in alignment retention of the devised opto-mechanical reference system and addresses the cause of thermal instabilities which determine its functional accuracy. This is clearly shown by the agreement between the measurement results of dynamically varying form error of the mirror surface with temperature and the theoretical estimations. The test equipments and methods to validate the alignment stability of the opto-mechanical reference system are also presented.

Key words: Opto-mechanical reference system, alignment drift, mirror materials, form error, alignment retention.

INTRODUCTION

Most opto-mechanical reference systems (ORS) are designed to meet specific customer needs, which include precise measurements, mapping and ranging for various scientific and military applications. The alignment retention of the ORS over a broad operating temperature range is a prime requirement, which forms the basis for system design parameters (Paquin and Vukobratovich, 1991). Alignment retention of an ORS can be defined differently depending upon the configuration of the optical system (Paul, 1992). Most often, it is an established reference setup wherein the optical axis remains aligned with respect to a mechanical reference axis at a predetermined range and helps in retaining this relationship as and when there is an alignment drift in the mechanical axis due to cantilever effect (Thermal bend). Alignment stability of an ORS seeks for a minimum wave front error of the reflected beam from the mirror surface in order to retain the beam positioning with reference to the initial configuration of ORS. This paper discusses the temperature effects on mirror materials of a simple ORS. The experimental results presented in this paper clearly reveal that the alignment drift due to dynamically varying from error of the mirror surface with temperature amounts to a time varying error in the actual measurement by ORS.

OPTO-MECHANICAL REFERENCE SYSTEM DESCRIPTION

A simple schematic diagram of an ORS is shown in Figure 1. Mirror 'A', is provided with an inbuilt, collimated

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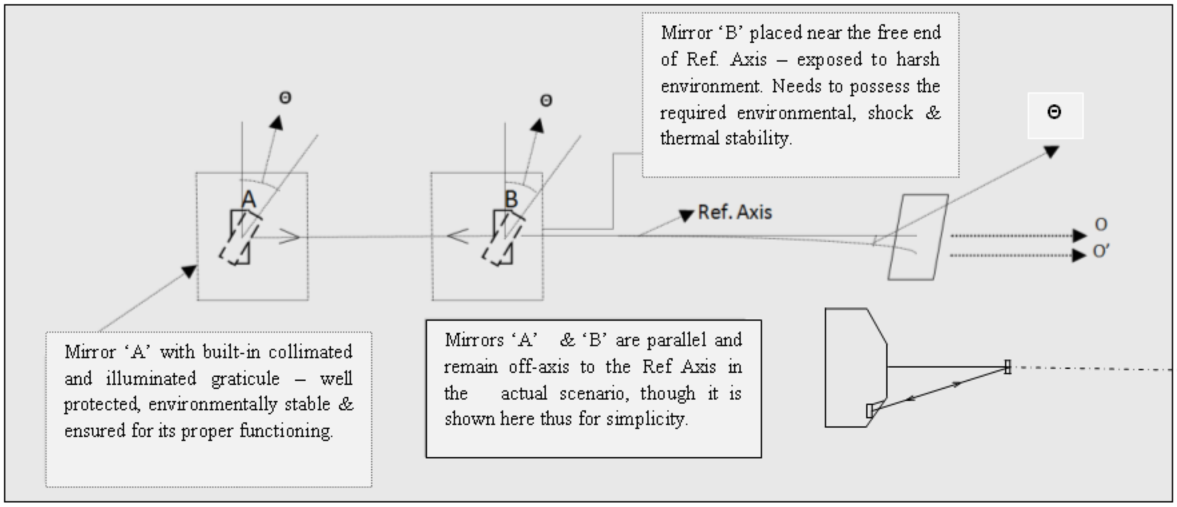


Figure 1. A simple schematic diagram of an opto-mechanical reference system.

and illuminated graticule. Mirror 'B' gives the axis reference at the free end of Ref. Axis, which is pointing towards some aiming point 'O' at a far off distance as indicated. The projected beam from the illuminated graticule is made to fall on mirror 'B' and gets reflected in the same direction provided, mirror 'A' is adjusted to achieve auto-collimation of the projected beam. The reflected image of the graticule then coincides with the original graticule, thus giving the reference position of mirror 'B' which corresponds to the Ref. Axis pointing towards 'O'.

When the Ref. Axis pointing towards O shifts to O' due to cantilever effect on account of thermal bend, there will be a relative angular shift Θ in the position of mirror 'B'. The separation now observed between the original graticule and its image gives a measure of the angular tilt on mirror 'B'. If there is no thermal bend, the graticule and its image will remain aligned as before, establishing the initial alignment stability of the ORS. Hence in order to retain the initial reference of the ORS over the working temperature range, the sources of variables on mirror material causing alignment instability have to be controlled within the specified requirements (Paquin, 1995; 1992). This paper mainly focuses on the dimensional stability requirements of mirror materials and the instabilities caused by temperature variations which affect the ORS alignment stability and hence the system performance when deployed in some real time application.

DIMENSIONAL STABILITY

Dimensional instability exists in all components to some extent irrespective of the material with which the component is made of. Hence, dimensional stability of a component implies the extent to which instabilities are controlled. It also represents the dimensional change that occurs in response to internal or external influences. Making intelligent choices in the selection of materials and processes for components help to achieve the stability design goals.

Types of instability

In general, the instabilities can be categorized as below:

Temporal instability

Temporal instability is the dimensional change that occurs in a component placed in a fixed environment. It is a permanent change.

Thermal/Mechanical cycling

Thermal/mechanical cycling is the dimensional change measured in a fixed environment after exposure of the component to a variable environment. It too is a permanent dimensional change.

Thermal instability

Thermal instability is the dimensional change measured in one fixed environment after a change from another fixed environment, independent of the environmental path. This change is reversible upon returning to the original conditions. Figure 2 shows evidence of such a change.

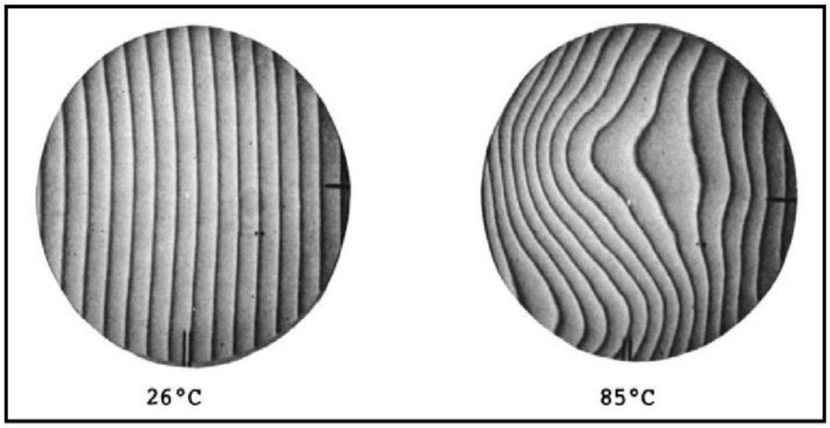
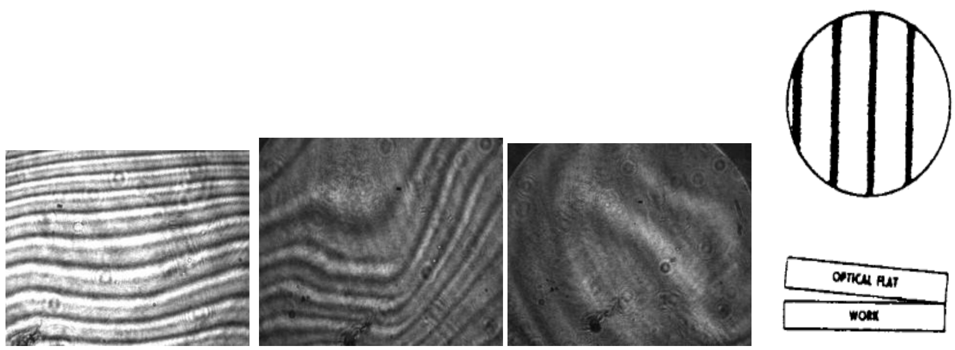


Figure 2. Surface figures of an electroless nickel-coated experimental beryllium alloy mirror (Paquin, 1992) showing thermal instability (reversible) of 2λ (approx).



(a) (b) (c) (d)

Figure 3. (a) to (c) Surface figure of mirror surface at 30, 45 and 55°C respectively, (d) Faithful representation of work piece surface figure in line with the ref optical flat.

Importance of uncoated metal mirrors

Uncoated metal mirrors are ideal for hostile environment applications where frequent cleaning is necessary. Superpolished metal surfaces having Angstrom level optical surface finish eliminates the necessity for expensive and lower performance metallic coatings. These coatings have inconsistent thickness variation, and may distort the wavefront of the reflected beam. Also, differences in the coefficient of expansion between the substrate and coating materials affect the mirror stability. Pure metal optics mirrors minimize distortion of the reflected image, and offers a very hard, scratch resistant surface with low thermal distortion. Significant progress has been reported in producing superpolished metal surfaces without the use of electroless nickel coatings, thereby avoiding the risks associated with these coatings. The material used is 17-4 pH precipitation-hardening stainless steel which has general engineering properties, as well as an unusual degree of dimensional stability (Paquin, 1997; Marschall and Maringer, 1977).

SURFACE FIGURE VARIATION IN A METAL MIRROR (SS) DUE TO THERMAL INSTABILITY

The variation of form error / surface figure of 'Mirror B' (in Figure 1) needs to be minimal, for retention of initial configuration of the ORS w.ref to Ref. Axis aiming point 'O'. It is therefore important to ascertain the thermal instability experienced by the mirror material over the working temperature range. The surface figure requirement for any polished optical flat surface is usually specified as surface form tolerance.

Variation of surface figure at elevated temperature

The surface figure variation in a stainless steel (SS) mirror at elevated temperatures was measured using a phase shifting interferometer. The results presented in Figure 3(a) to (d) show the dynamically varying surface figure of the mirror surface at elevated temperatures indicating the induced thermal instability in the mirror

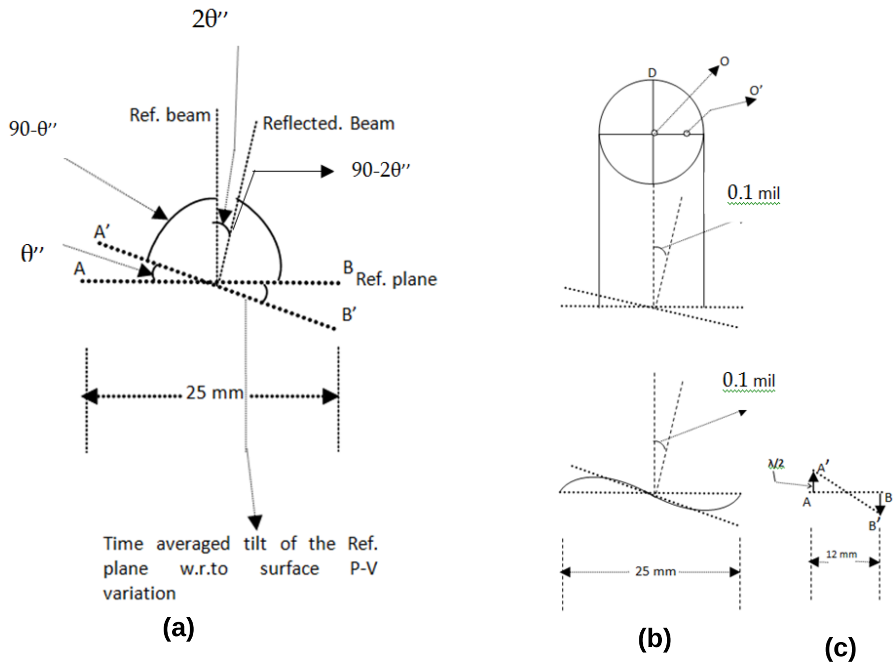


Figure 4. (a) Time averaged tilt of the Ref. plane due to dynamically varying form error of mirror surface, (b) Surface P-V variations of 1λ over 25 mm of the mirror surface, (c) Surface P-V variation of ±λ/2 considered over 6 mm from the midpoint of Ref. plane AB on either side, causes 0.05 mil tilt in the Ref. plane.

material. The variation of surface contour (P-V value) in the ratio 1:2 is observed for a change in temperature from 30 to 55°C. The maximum permissible figure distortion within the working temperature range should be such that the alignment error due to wavefront distortion in the optical path for the set configuration remains within specified limits.

THEORETICAL ESTIMATION OF ORS ALIGNMENT ERROR DUE TO MIRROR SURFACE P-V VARIATIONS

Surface P-V variations of the mirror 'B' (in Figure 1) due to thermal instability would cause a tilt in the reflected wavefront (virtual dis-positioning of the mirror surface) and thereby, add an error to the actual measurement by the ORS. Since the pointing reference measurement is done using reflected light from the mirror surface, any tilt of the surface would cause the reflected beam to deviate at twice this angle. Figure 4(a) and (b) show the geometrical considerations used for estimating the alignment error introduced in ORS measurements. It is seen that P-V variations to the extent of 0.625 µm (~ 1 λ for He-Ne laser source) over 25 mm of the mirror surface would result in an angular tilt of θ'' = 10" (0.05 mil) of the Ref. plane AB which would cause an ORS measurement error of θ'=2θ''= 0.1 mil. This is arrived at by considering a PV variation of ± λ/2 over the reference plane AB≈12 mm as shown in Figure 4(b). The peak and valley points lie ≈ 6 mm from the midpoint of AB at A and B, respectively causing the reference plane AB to tilt by 0.05 mil to A'B'. If dynamic variation in the surface figure with temperature is of two to three times its initial value, is taken into consideration, the measurement error of the ORS can be as much as 0.3 mil at the highest operating temperature. This implies that for realizing an ORS with a measurement accuracy of < 0.1 mil over the operating temperature range, the initial surface figure of the mirror should be better than λ/4 over 25 mm size at room temperature. Hence a proper selection of the mirror material having a high dimensional stability (low coefficient of thermal expansion) and its surface preparation for high optical flatness are both equally important for the stable performance of a high accuracy ORS. The theoretical notion presented here agrees well with the experimental results presented in Table 1.

MEASUREMENT TOOLS FOR OPTICAL ALIGNMENT DRIFT DUE TO THERMAL EFFECT

The autocollimator is widely used for measuring alignment drift in optical systems due to thermal effects, which thereby helps to establish the required alignment accuracy and stability. The basic autocollimator, shown in

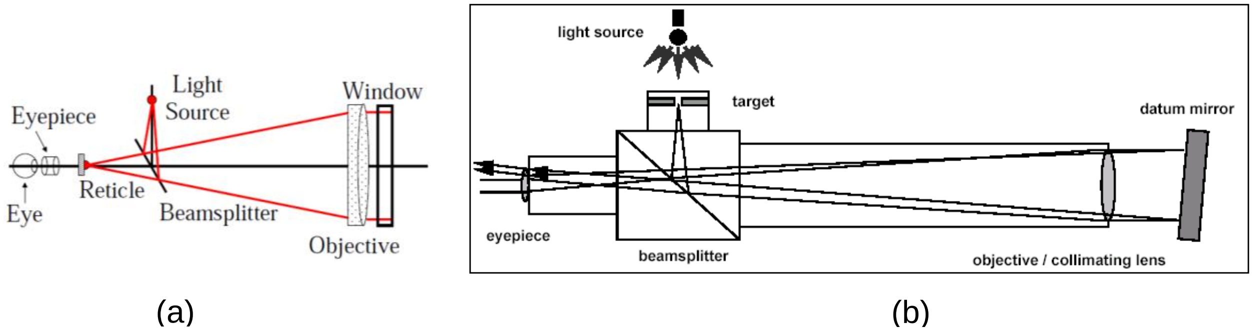


Figure 5. (a) Basic autocollimator, (b) Measurement of small angular deviations of a flat mirror.

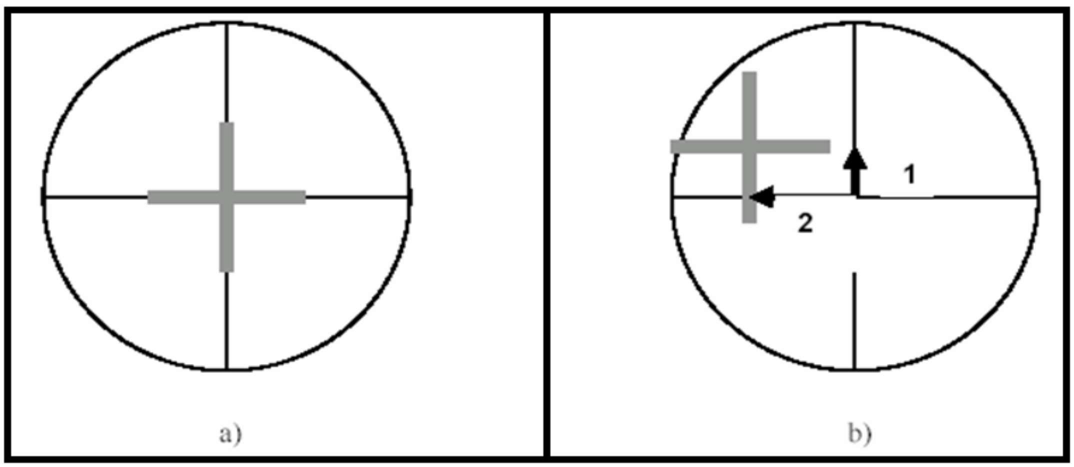


Figure 6. Visible Autocollimator - a) Return image aligned with autocollimator axis, b) Typical alignment drift in the return image due to thermal instability of mirror ‘B’ (Figure 1).

Figure 5(a), is a calibrated instrument that emits collimated light and requires its return from a flat mirror like surface. It is used to measure small angular deviations of a flat mirror as shown in Figure 5(b). Visible autocollimators project a target, usually an illuminated reticle placed at the focal plane of the autocollimator OG, and the return target is imaged in an eyepiece for viewing. When the autocollimator is aligned with the mirror, the return target coincides with the reference reticle, as shown in Figure 6(a).

If the ORS has alignment issues over temperature, tests can be run on various components to measure their sensitivity to temperature changes. Dielectric mirrors, beam splitters, beam expanders etc., are some components that are easy to test since they all pass collimated light in and out. This allows the autocollimator to measure small angular deviations in the optical path with respect to a reference. The observed change in the spacing between the return target and the reference reticle with change in temperature as shown in Figure 6(b) gives a measure of thermal stability of the ORS. The following case studies reveal the magnitude of alignment error caused in the optical path of the ORS due to temperature dependent surface figure variation of the mirror ‘B’ (Figure 1).

Case 1 (Mirror 1)

The measurements were done on a mirror having a small initial form error of 0.4 λ at 632.8 nm. Figure 7(a) shows the mirror surface figure at 25°C when it is in the initial alignment configuration of ORS. The surface figure changes from 0.4 to 0.7 λ (P-V), when the temperature of mirror surface raises from 25 to 60°C (Figure 7b). The variation in the surface figure due to change in temperature imparts an angular error of about 0.02 and 0.04 mil in the vertical and horizontal planes respectively.

Case 2 (Mirror 2)

Figures 8 to 10 show the measurements done on a

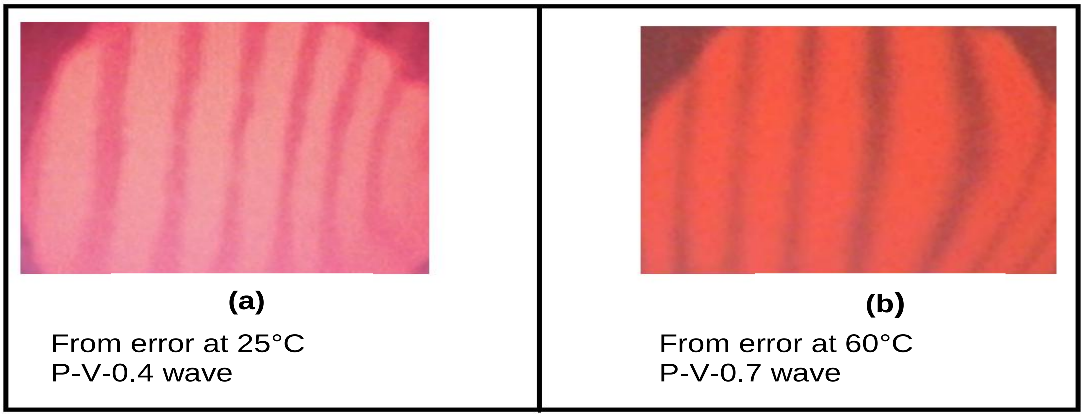


Figure 7. Variation of mirror surface figure with temperature.

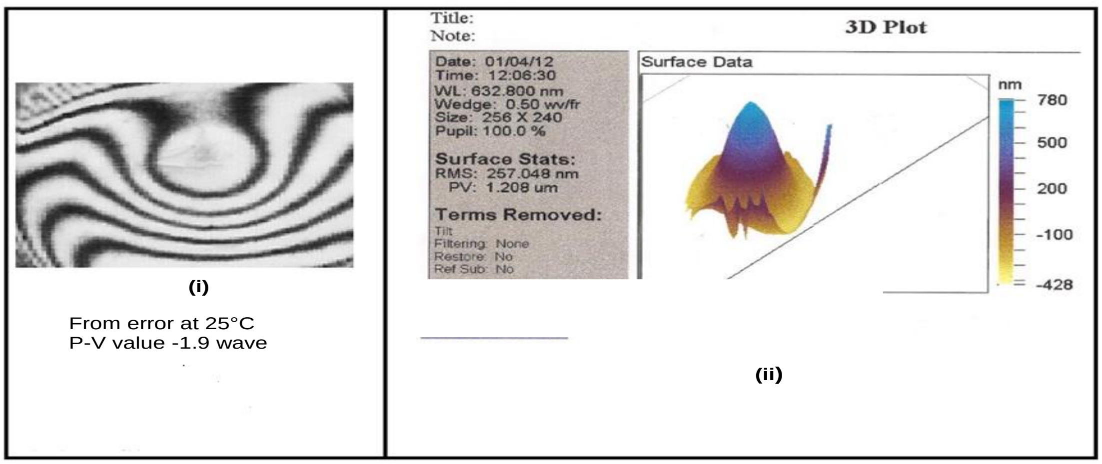


Figure 8. Variation of mirror surface figure with temperature.

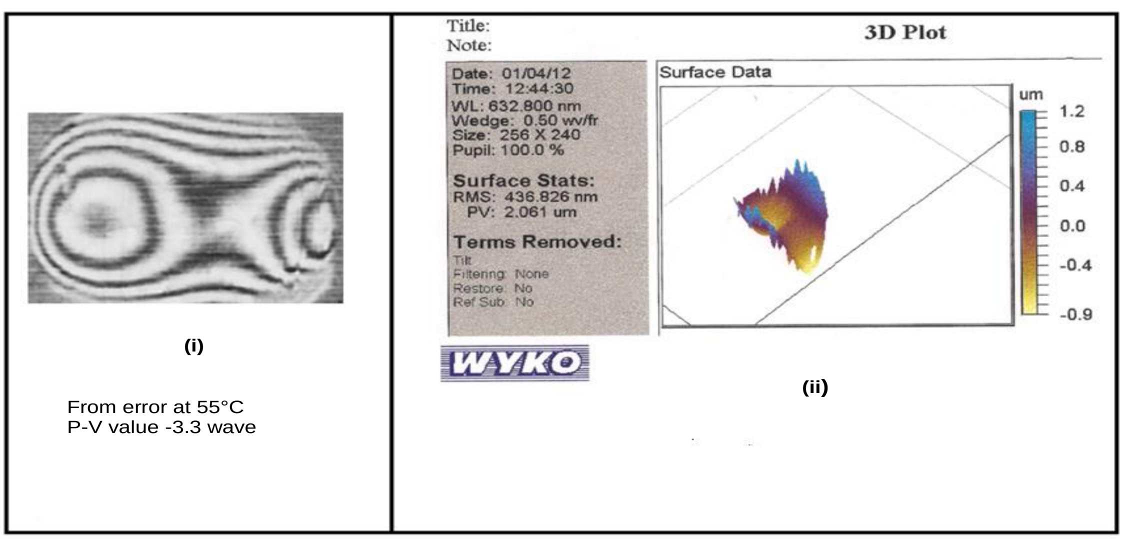


Figure 9. Variation of mirror surface figure with temperature.

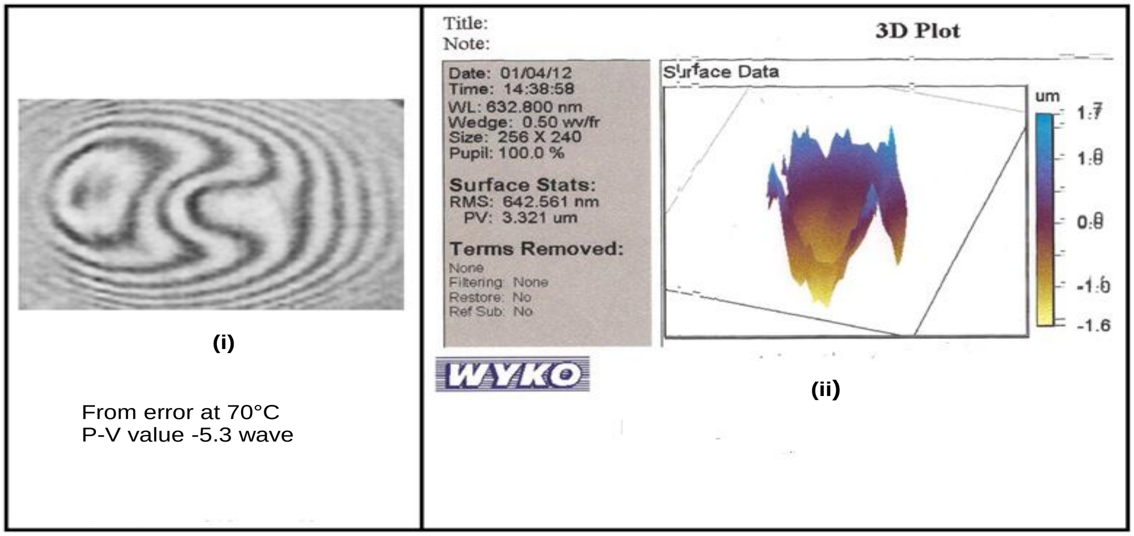


Figure 10. Variation of mirror surface figure with temperature.

Table 1. Variation of beam alignment error with change in surface figure.

Mirror surface temp (°C)	Surface figure measure at 632.8 nm (P-V value in λ)	Beam alignment error as shown in Figure 6(b) (mils)	Surface figure References
25	1.9	Initial (0.00, 0.00)	Figure 10 (i) and (ii)
55	3.3	(0.09, 0.14)	Figure 11 (i) and (ii)
70	5.3	(0.29, 0.22)	Figure 12 (i) and (ii)

Table 2. Surface figure tolerance for a specific type of application

Tolerance	Loose	Commercial	Precision	Ultra-precision
Power / Irreg.	10/5	5/2	3/1	1/0.25

second mirror having a large initial form error of 1.9 λ (P-V value 1.208 µm) at 25°C when it is in the initial alignment configuration of the ORS. The mapping between the surface figure change with temperature and the measurement of beam alignment error is summarized in Table 1. Table 2 gives the general guideline to be followed on surface figure tolerance, specific to the type of application of optics. The total surface figure is commonly specified in terms of *"power/irregularity"* in fringes.

Conclusion

Opto-mechanical reference systems used in scientific and military applications should have excellent thermal stability for maintaining their pointing accuracy as they will be exposed to large environmental temperature changes during their operational life. It is shown that the surface figure of the mirror material and its variation with temperature can cause alignment drift in the ORS and thus reduce its measurement accuracy. The spatial distribution of surface contour P-V variations of the mirror surface will determine ORS measurement error in the azimuth/ elevation planes. Experiments carried out with different mirror samples show that measurement error to the extent of 0.3 mils can occur at high temperatures. This is in good agreement with the theoretical estimations shown, for an initial surface figure of λ (He-Ne) over 25 mm of mirror surface and its excursion of 2 to 3 times with temperature. For achieving high measurement accuracies with the ORS (< 0.1 mil) over the operating temperature range, the induced error due to thermal instability has to be made as small as possible. This can be done by increasing the optical flatness of the mirror surface to better than λ /4 and by choosing a suitable mirror material with higher dimensional stability.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge valuable discussions with my senior colleagues in DRDO, who have given immense support for successful completion of this paper. This work was supported by the Director, Combat Vehicles Research and Development Establishment (DRDO), Chennai, India.

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