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Angular Alignment Testing of Laser Mirror Mounts Under Temperature Cycling

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Acknowledgments

This paper is dedicated to the memory of Kyle Bullock, who passed away suddenly near the end of this research effort. His hard work and friendly attitude will long be remembered by his coworkers. Also, thanks is given to Rasheed McWilliams, who carried out the analysis of the data presented here.

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Abstract

A number of commercial and custom-built laser mirror mounts were tested for angular alignment sensitivity during temperature cycling from room temperature (20°C) to 40°C. A Nd:YAG laser beam was reflected off a mirror that was held by the mount under test and was directed to a position-sensitive detector. Horizontal and vertical movement of the reflected beam was recorded, and the angular movement, as a function of temperature (coefficient of thermal tilt (CTT)) was calculated from these data. In addition, the amount of hysteresis in the movement after cycling from room temperature to 40°C and back was determined. All commercial mounts showed greater angular movement than the simpler National Aeronautics and Space Administration Lidar Atmospheric Sensing Experiment (NASA LASE) custom mirror mounts.

Introduction

Laser systems incorporate mirror mounts to direct precisely the laser beam throughout the optical system. A problem with mirror mounts occurs when the environment changes, for example, between time of calibration and operation of the laser system. A variation in the temperature between calibration and operation can affect the system optical alignment and cause the performance to be less than adequate for the desired measurement. Laser cavities are especially sensitive to the alignment of the laser mirrors; great care must be taken to ensure that temperature variations have not misaligned the laser mirror mounts, which, in turn, could result in significantly lower laser energy.

Optical receivers and laser systems for remote sensing typically require stringent tolerances on the alignment of optical elements within the system. Both linear and angular alignment are important concerns, but angular alignment is most often the critical tolerance to control. The large, bulky optical and laser systems of the past used size and mass to control thermal and structural effects on the alignment of optical elements. As optical sensors and lasers have become more prevalent solutions to remote sensing problems, a trend leading to smaller and lighter systems both in aircraft and space-based systems has developed. In these smaller, lower mass systems, it is no longer practical to use large, massive structures to maintain the alignment of optical elements in the presence of thermal and vibrational loads. An example of the trend toward smaller, lighter electro-optical systems for remote sensing is the Lidar Atmospheric Sounding Experiment (LASE) instrument. LASE is a Differential Absorption Lidar (DIAL) system that fits into the ER-2 high-flying aircraft. The high power laser that is a critical part of this instrument must fit into a large suitcase. In addition, there are strict limitations on the mass of the laser. The laser design calls for a long, folded cavity and for the laser to be seeded by a laser diode. Both requirements place tens of microradian level tolerances on the angular stability of the optical elements within the laser. To complicate the design further, the laser must operate at 40°C, although alignment is performed while the mounts experience temperature gradients of 10°C to 15°C. Thus, the mounts for the LASE system must be small and lightweight yet allow less than 10 microradians of angular motion over a 20°C temperature swing.

This research effort focuses on determining the sensitivity of angular alignment to changes in temperature for several commercial and custom-built laser mirror mounts. The NASA LASE program has experienced misalignment problems in which laser alignment was performed at room temperature (20°C), but the laser was allowed to cycle between room temperature and 40°C. Therefore, these experiments will concentrate on measuring the change in angular alignment of several types of mirror mounts over the temperature range from 20°C to 40°C. From these data, an indication of the amount of angular misalignment (as a function of temperature change) can be determined, and as a result, a more temperature-insensitive optical mount can be designed.

Experimental Setup

In order to make the measurements described above, it was necessary to test the mount in a thermally controlled, evacuated environment. A chamber built to measure the coefficient of thermal expansion (CTE) of optical structures was used. Temperature cycling was accomplished by using a copper tubing heat exchanger connected to a constant temperature circulator (fig. 1). Fluid can be circulated through the copper tubing at temperatures ranging from 0°C to 100°C, depending on the predetermined setting. To reduce the heating time of the optical mount, a heat lamp behind the mount helps the mount reach the desired temperature. Ceramic posts or feet extend from the bottom of the chamber through holes in the copper heat exchanger to support a ceramic breadboard. The breadboard surface is lined with threaded holes for securing the laser mount to be tested. For the tests, all mounts were secured to a 6- by 1.75- by 1/2-inch thick stainless steel plate. Figure 2 depicts the overhead view of the test setup. A diode-pumped YAG laser (1.06 μm) (Lightwave Electronics, Inc., 120-01A) was mounted on an optical table outside the chamber. The beam from the YAG laser enters through a window and reflects off the mirror being tested and through a second window to a position-sensing detector (PSD) mounted on a second optical table. The distance between the mount and the PSD is between 3.4 and 3.8 meters, depending on the mount tested. The United Detector Technology (UDT) Model 531 Optical Position Monitor (10 mm by 10 mm) was used to detect the movement of the beam in the horizontal (x) and the vertical (y) dimensions.

As the temperature within the chamber changes, the optical mount material expands or contracts, causing the mirror surface to tilt. This tilt causes the position of the laser beam on the PSD sensor to move (measured in micrometers). By using this information and by knowing the distance between the mount and the detector, the angular movement for the mount can be determined (measured in microradians) by dividing the detected beam movement by the distance between the UDT detector and the mirror mount.

This measurement system is limited by a number of error sources. These include uncertainty in the angular and linear stability of the platform which supports the device under test, steering of the beam by variations in the index of refraction of the atmosphere and the laser crystal, linear stability of the detector, the relative positions of the platforms supporting the laser and the detector, and by detector and electronic noise in the PSD. All these error sources are enhanced by thermal fluctuations; thus the laser and PSD are located outside the thermal vacuum chamber. Tests to quantify the combined errors of laser pointing, linear positional stability of the detector, relative platform stability, and movement of the PSD were performed by pointing the laser at a quartz mirror cube and separating the laser and detector by a distance equal to that used in the mount testing. These tests indicated that an angular resolution of approximately 40 by 15 microradians was achievable (fig. 3). The detector itself had 3 microradians resolution in both the vertical and horizontal directions.

To begin a test, the mount was positioned in the chamber and secured to the stainless steel plate that was secured to the ceramic optical bench. The laser beam was directed to the mirrored surface so that the reflection exited the chamber through the second window approximately 90° from the first and then hit the position sensor. A thermocouple positioned in a small hole on the top of the mounts was used to record the mount temperature. After the chamber was pumped down to approximately 10 microradians, the vacuum pump was turned off. The fluid heater temperature was set to the desired temperature of 20°C (room temperature) to allow the chamber to reach steady state. The distance between the optical mount and the PSD sensor was recorded. The initial position of the laser signal on the detector was recorded, along with the signal intensity in microamps.

The time interval for a single test phase was 40 minutes, and the time interval between data points was 90 seconds. Once the test started, the actual fluid temperature and the fluid set temperature were recorded along with the time and the optical mount temperature. After enough data points were taken to show the trend, usually 5 to 10 minutes, the heat lamp in the chamber was turned on and the fluid temperature was increased to 40°C. Temperature measurements were taken at 20-minute intervals. Once the mount temperature reached 40°C, the heat lamp was turned off, and the fluid temperature was set to –20°C to reduce the time required to reach room temperature. Once the mount reached room temperature (20°C), the cycle was repeated with the heating phase for the desired number of cycles, usually two heating and two cooling cycles for each mount. All mirror mounts tested are shown in table 1. The mounts fall into two major groups: custom-designed mounts and commercial mounts. The characteristics of some of the custom-designed and commercial mounts are presented in table 2. Mirror cube test results are also presented in table 2.

Experimental Results

Figures 4 through 18 show the amount of mirror misalignment given by the x and y movements of the YAG laser beam for each mount as the temperature cycled from 20°C to 40°C. Approximately four cycles were performed on each mount to determine any hysteresis effects. Data points were connected to give the line curves that are shown. All mount tests were started from room temperature condition.

Before any tests were run on the optical mounts, a 1-inch cube mirror was placed inside the evacuated chamber and was temperature cycled. Figure 3 shows the results at the beginning, and figure 19 shows the results at the end of the experimental program. Since the cube had no moving parts, this test gave the baseline system stability (chamber, optic tables, laser stability). The UDT detector position resolution was about 3 microradians.

NASA LASE Aluminum Mount

The NASA LASE small aluminum mount holds a 1-inch-diameter mirror. Two surfaces, one holding the 1-inch-diameter mirror, are held in frictional tension with two screws. No finger adjustments are on these mirrors; screws are alternatively loosened and tightened to move the mirrors in the x and y directions. This simple adjustment was expected to provide a stable mirror mount design. The total displacement observed (fig. 4) was approximately 50 microradians in the *x* direction and 65 microradians in the *y* direction.

NASA LASE Ceramic Mount

The NASA LASE ceramic mount is the same design as the aluminum mount but is made of a ceramic material (NZP), which is manufactured by LoTEC Inc. of Salt Lake City, Utah. The total displacement observed was approximately 70 microradians in the *x* direction and 125 microradians in the *y* direction.

NASA LASE G-10 Mount

The NASA LASE G-10 mount is the same design as the aluminum mount but is made of G-10 composite material. The total displacement was 70 microradians in the *x* direction and 270 microradians in the *y* direction.

Oriel Mount 17720

The 2-inch Oriel 17720 optical mount (fig. 7) is adjusted by tapered screws that move the mirror in the horizontal and vertical directions. The total movement in the *x* direction was 175 microradians and the total movement in the *y* direction was 525 microradians.

Oriel Mount 17500

The 2-inch Oriel 17500 mount (fig. 8) is constructed very simply. Two plates, one holding the mirror, are separated by rubber bushings. Hex head bolts are used to adjust the horizontal and vertical directions by applying pressure on the rubber bushings. The total movement in the *x* direction was about 300 microradians and the total movement in the *y* direction was 600 microradians. This mount showed no tendency to go back to its original position when heat was removed, as compared to the other mounts.

Lee's Mount LM3-2027-0

The 2-inch Lee's LM3-2027-0 mount (fig. 9) has two aluminum plates, one holding the mirror and the other having three 80-pitch adjustment screws. Two springs give tension between the mirror plate and the screws. The tips of the screws have steel balls, one of which rests on a flat insert. This mount had a total *x* movement of 150 microradians and a *y* movement of 250 microradians. Of the commercial mounts tested, this mount gave less misalignment with temperature cycling and also had good hysteresis because it usually returned to its original position when heat was removed.

Newport U100-A Mount

The 1-inch Newport U100-A mount (fig. 10) encloses only half the mirror. Two fine-thread pitch screws are used for the mirror plate adjustment. Two springs give the necessary tension. The total *x* misalignment was about 225 microradians and the *y* misalignment was 300 microradians. A hysteresis effect was noted when the heat was removed.

Newport GM-2 Mount

The 2-inch Newport GM-2 mount (fig. 11) has spring tension with two small adjustment screws. The horizontal mirror adjustment pivots around the centerline (unique to this mount) of the mirror axis. The total *x* misalignment was 80 microradians and the *y* misalignment was 450 microradians.

New Focus 9852 Mount

The 2-inch New Focus 9852 mount (fig. 12) has three adjustment screws with spring tension. A steel ball at the end of each screw rests on a small sapphire insert in the mirror plate. The total *x* misalignment was 500 microradians and the *y* misalignment was also 500 microradians. The mount showed large misalignments during heating, but when heating was turned off, the mount usually drifted to its original position.

New Focus 9853 Mount

The 2-inch New Focus 9853 mount (fig. 13) is basically the same construction as the 9852 mount except that only one spring provides the tension between the mirror plate and the adjustment screws. The total *x* misalignment was 250 microradians and the *y* misalignment was 200 microradians.

New Focus 9807 Mount

Figure 14 shows the New Focus 9807 1-inch mount characteristics with temperature cycling. This mount uses three screws with two tension springs. The screw balls rest on sapphire inserts in the mirror plate. Interestingly, the hysteresis effect improved after initial heating. After the initial heating, the total misalignment was about 100 microradians in the *x* direction and 300 microradians in the *y* direction.

New Focus 9871 Mount

The New Focus 9871 mount (fig. 15) that holds a 1/2-inch mirror was the smallest mount tested. Three Allen screws (Allen Manufacturing Company) are used with two springs for tension on the mirror plate. The total *x* misalignment was 350 microradians and the *y* misalignment was 1400 microradians.

Thorlabs GF-100 Mount

The Thorlabs GF-100 mount (fig. 16) is a 1-inch version of the Oriel 17720 mount. The total misalignment increased with temperature cycling and was 525 microradians in the *x* direction and 450 microradians in the *y* direction.

Thorlabs KM1-SH Mount

The inexpensive Thorlabs KM1-SH 1-inch mount that uses two Allen screws and two springs for mirror-plate tension is shown in figure 17. A steel ball is used for the fixed point. The total *x* misalignment was 450 microradians and the *y* misalignment was 1400 microradians. The mount continuously became misaligned during temperature cycling.

Klinger/Newport SL25.4BHc Mount

The Klinger/Newport SL25.4BHc 1-inch steel mount (fig. 18) has four springs that provide tension on the mirror plate. The total *x* misalignment was 300 microradians and the *y* misalignment was 120 microradians.

Concluding Remarks

All optical mounts that were tested experienced angular movement greater than the baseline system measurement capability when the temperature cycled from room temperature (20°C) to 40°C. All mounts showed some hysteresis effects, and no mount ever returned to its original position after temperature cycling. Some mounts simply kept moving with temperature cycling, never attempting to return to their original position.

A listing is presented of the optical mounts tested and the measured results. The *x* and *y* axis coefficients of thermal tilt (CTT) were calculated by dividing their angular movement in microradians by the temperature increase. In general, larger mounts had a lower CTT than small mounts. Also, the simple adjustment of the National Aeronautics and Space Administration Lidar Atmospheric Sensing Experiment (NASA LASE) mounts resulted in lower CTT than did the easily adjustable commercial mounts.

The *x* and *y* axis hystereses were the difference in the *x* and *y* positions after going up and back down to room temperature. Again, the simple NASA LASE mounts showed lower hysteresis effects than the commercial mounts.

The NASA LASE and some of the commercial mounts were compared. Of the NASA mounts, all similarly constructed, the aluminum and ceramic mounts were superior to the G-10 (composite) material mount. Of the commercial mounts, the Lee’s mount was excellent in low hysteresis effect, but the New Focus 9853 was excellent in movement in terms of microradians/°C. All commercial mounts showed greater movement/°C and hysteresis effect than the simpler NASA LASE mounts.

The mirror cube test result is also given. The results of the first and last test are averaged. These results indicate the measurement system sensitivity. All mounts had greater movement than the mirror cube results.

From these tests, commercial mounts that are easily adjustable show more movement with temperature change than simple lockable mounts such as the NASA LASE mounts. The Oriel 17500 mount that used rubber bushings for tension showed the greatest hysteresis effect and thus should not be used for laser systems requiring temperature cycling.

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April 10, 1997

Table 1. Mirror Mount Characteristics

Manufacturer	Model	Material	Mirror size (diameter), in.	*x*-axis movement/ temperature change, microradians/°C	*y*-axis movement/ temperature change, microradians/°C	*x* hysteresis, microradians	*y* hysteresis, microradians
In house							
NASA	LASE	Al	1	1.6	3.2	5	44
NASA	LASE	Ceramic	1	2.1	0.5	14	20
NASA	LASE	G-10	1	2	7.4	47	50
Commercial							
Oriel	17720	Al	2	2.6	20.8	92	125
Oriel	17500	Al	2	6.7	4.9	203	300
Lee’s	LM3-2027-0	Al	2	5.3	12.7	35	0
Newport	U100-A	Al	1	9.2	8.1	46	140
Newport	GM-2	Al	2	0.7	14.2	47	100
New Focus	9852	Al	2	12.8	15.4	37	270
New Focus	9853	Al	2	2.1	1.1	165	100
New Focus	9807	Al	1	9.3	10.9	110	75
New Focus	9871	Stainless steel	1/2	12.6	41.9	250	25
Thorlabs	GF-100	Al	1	17.2	13.2	350	0
Thorlabs	KM1-SH	Al	1	7.6	44.4	194	449
Klinger/Newport	SL25.4BHc	Steel	1	11.5	0.6	190	49

Table 2. NASA and Commercial Mount Characteristics

Manufacturer	Model	Material	Mirror size (diameter), in.	*x*-axis movement/ temperature change, microradians/°C	*y*-axis movement/ temperature change, microradians/°C	*x* hysteresis, microradians	*y* hysteresis, microradians
In house							
NASA	LASE	Al	1	1.6	3.2	5	44
NASA	LASE	Ceramic	1	2.1	0.5	14	20
NASA	LASE	G-10	1	2	7.4	47	50
Commercial							
Klinger/Newport	SL25.4BHc	Steel	1	11.5	0.6	190	49
Lee’s	LM3-2027-0	Al	2	5.3	12.7	35	0
Newport	GM-2	Al	2	0.7	14.2	47	100
New Focus	9853	Al	2	2.1	1.1	165	100
Baseline							
Mirror cube	Test device	Glass	1	0.22	0.39	5	24

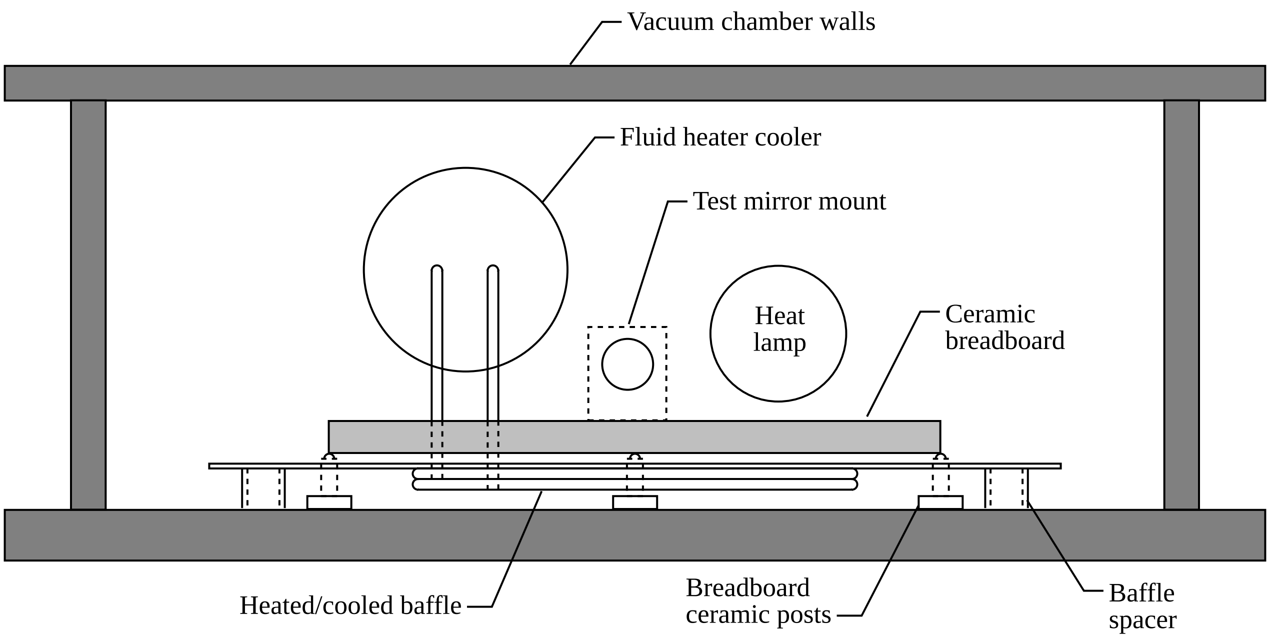

Figure 1. Vacuum chamber with internal components.

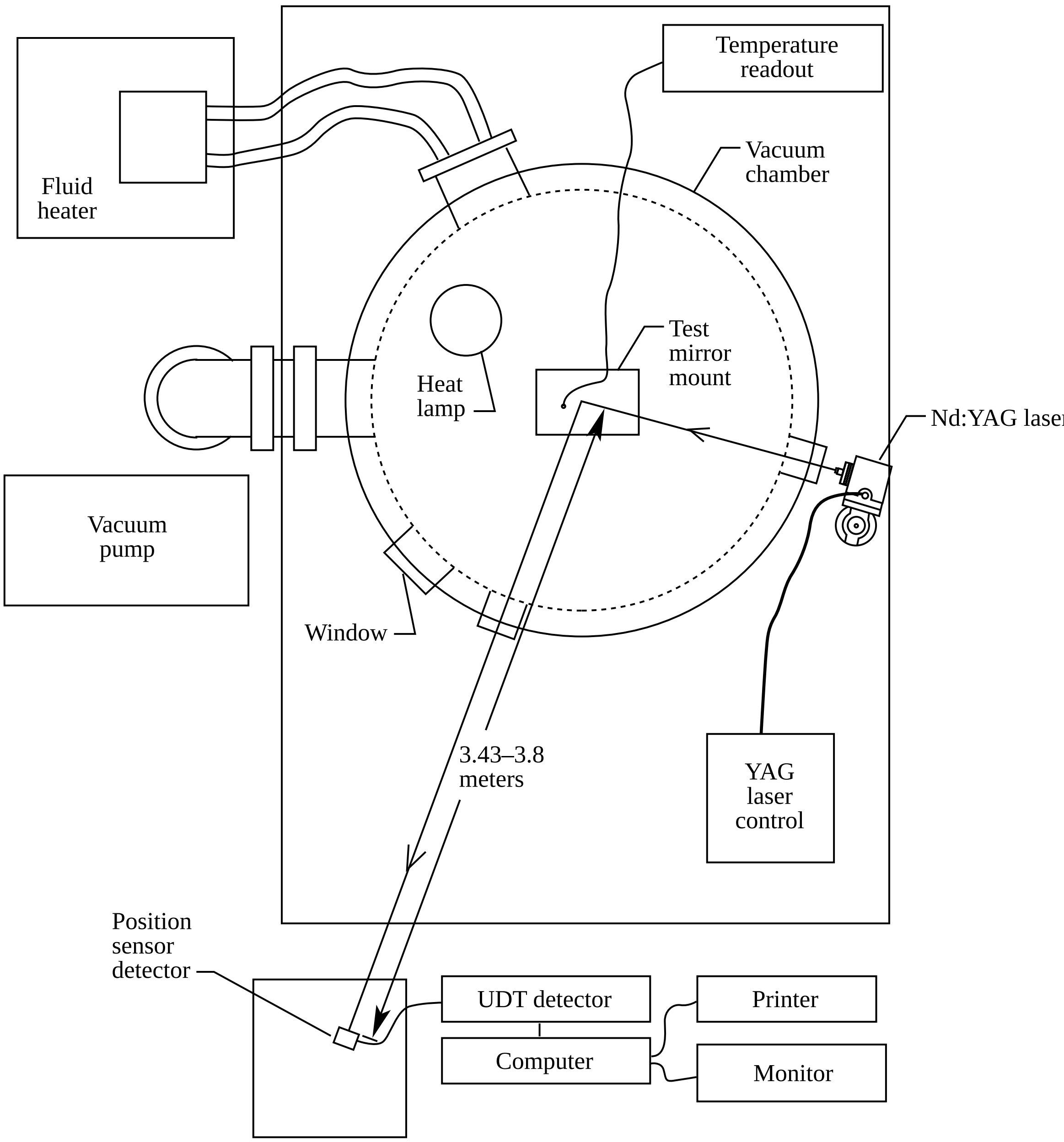

Figure 2. Overhead view of test setup.

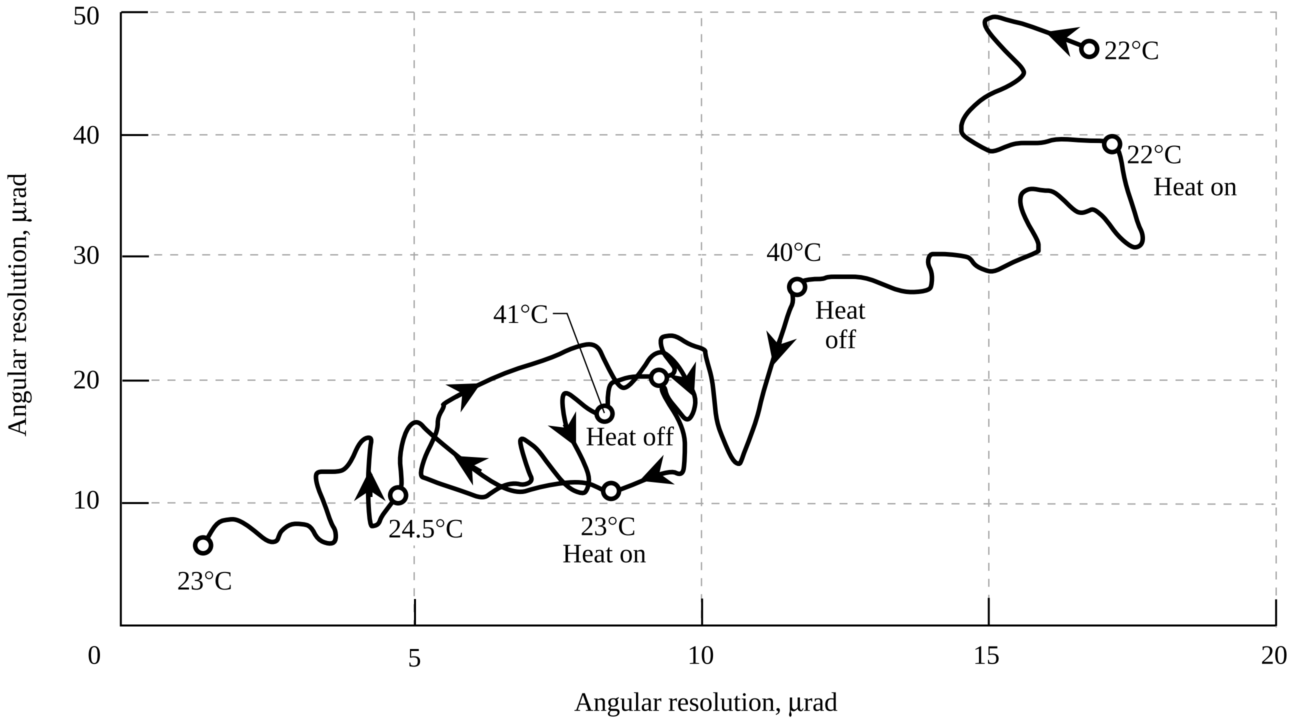

Figure 3. Glass mirror cube movement recorded to establish baseline sensitivity. The detector resolution was 3 μrad (much less than the system movement).

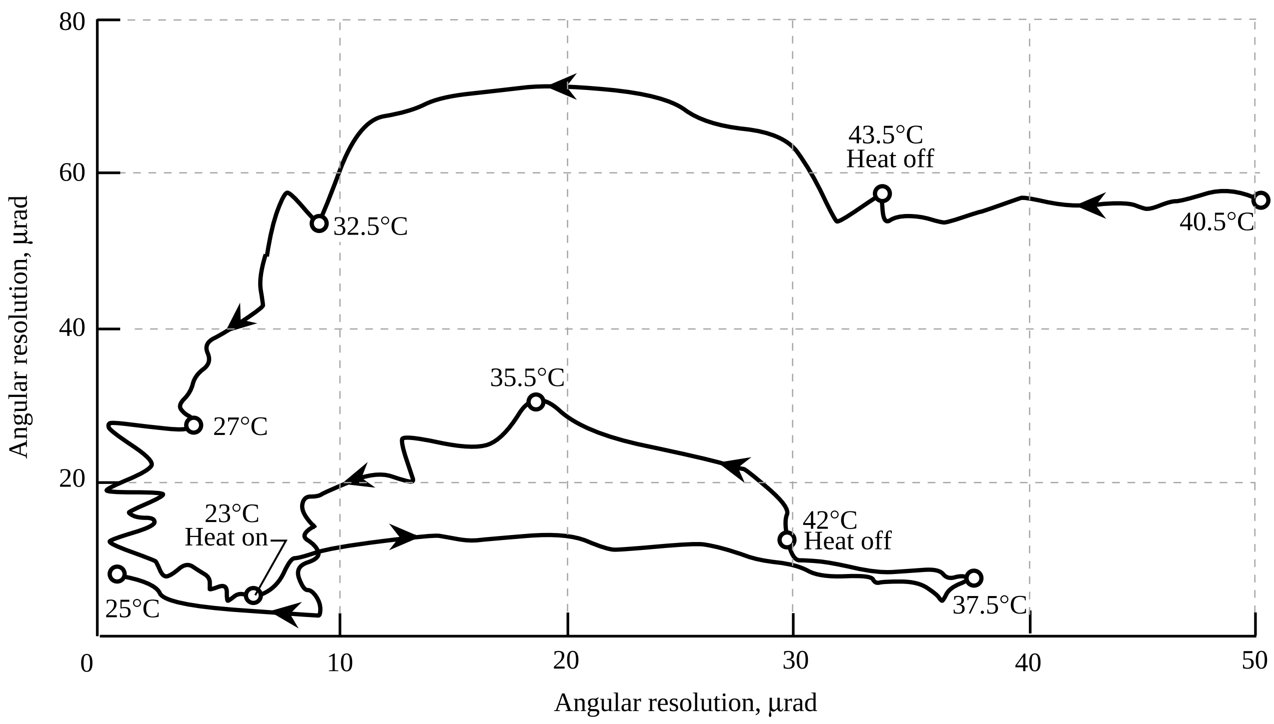

Figure 4. NASA LASE aluminum mount with lockable adjusters for *x* and *y* movement.

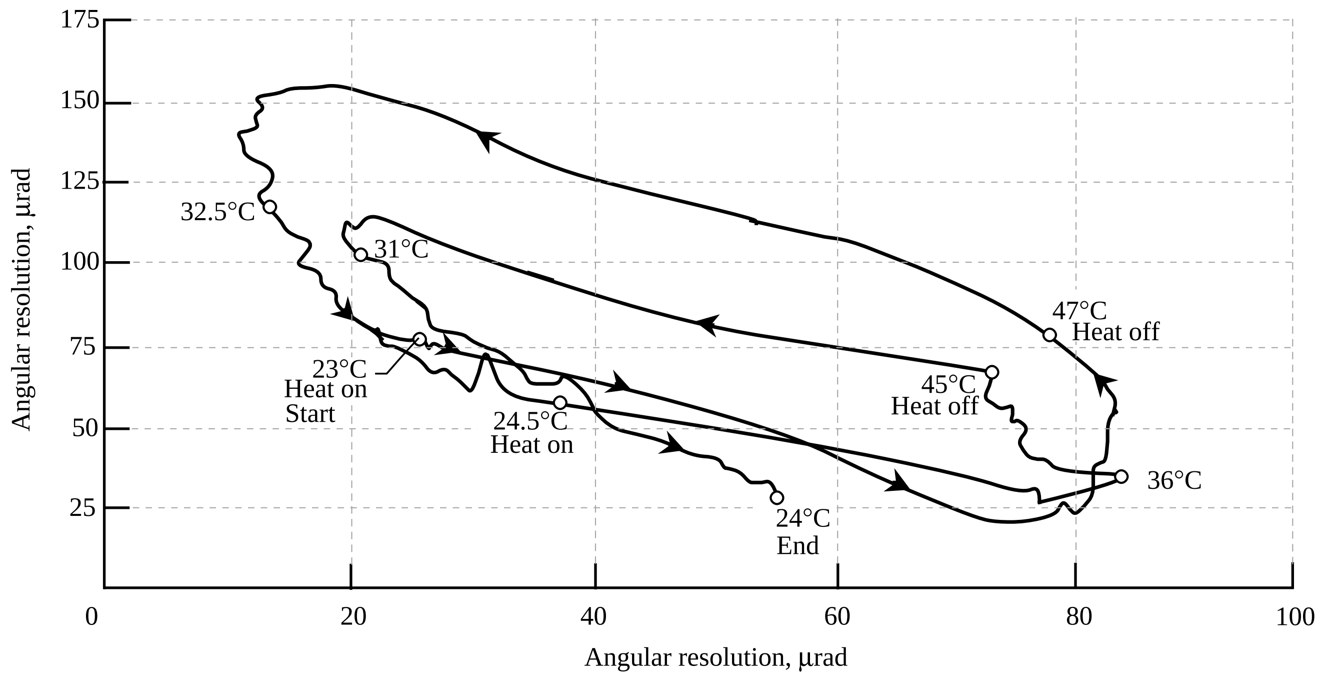

Figure 5. NASA LASE mirror mount made from ceramic material.

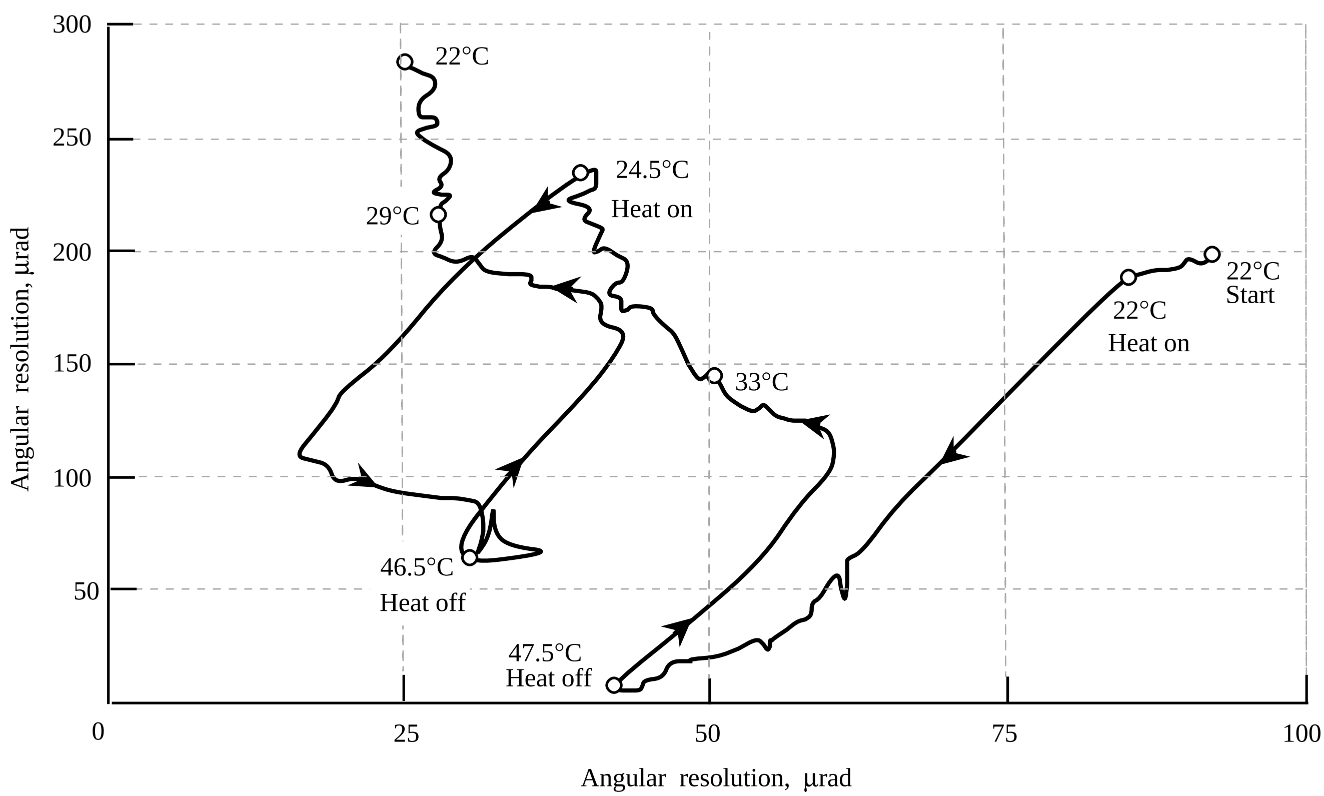

Figure 6. NASA LASE mirror mount made from G-10 material.

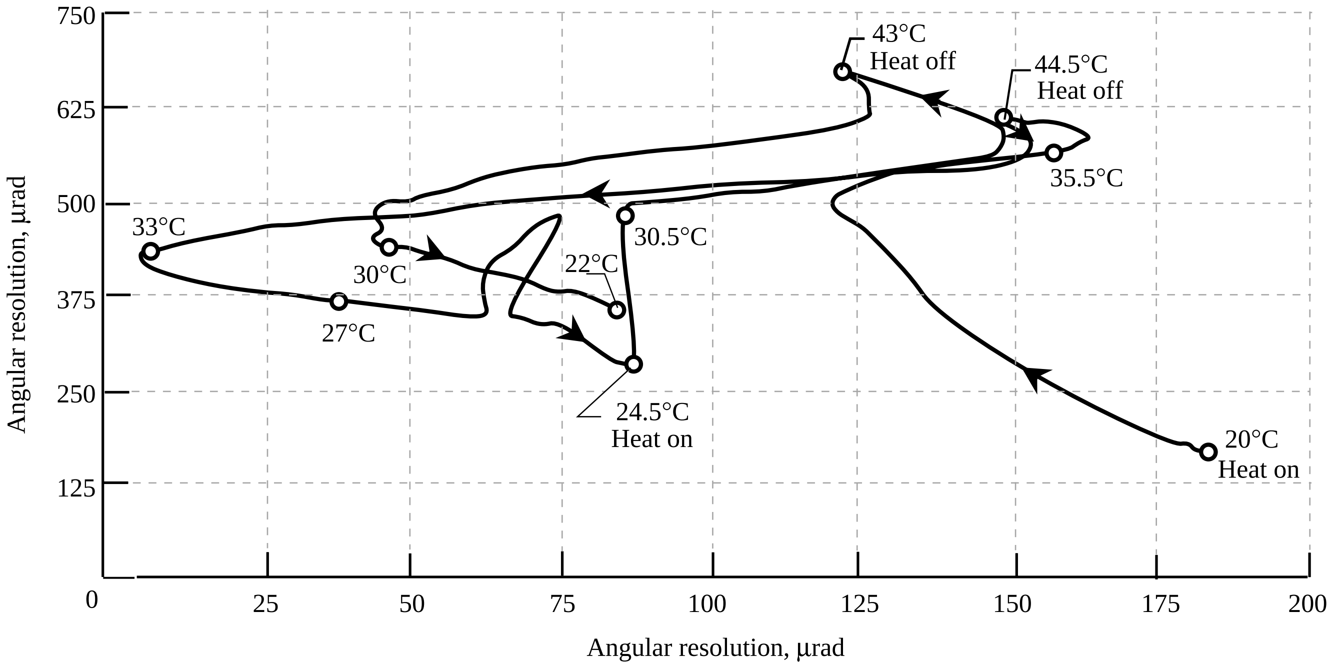

Figure 7. Oriel 2-in. mirror mount 17720 tested during temperature cycling.

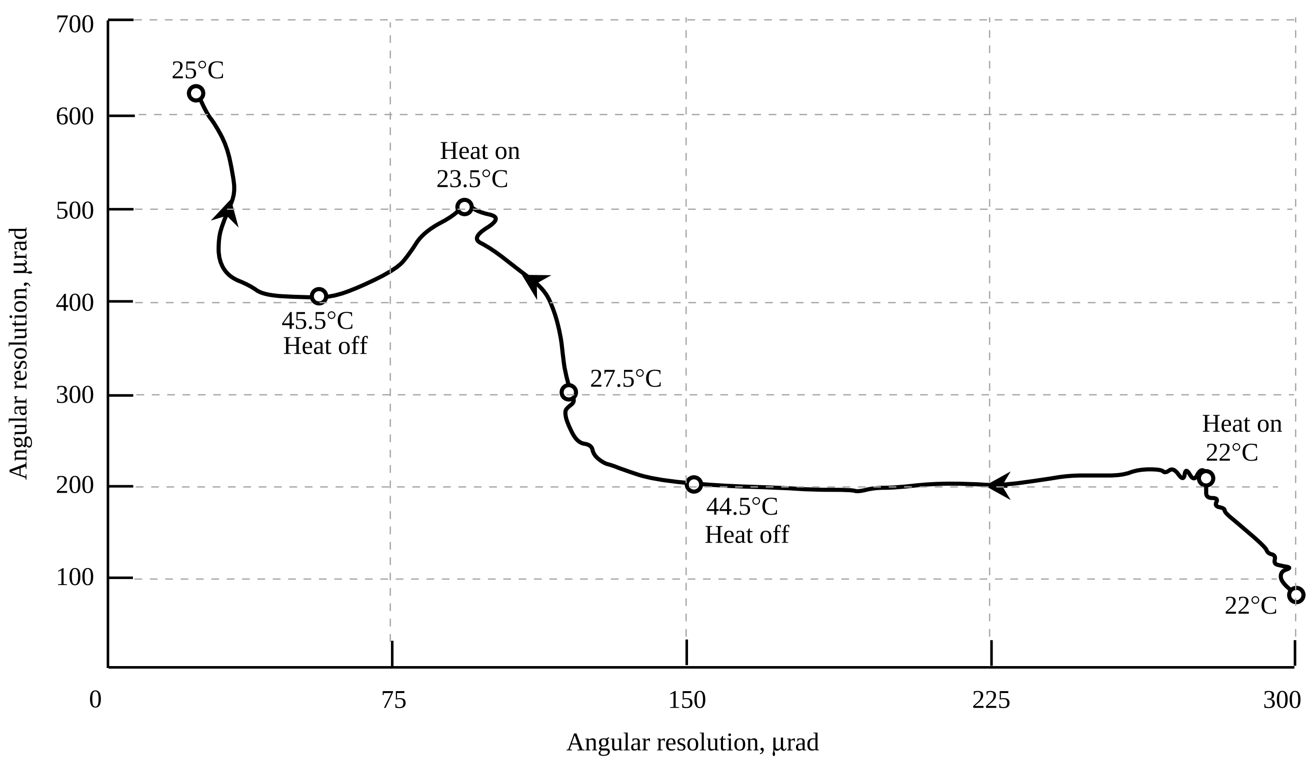

Figure 8. Oriel 2-in. mirror mount 17500 tested during temperature cycling.

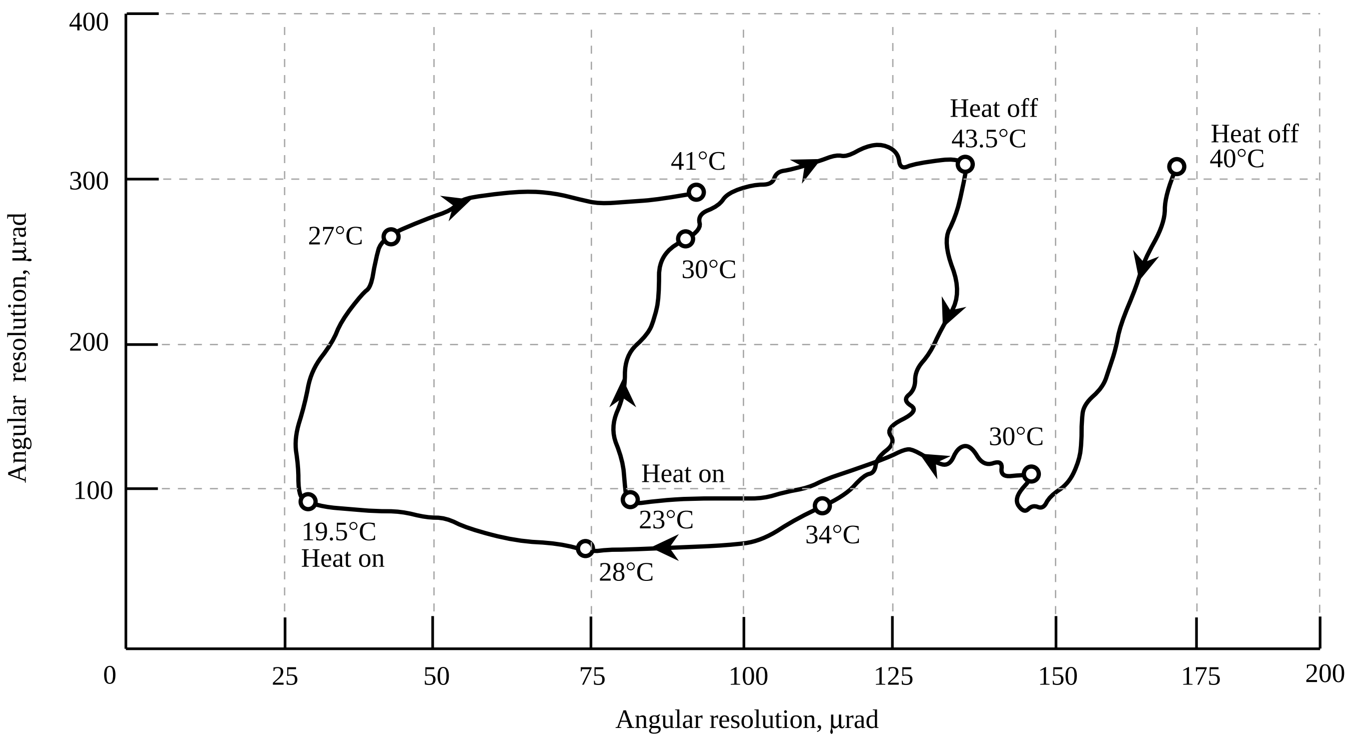

Figure 9. Lee's 2-in. mirror mount tested during temperature cycling.

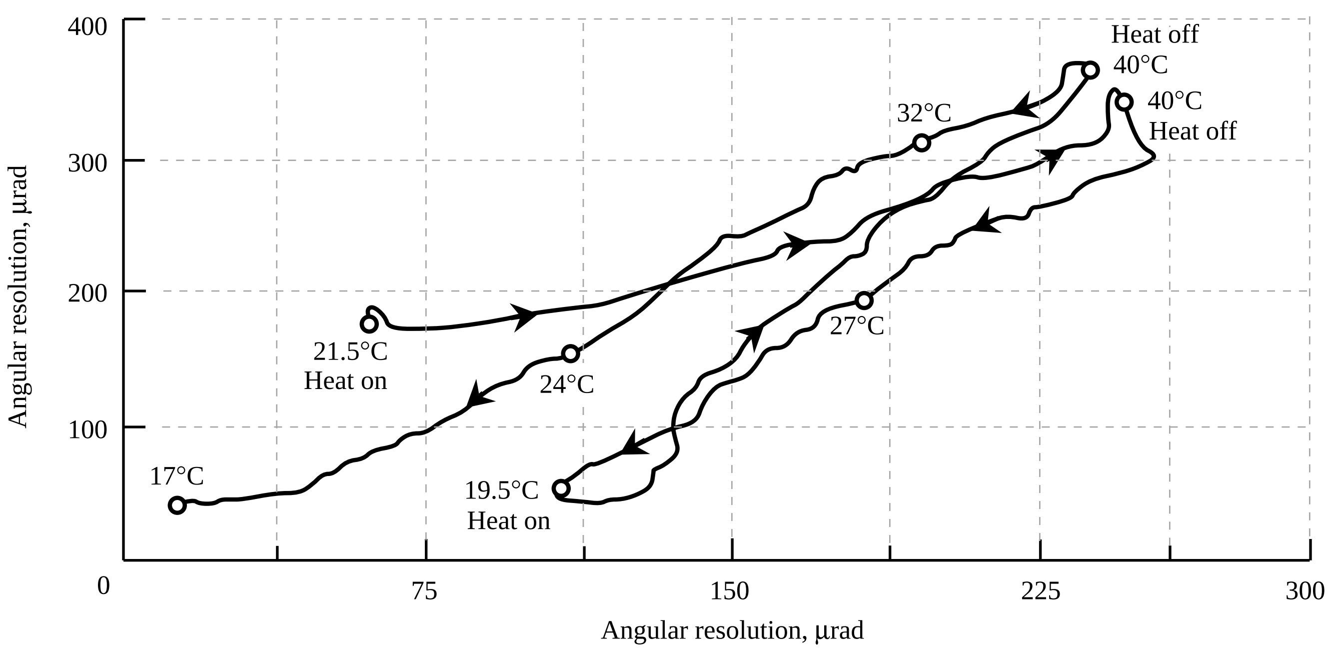

Figure 10. Newport half mount U100-A tested during temperature cycling.

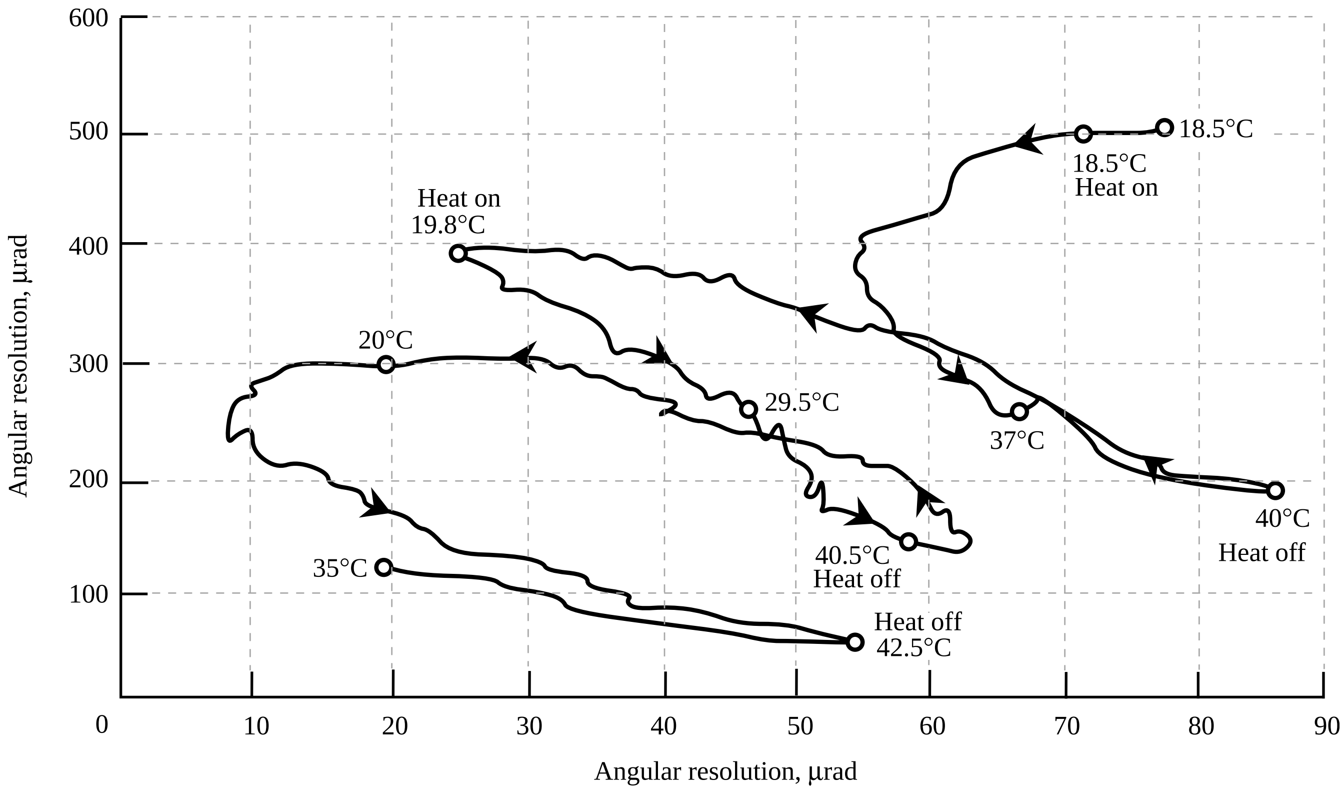

Figure 11. Newport GM-2 2-in. mirror mount tested during temperature cycling.

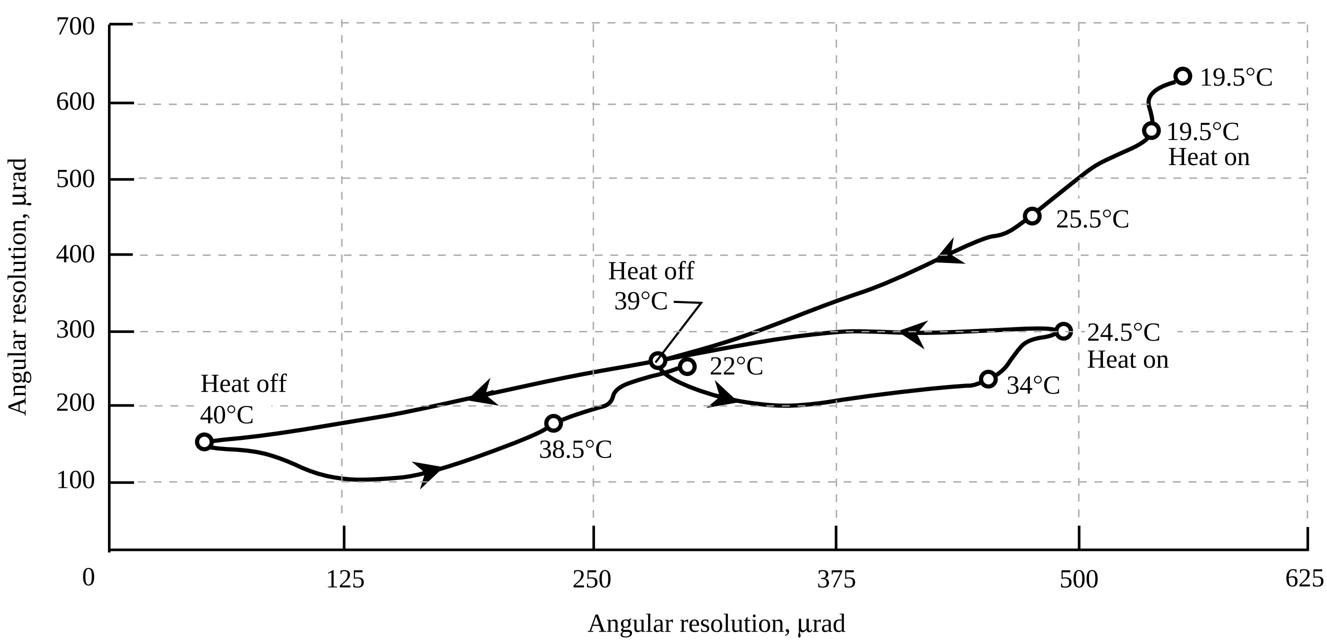

Figure 12. New Focus 2-in. mirror mount 9852 tested during temperature cycling.

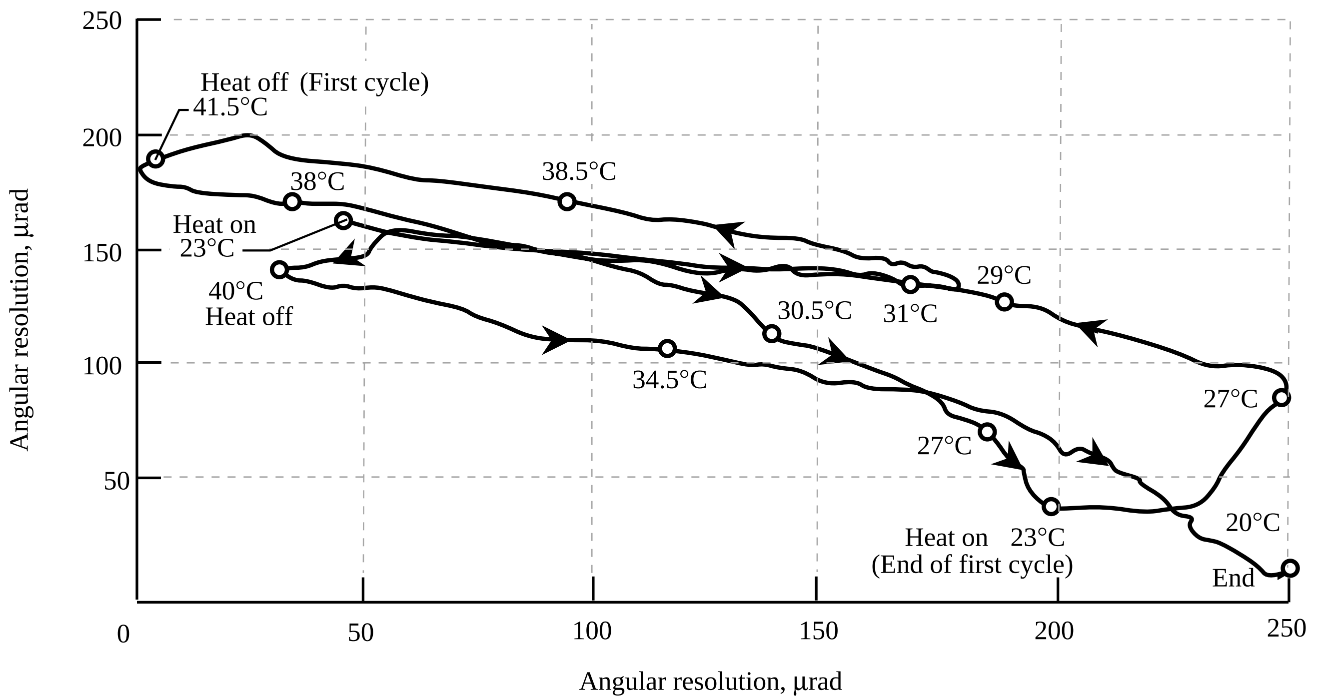

Figure 13. New Focus 2-in. mirror mount 9853 tested during temperature cycling.

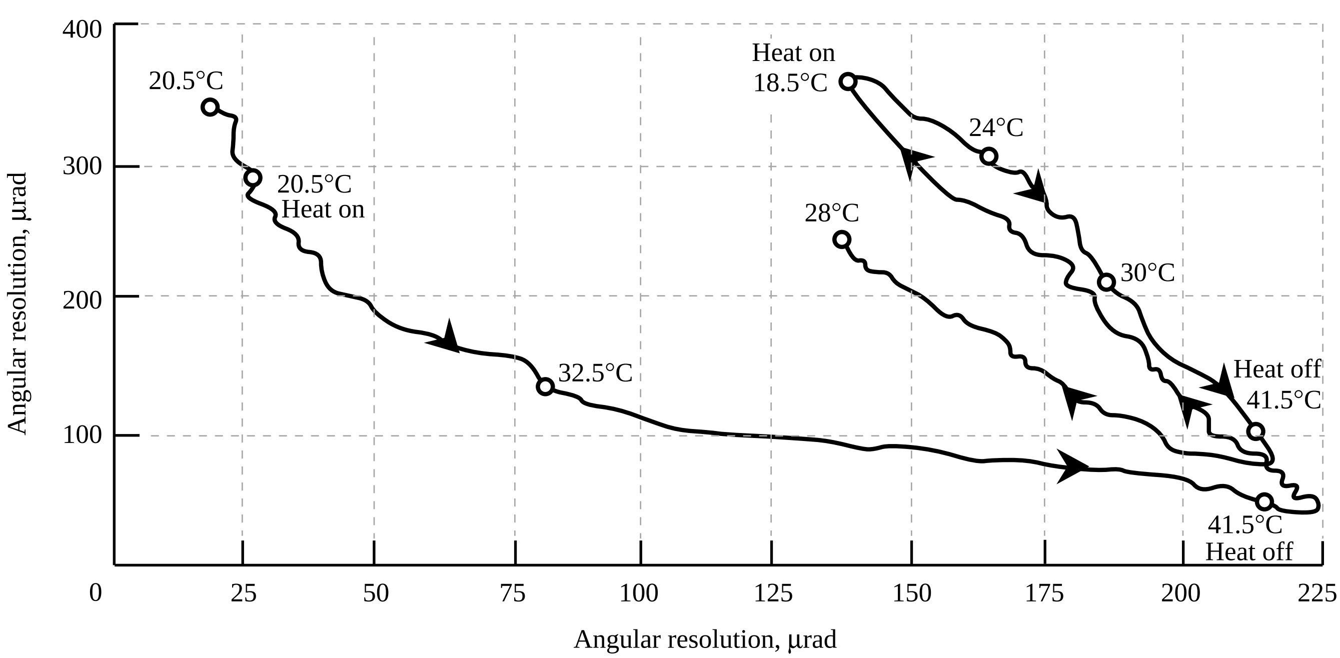

Figure 14. New Focus 1-in. mirror mount 9807 tested during temperature cycling.

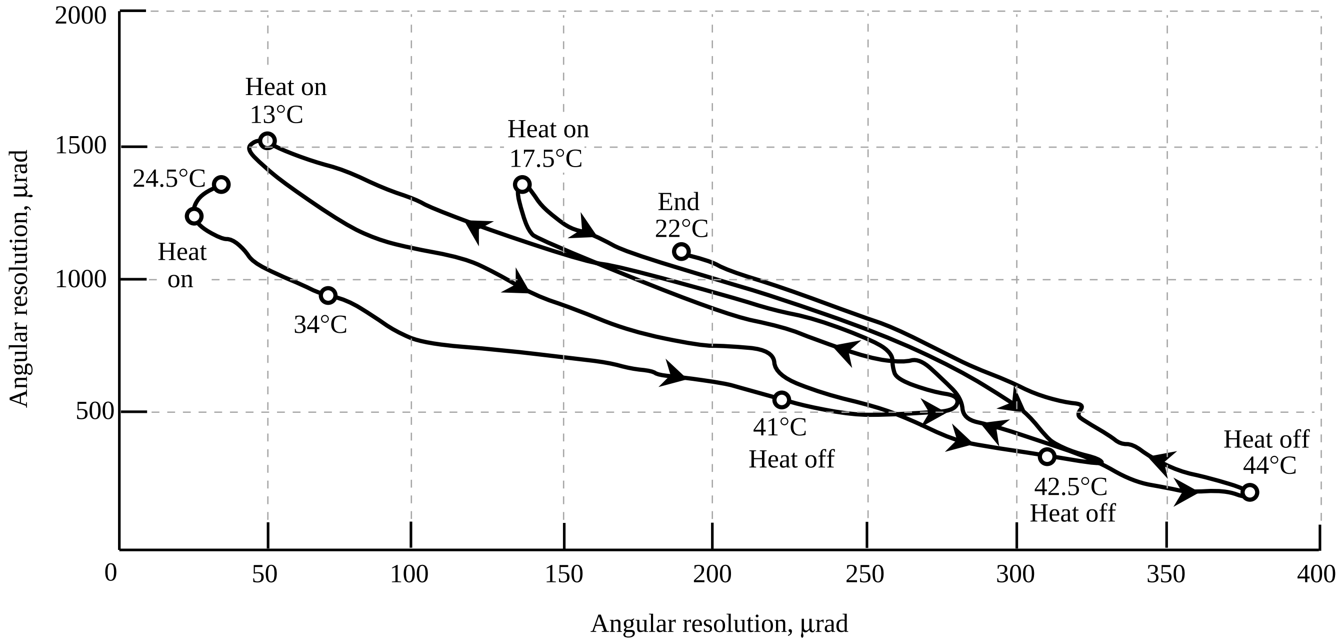

Figure 15. Small 1/2-in. New Focus mirror mount 9871 tested during temperature cycling.

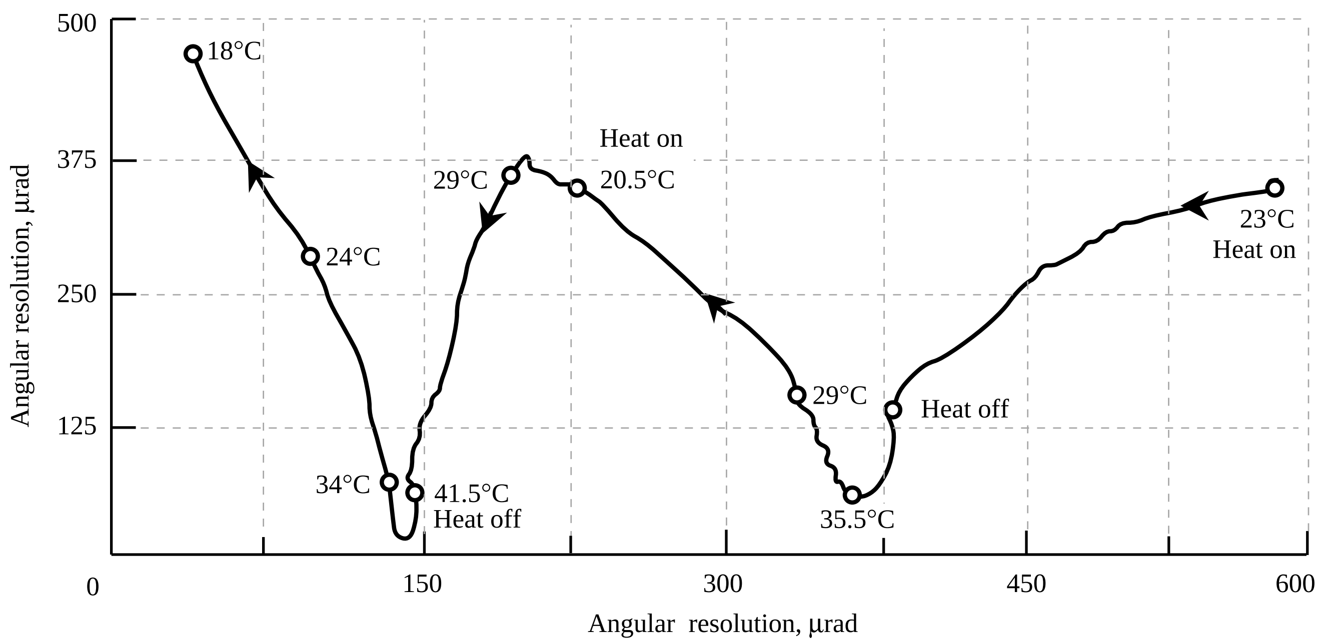

Figure 16. Thorlabs GF-100 mirror mount tested during temperature cycling.

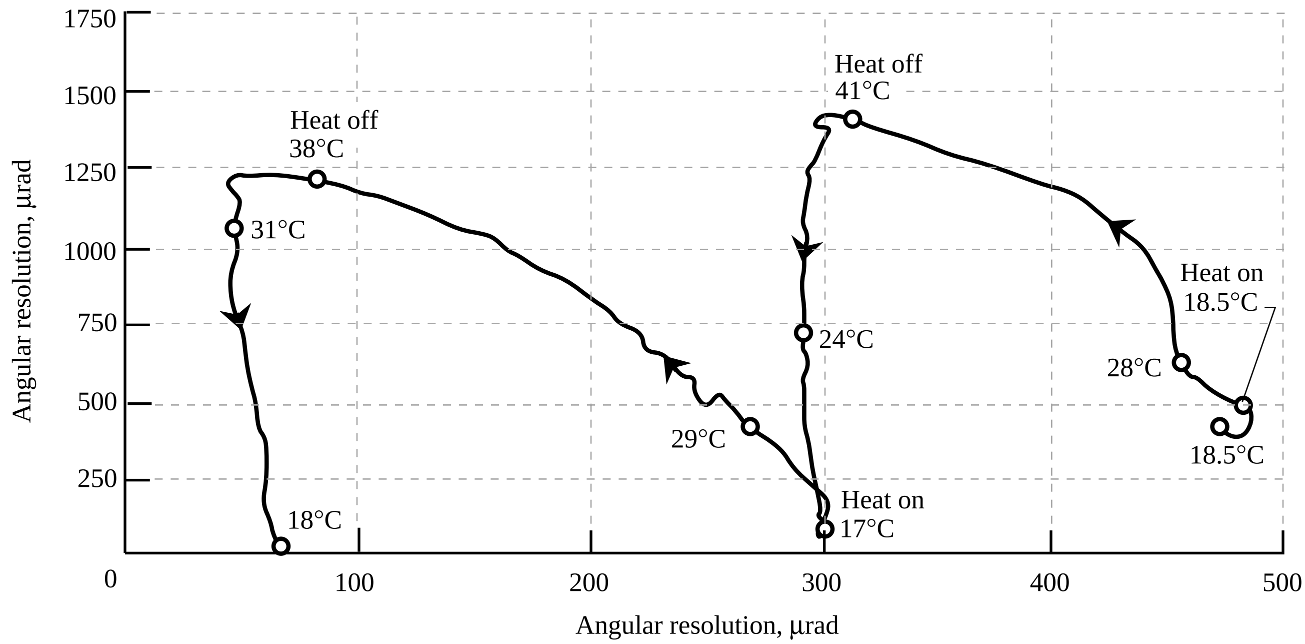

Figure 17. Thorlabs KM1-SH 1-in. mirror mount tested during temperature cycling.

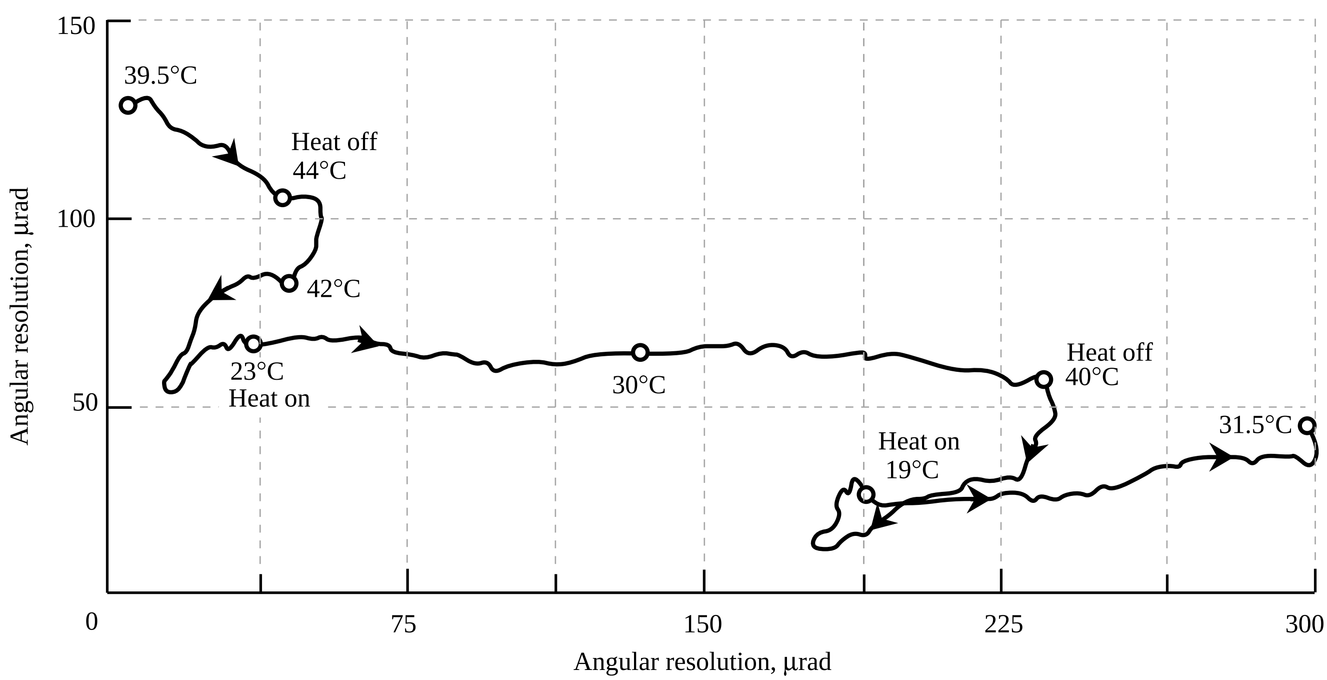

Figure 18. Klinger Newport SL25.4BHc 1-in. mirror mount tested during temperature cycling.

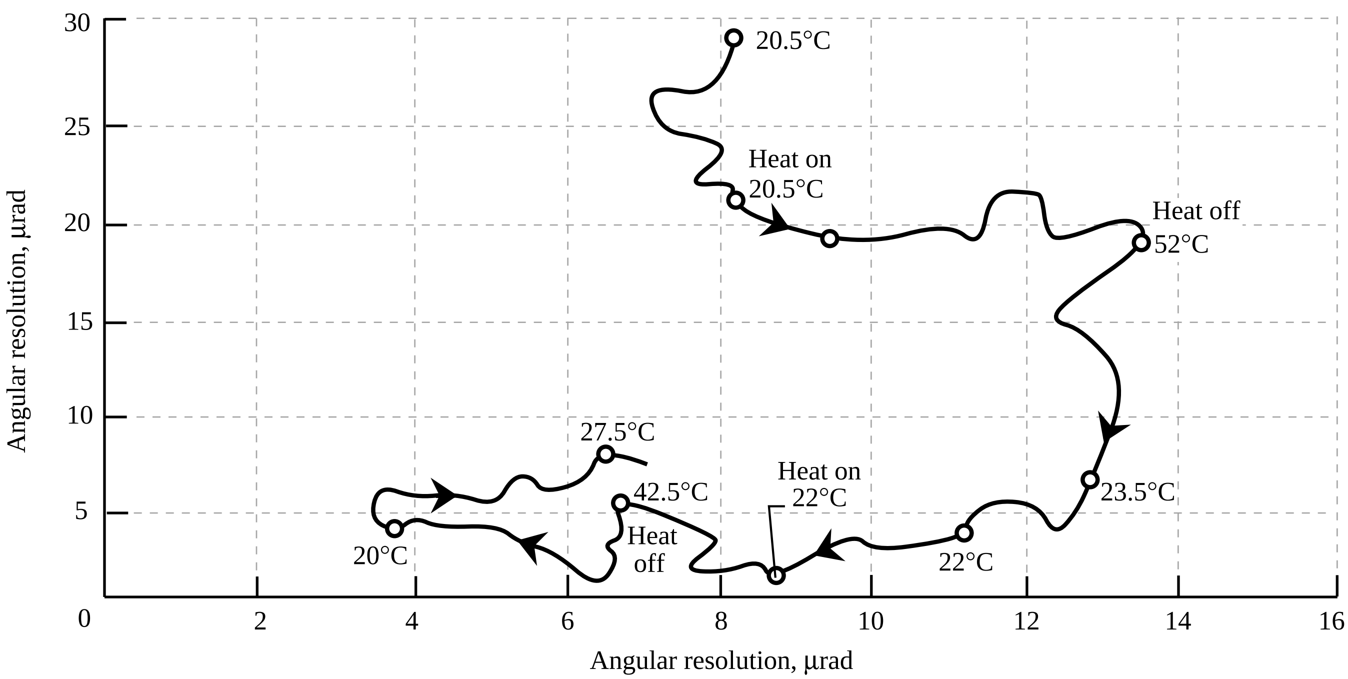

Figure 19. Mirror cube retested for system stability and resolution. Movement indicates inherent system resolution. Detector resolution was 3 µrad in both the *x* and *y* directions (substantially less than the system resolution).

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