Acceptance Test of the Remanufactured PRS110 Rotation Stages

Spartan Infrared Camera for the SOAR Telescope

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We measured the response of the Micos PRS110 rotation stages to torque at room temperature and at 77 K after Micos fabricated new housings to make the bearings tighter. The response of the rotation stage 02040-075 to radial torque is 5 μrad/N/m, which is a factor of 50 better. The hysteresis upon application and removal of a 9 N-m torque is 15±6 μrad at room temperature and <13 μrad (2σ) at 77 K, which is a factor of 30–50 better. The tilt changes linearly with torque. Rotation stages 02060-098, 02060-099, and 02060-100 are comparable. Rotation stages 000 and 02060-097 are not as good: the response (tilt vs. torque) is not linear, which we attribute to inadequate preloading.

To find the response to the actual loading, we installed rotation stage 02060-098 in the f/12 camera assembly and measured the tilt of the mirror as a function of the direction of gravity at room temperature. (On the telescope, the entire instrument turns about the Nasmyth axis to follow a star.) At room temperature, 02060-098 holds the mirror with a tilt of less than 34 μrad, which translates to a 3-pixel shift of the image, and a translation in the direction of focus of less than 12 μm. (Both are 2-σ upper limits.) Therefore 02060-098 and the four comparable rotation stages are acceptable to hold mirrors at room temperature and most likely at 77 K where they are tighter.

1 Introduction

Micos PRS110 rotation stages drive all of the mechanisms in the Spartan Camera, and the most exacting mechanisms are those holding mirrors, where the requirement is 11 μrad for the f/21 collimator and 16 μrad for the f/12 camera to maintain pointing within 1 pixel.

Rotation stage 02040-075 was very loose at room temperature: with a small torque, it tilted 1.8 mrad. At 77 K, the tilt was 0.4mrad,[1] which is 40 times greater than the requirement. Biel & Loh 2002[2] measured the prototype, rotation stage 000 and found the stage is not loose. Micos

[1] Baker, D., & Loh, E., 2005, "Rotation Stage 02040–075," www.pa.msu.edu/~loh/SpartanIRCamera

[2] Biel, J., & Loh, E., 2002, "Test of the PRS 100 Rotation Stage," www.pa.msu.edu/~loh/SpartanIRCamera

made new rotation stage housings with tighter bearing seats for 02040-075, 02060-097, 02060-098, 02060-099, and 02060-100.

The PRS110 rotation stage contains a pair of angular-contact ball bearings (Figure 1) placed back to back. The angle between the radius and the line between the contact points of a ball is 40°. The bearing pair supports axial loads, radial loads, and radial torques.

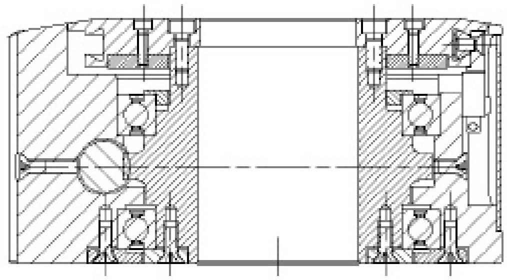


Figure 1 Cross sectional drawing from Micos GMBH of the PRS110 rotation stage. Note the pair of ball bearings.

This reports the measurements of the remanufactured rotation stages.

The procedure for keeping the rotation stage dry when measuring at 77 K is from Brandon Hanold's notes and from Baker & Loh 2005.[1]

Response to Torque

We measure the tilt of the rotating face of the rotation stage in response to torque. The tilt and torque are perpendicular to the rotation axis.

1.1 Method

A test jig (Biel & Loh 2002) allows measurement of the tilt and application of torque while the rotation stage is submerged in liquid nitrogen (Figure 2). The base-forcing and face-forcing posts enable application of the torque by means of weights on a string. The base-forcing post is attached to the base, and the face-forcing post is attached to the rotating

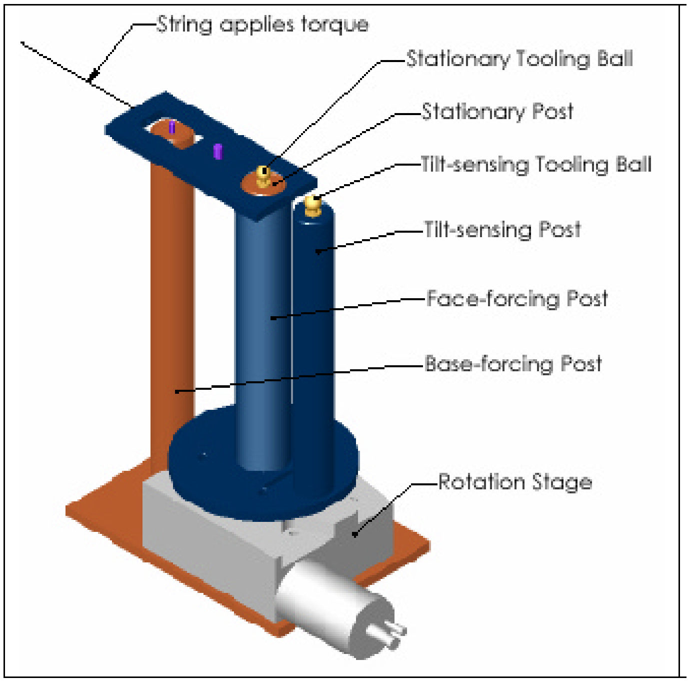


Figure 2 Test jig. The base (brown) is bolted to the stationary housing of the rotation stage (grey). The top (blue) is attached to the rotating face of the rotation stage. The rotation stage is submerged in liquid nitrogen, and the tops of the posts are at room

face of the rotation stage. The stationary and tilt-sensing posts enable sensing the tilt of the rotating face. Tooling balls on the top of the posts allow measurement with a coordinate-measuring machine. The jig is made of stainless steel to minimize thermal conduction.

Table 1 Measurement details: (1) whether a negative torque precedes each measurement, (2) whether a coordinate-measuring machine (CMM) or a micrometer is used for metrology, and (3) standard deviation of the residuals from the fits shown in Figures 6 and 7.

	Neg. torque		Metrology				Stddev[μrad]	
			294K		77K		294K	77K
SN	Now	Old	Now	Old	Now	Old	Now	Now
000	y		CMM		CMM		11	14
075	n	y	CMM	Micro.	CMM	Micro.	8	12
097	y		CMM		CMM		250	8
098	n	y	CMM	CMM	CMM	CMM	26	12
099	n	y	CMM	Micro.	CMM	Micro.	6	12
100	n	y	CMM	Micro.	CMM	Micro.	15	17

A DEA Diamond 01.02 coordinate measuring machine (CMM) is used for metrology. A measurement of a tooling ball consists of seven points at approximately latitude and longitude (0°, 0°), (0°, 90°), (0°, 180°), (0°, 270°), and three points at latitude 90°. The extra points at latitude 90° force the software to weigh all three directions equally.

For the earlier measurements, a micrometer is used to measure steel pins, which were put where the tooling balls are. See Table 1.

To apply a torque τ, a weight, which is tied to a string, pulls the face-forcing post to the left in Figure 2 and toward the base-forcing post.

The sequence of the measurements is to start with a negative torque of 5 N-m, remove the torque, and to make measurements of the tooling balls with increasing positive torque, and finally to remove the torque and make a measurement. For the earlier measurements, a negative torque preceded each measurement (Table 1).

1.2 Results

1.2.1 Detailed Results for Rotation Stage 02040-075

Examination of the 3-dimensional positions of the stationary and tilt-sensing tooling balls shows some of the problems, even though only the difference in the y-positions determines the tilt. The y-axis is approximately parallel to the string that applies the torque. The string is 238 mm from the center of the two bearings of the rotation stage. The posts are parallel to the z-axis.

Consider the x-y positions of the tooling balls at room temperature (upper panels of Figure 3). The torque increases from torque point 1 to 8; the torque is 0 at point 9 (lower-left panel of Figure 4). Even though the test jig is clamped to the table of the coordinate-measuring machine, the stationary tooling ball moves (torque point 8 in Figure 3). The x-motion of the tilt-sensing tooling ball is primarily a rotation of 4 steps (lower-left panel of Figure 3). The position does not return when the torque is removed (torque ordinal number 9 in Figure 3). The z-positions of the two balls shift by 3 μm, which if real indicates a tilt of 80 μrad in the direction perpendicular to the applied torque.

At 77 K, the test jig is clamped to a support, not directly to the table, and the stationary tooling ball moves considerably in the x-y direction (upper panels of Figure 4). The positions do not return after the torque is removed. The movement in the x-direction of the tilt-sensing ball relative to the stationary ball is less than one rotation step (lower-left panel of Figure 4). The motion in the z-direction is much more than that at room temperature. The reason may be the temperature gradient of the posts. The bottoms of the posts are at 77 K. A change in the temperature of the top of a post of 10 C causes a change in length of 44 μm. The top of the posts were occasionally heated to remove ice.

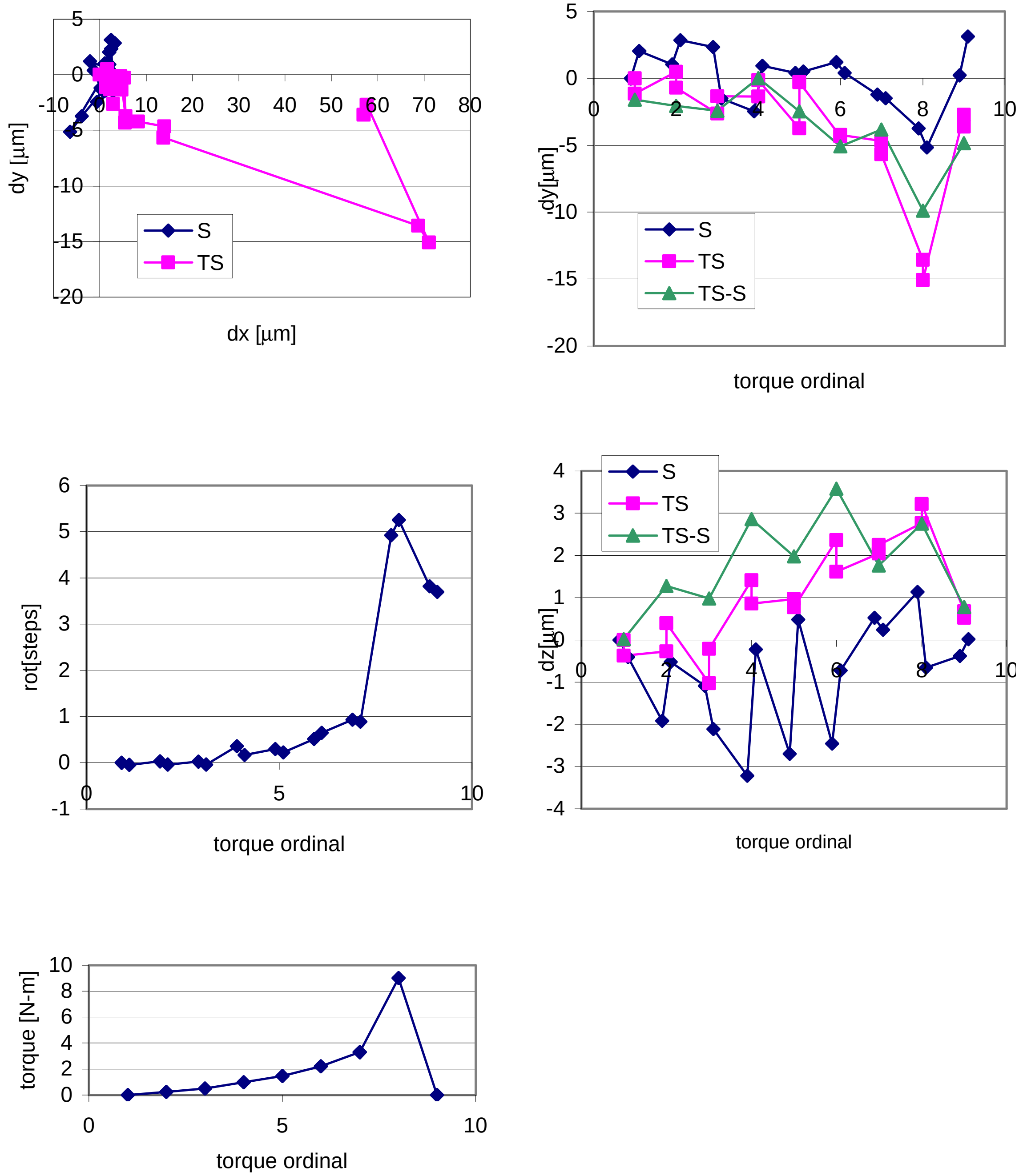


Figure 3 Measurements of the positions of the stationary tooling ball (S), tilt-sensing tooling ball (TS), and differences (TS-S) at room temperature for RS02040-075. The test jig is clamped to the bed of the coordinate-measuring machine, which is in the x-y plane. The force is in the y direction. (a) Top left: movement in the x-y plane. (b) Middle left: Movement of the tilt-sensing tooling ball in the x-direction expressed as steps of the stepper motor. (c) Upper right: movement in the y-direction, for which the difference TS–S is proportional to the tilt of the rotation stage parallel to the torque. (d) Middle right: movement in the z-direction, for which the difference TS–S is proportional to the tilt of the rotation stage perpendicular to the torque. (e) Lower left: Correspondence between the torque ordinal and the torque.

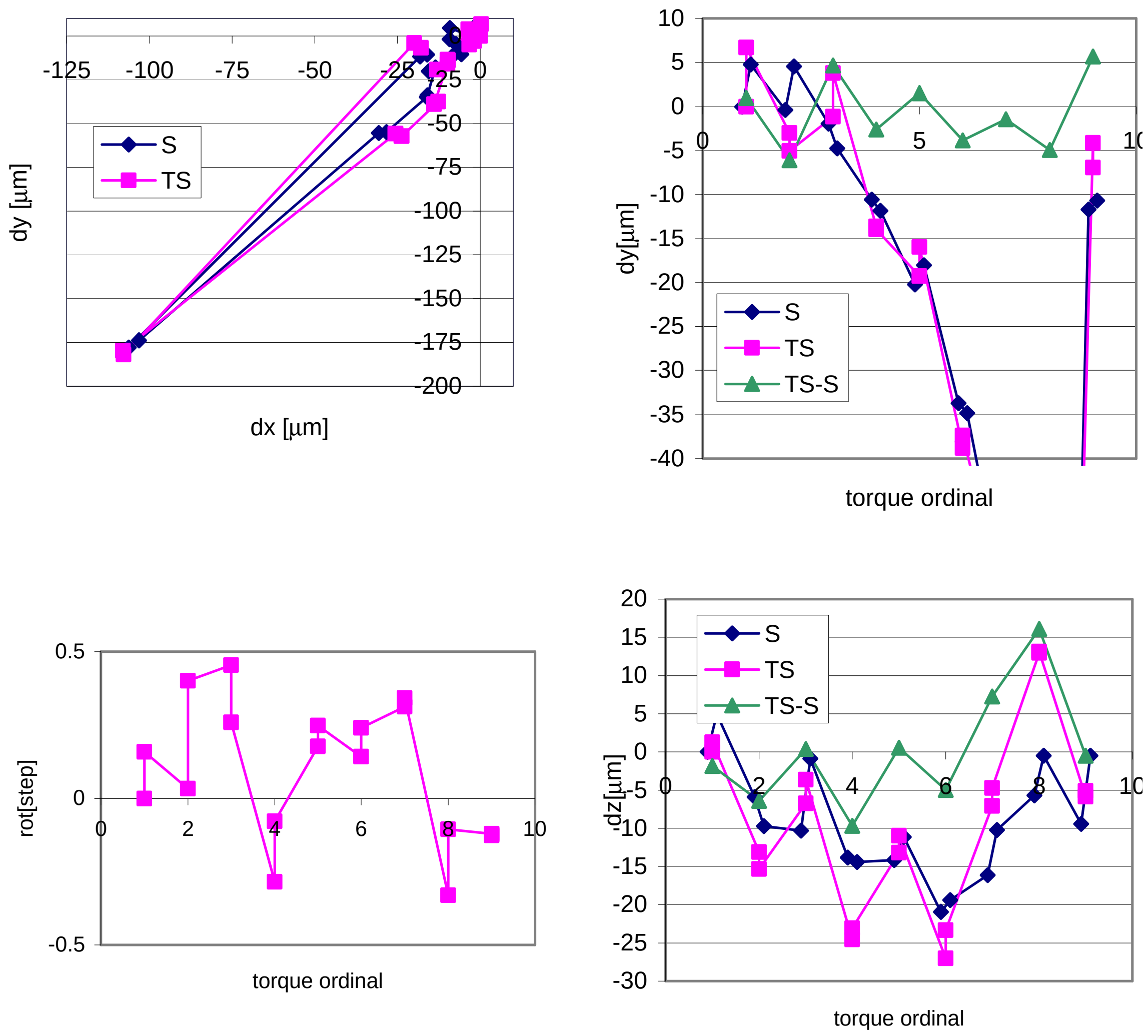


Figure 4 Measurements of the positions of the stationary tooling ball (S), tilt-sensing tooling ball (TS), and differences (TS-S) at 77 K for RS02040-075. The test jig is clamped to an arm. The bed of the coordinate-measuring machine is in the x-y plane. The force is in the y direction. (a) Top left: movement in the x-y plane. (b) Middle left: Movement TS-S in the x-direction expressed as steps of the stepper motor. (c) Upper right: movement in the y-direction, for which the difference TS–S is proportional to the tilt of the rotation stage parallel to the torque. (d) Middle right: movement in the z-direction, to which many sources—tilt of the rotation stage perpendicular to the torque, tilt of the entire jig, and expansion of the stationary and tilt-sensing posts—contribute.

The response (tilt vs. torque) of rotation stage 02040-075 with the new housing is much better than that with the old housing (Figure 5). With the old housing, the tilt increases steeply with increasing torque up to 2 mrad. Beyond that, the system stiffens. For the old housing, the bearing seat is too large, and the bearing moves in the direction perpendicular to the rotation axis (Amelung 2005)[3]. With the new housing, the response is linear. With the old housing, the hysteresis, defined to be the

[3] Amelung, L., 2005, Micos GMBH, private communication

difference between the tilt at zero torque after applying a large positive and that after applying a large negative torque, is 800 μrad at 294 K and 340 μrad at 77 K. With the new housing, the hysteresis (found from fitting the data) is (15±6) μrad at 294 K and (–6±6) μrad at 77 K.

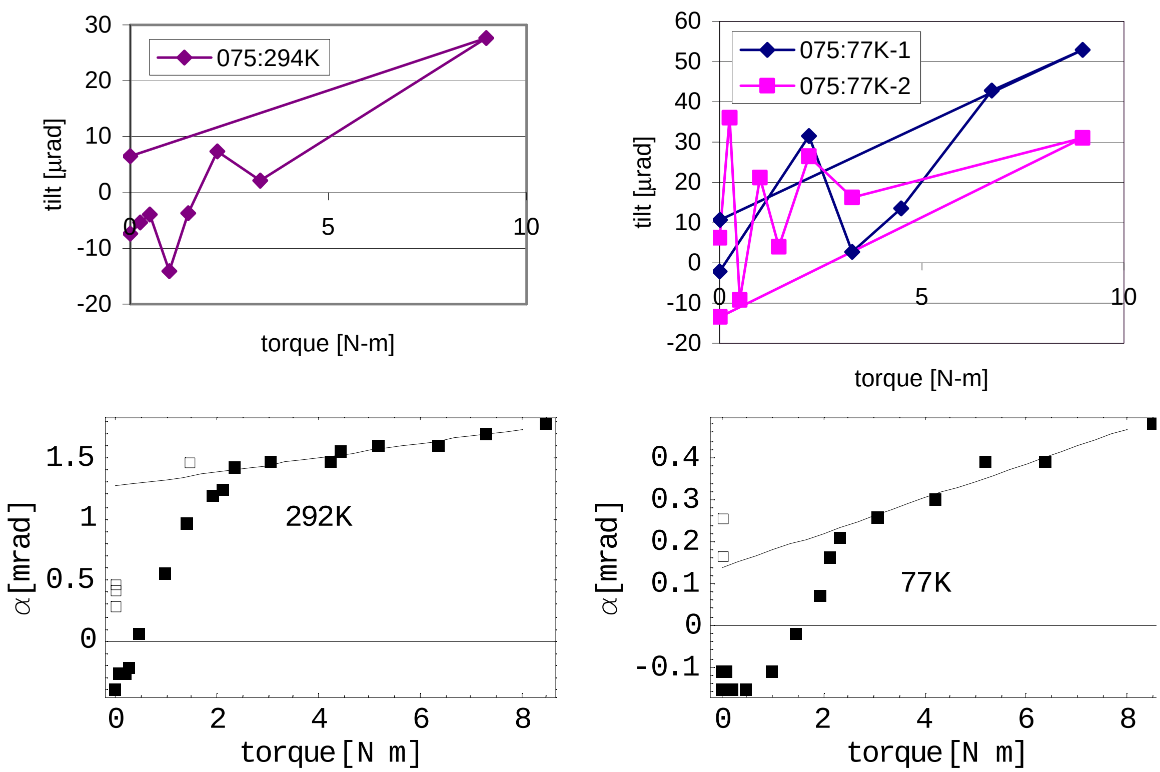


Figure 5 Response at room temperature (left) and at 77K (right) for RS02040-075 with new housing (top) and with old housing (bottom). For the closed boxes, a large negative torque was applied first. For the open boxes, a large positive torque was applied first. The points are averages.

1.2.2 Results for All Rotation Stages

The measured parameters derived from the data in Figure 7, which show the tilt α of the load bearing face of the rotation stage in the direction of the applied torque τ, are in Table 2. Let $\alpha(\tau;\tau_p)$ be the tilt at torque τ with past torque τ_p. The hysteresis $h = \alpha(0;+) - \alpha(0;-)$ is the difference between the tilt at zero torque after applying a large positive and that after applying a large negative torque. The large response tilt $\alpha_L = \alpha(9\text{ N-m};-) - \alpha(0;-)$. The inverse spring constant $\kappa = d\alpha(1\text{ N-m};-)/d\tau$.

Table 2 Parameters, hysteresis, large-response tilt, linearity, and inverse spring constant for the rotation stages. In cases where the tilt is nonlinear, the power β (defined by $\alpha=\tau^{\beta}$) is given.

	Hysteresis μrad				Large-response tilt μrad				Tilt vs torque is linear or power β				κ @ 1 N-m μrad/N/m	
	294K		77K		294K		77K		294K		77K		294K	77K
RS	Now	Old	Now	Old	Now	Old	Now	Old	Now	Old	Now	Old	Now	Now
000	18±10		5±8		740		200		0.43		0.83		124±15	28±7
075	15±6	800	-6±6	340	35	2200	50	700	yes	no	yes	no	4.0±0.7	4.9±0.7
097	2000		10±6		1000		80		0.4		yes		350±30	8.3±0.8
098	55±20	1700	-3±6	150	120	2300	60	500	yes	no	yes	no	13±3	5.0±0.7
099	11±5	2200	-12±5	40	90	2400	40	340	yes	no	yes	no	10.0±0.6	3.0±1.0
100	15±11	1500	0±13	80	110	1800	50	350	yes	no	yes	no	12±1	2.5±1.5

Notes
1. RS 000 was not remachined.
2. RS 097 was not measured before remachining.

The response $\alpha(\tau)$ reveals problems with preloading and looseness of the bearings in their seats. The tilt α scales with torque τ as $\alpha \propto \tau^{2/3}$, if the preload of the ball bearings is small compared with the load due to the applied torque, and the power β increases from 2/3 to 1 with increasing preload, as can be shown. The tilt α in response to torque τ (Figure 7 and Table 2) is linear for most rotation stages. For them, there is sufficient preloading.

For RS000, the power is 0.45 at room temperature and 0.83 at 77K. At 77K, there is some preload. At room temperature, there is no preload, since the response is not as stiff as that of a ball. For RS097 at room temperature, the tilt does not change for τ<1 N-m. We conclude that the bearings slide in their seats.

Figure 6 compares the hysteresis and inverse spring constant for all of the stages.

- The hysteresis at 77 K is less than 13 μrad (2σ).
- The hysteresis at room temperature is consistent with 13 μrad for RS000, 075,

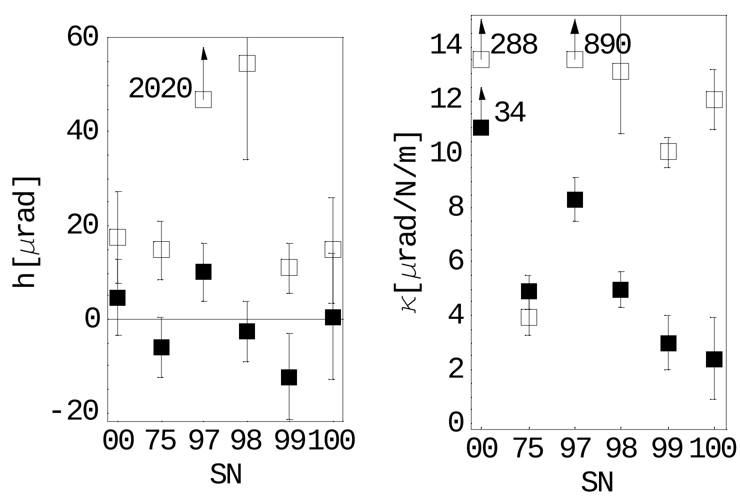


Figure 6 Hysteresis *h* (left) and inverse spring constant κ (right) for rotation stages at room temperature (open squares) and at 77 K (solid squares).

099, and 100. RS098 is marginally inconsistent. The hysteresis for RS097 is 2020 μrad.

- At 77 K, the inverse spring constant is consistent with 4.6 μrad/N/m for RS 075, 098, 099, and 100. It is slightly higher for RS 097 and considerably higher for RS 000.

- At room temperature the inverse spring constant is 4 μrad/N/m for RS 075, which is the same as that at 77 K. The inverse spring constant is 11 μrad/N/m for RS 098, 099, and 100.

- At room temperature, the inverse spring constant is large for RS 000 and 097. These two are also the ones with a nonlinear response.

1.2.3 Conclusions for the Measurement of the Response of the Rotation Stages

At 77K, the hysteresis is probably sufficiently small. For the mirrors supported by rotation stages, the hysteresis of 11 μrad translates to a shift of 1 pixel on the detector for the f/21 collimator. Because the mirror arms are balanced to better than 0.5 N-m and the hysteresis is measured with a torque of 9 N-m, the actual hysteresis will most likely cause a shift smaller than one pixel.

The inverse spring constant is sufficiently small. If the balance is better than 0.5 N-m, the shift of the image due to the spring constant of the f/21 collimator is at most 0.2 pixel for the instrument turning 90°. That can be measured and corrected with a look-up table.

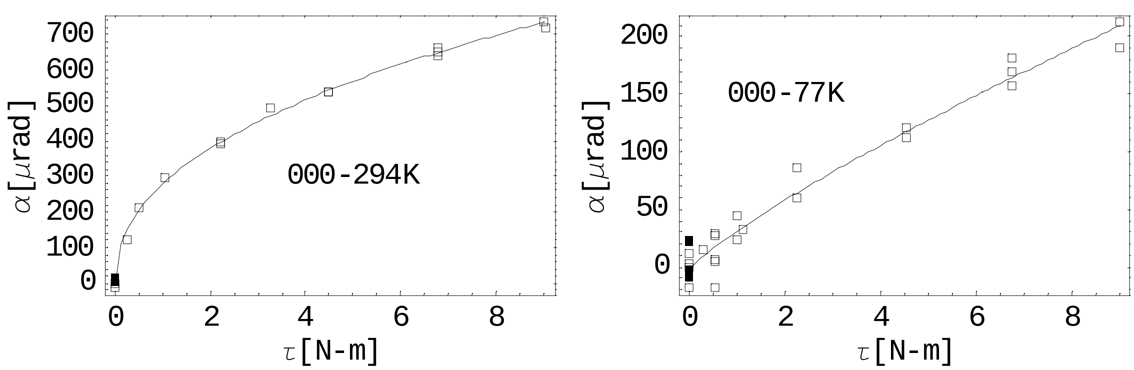
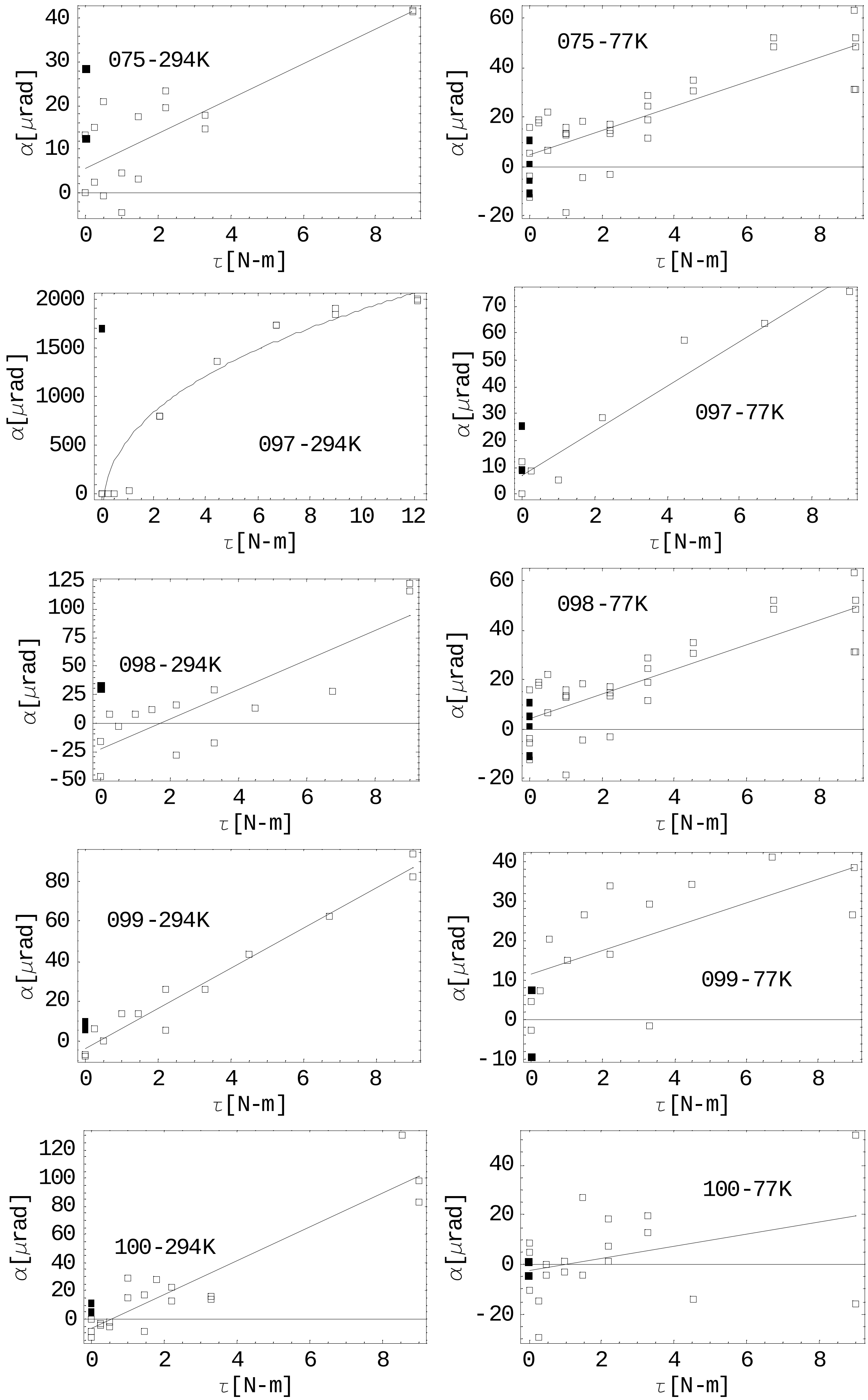


Figure 7 Response at room temperature (left) and at 77K (right) for rotation stages 000, 02040–075, 02060–097, 02060–098, 02060–099, and 02060–100. The torque was released for the solid points; otherwise the torque was increased. (Figure continued on next page.)


075-294K
075-77K
097-294K
097-77K
098-294K
098-77K
099-294K
099-77K
100-294K
100-77K
α[μrad]
τ[N-m]

2 Tilt of the Mirror Assemblies Due to Gravity

Rotation stages hold the f/12 camera and f/21 collimating mirrors, and they must not tilt by more than 15 and 10 μrad, respectively to keep the image from shifting more than one pixel at the detector.

We measure the principal normal vector of the mirror arm, which is nearly parallel to the axis of the mirror, with respect to the coordinate system that is tied to the cradle (Figure 8). The tilt is the change in the principal normal as the direction of gravity changes. The assembly for the f/21 collimator is nearly the same.

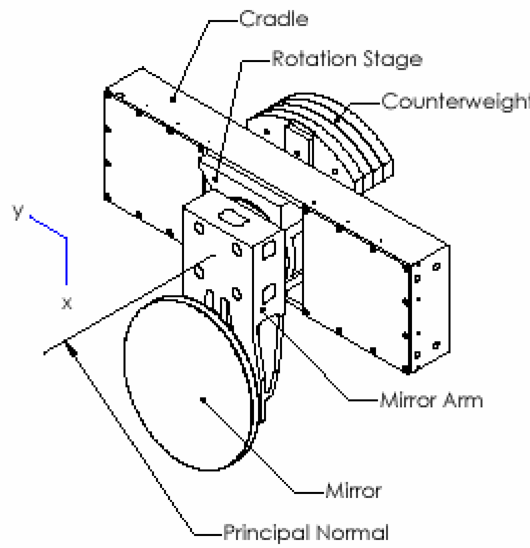


Figure 8 f/12 camera mirror assembly at 270° orientation. The coordinate system is tied to the cradle. Inside the instrument, this assembly turns along the y-axis as the telescope tracks a star.

The load on the rotation stage is nearly free of torque because of the counterweights (Figure 8). There is an anti-backlash spring to provide a small torque parallel to the rotation axis.

The best technique for measuring the principal normal is to measure three well-separated points on the surface of the mirror arm and to always measure the same three points. The deviation of the mirror arm from a plane is 12 μm. If different points are used, the defined plane is different, and the magnitude of the error of the principal normal on the 80-mm face is 140μrad. Using the same points, we achieve a standard deviation of the principal normal of 20 μrad.

The accuracy of the coordinate-measuring machine is 3 μm over the entire measuring volume, which translates to 40 μrad for this measurement. Since the part is much smaller than the 660×460×1020-mmmeasuring volume of the CMM, the accuracy is better than 40 μrad, although the exact value is unknown.

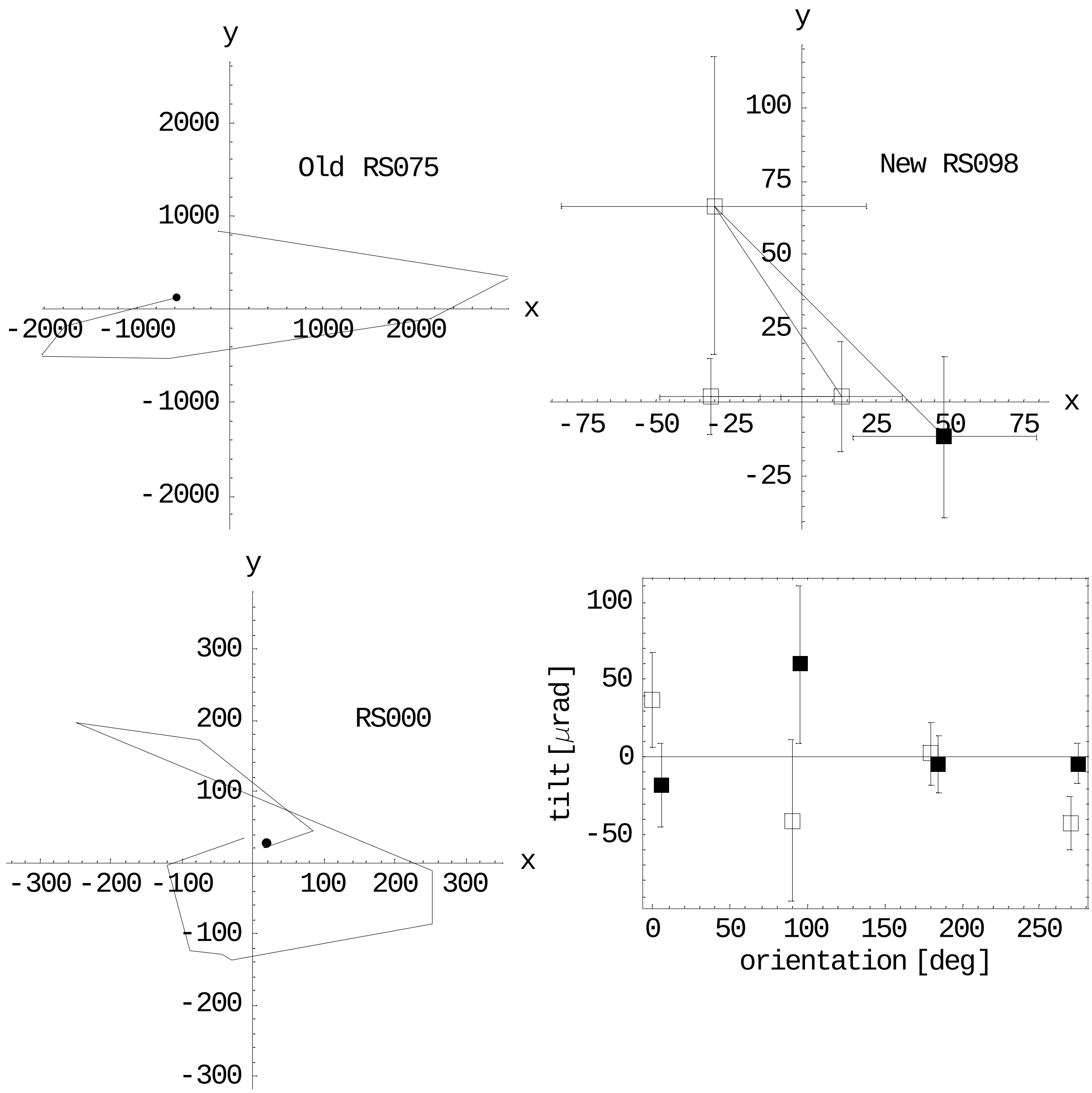


Figure 9 Tilt *dN* due to the orientation of gravity of the principal normal of the f/21 collimator. The units are μrad. Upper left: f/21 collimator arm with the original RS 075. The orientations are 0 (marked with a large dot), 45, 90, 180, 270, and 312°. Lower left: f/12 camera arm with RS 000. The orientations are 0, 0, 45, 90, 135, 180, 270, 281, 293, 303, 315, and 360°. Upper right: f/12 camera arm with the refabricated RS 098. The orientations are 0 (marked with a solid square), 90, 180, and 270°. Lower right: same plotted against orientation. Open boxes are for the tilt of the normal in the long direction of the cradle. Closed boxes show the tilt in the perpendicular direction.

The results (Figure 9) are expressed as the difference between the measured principal normal vector *N* and the average $dN = N - N_{avg}$. Since $|dN| << 1$ and N is approximately in the negative z-direction, the tilt in the x-direction $\theta_x = -dN_y$ and $\theta_y = dN_x$. These are the findings:

- The tilt of the f/21 collimator assembly with the unmodified RS 075 was 5000 μrad (peak-to-valley). See the upper left panel of Figure 9. The measured y-component of the hysteresis (Table 2) accounts for the tilt dN_y. The measurement of the response of RS 075 is not sensitive to dN_x.

- The tilt of the f/12 camera assembly with RS000 is better; the peak-to-valley tilt is 570 μrad. We believe that insufficient preloading of the bearings accounts for the tilt. (Recall that the power β=0.43 is less than the value 2/3 for lightly loaded bearings.) As the direction of gravity changes, the load shifts between the two bearings.

- The tilt of the f/12 camera assembly with the modified RS098 is excellent (upper right panel of Figure 9). The tilt changes with orientation by less than 34 μrad (2σ) in the x-direction and 15 μrad in the y-direction. The fit of tilt ϕ vs. orientation θ to the model $\phi = a \cos\theta + b \sin\theta + c$ shows no significant dependence on orientation. The Fisher F-ratio is 0.4 and 0.08 for ϕ_x and ϕ_y, respectively.

- The movement of the f/12 camera assembly with the modified RS098 over changes in the direction of gravity is small. The distance between the principal plane, the one to which the mirror bolts, and the centre of the rotation stage (Figure 10) is constant within a few μm. The change may be due to errors in the calibration of the CMM, since different sections of the rulers of the CMM are used for the various orientations. Therefore as the 5-kg load moves from one bearing at 0° to the other at 180°, the bearings keep the load secure to a few μm.

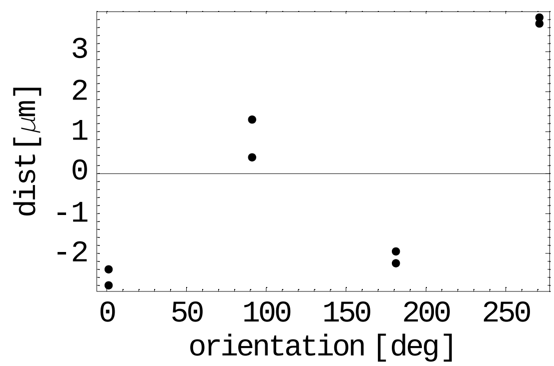


Figure 10 Distance between the principal plane of the f/12 camera arm and the center of the rotation stage 098. A constant of –72.199 mm has been removed.

2.1 Conclusion of the Measurement of the f/12 Camera Assembly

This upper limit translates to a shift of 3 and 1.5 pixels for the f/21 collimator and to 2 and 1 pixels for the f/12 camera mirror.

At room temperature, RS098 holds a mirror arm with less than a 3-pixel shift of the image over all directions of gravity. Therefore we are able to test the flexure of the entire instrument at room temperature before testing it at 77 K.