# Lesson and experience learned from tracking test of LAMOST model mount


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## ABSTRACT

The behavior of future LAMOST mount tracking is one of crucial issues for the telescope's overall performance. In order to demonstrate and to sense the real situation to some degree, the LAMOST team has set up a model mount at the camps of Nanjing Institute of Astronomical Optics & Technology. Painstaking effort has been made during the course of the interim outdoor test to improve the accuracy of the model mount tracking. The major test progress, starting from scratch to date, has been recorded in this paper, such as the anti-disturbance measures taken, the cascaded feedback application, the two-motor-differential drive till the overhaul of the model mount in its drive mechanism, etc. The tracking accuracy has been dramatically improved up to 0.35"-0.42" RMS, promising the future LAMOST tracking requirement will be met given more reliable mount and sophisticated control system.



**Keywords:** model mount, tracking, drive system, LAMOST


## 1. INTRODUCTION

The unconventional design concept of LAMOST telescope has brought an extraordinary challenge to its control system. The telescope's reflecting Schmidt corrector mirror consists of 24 segment mirrors, which need to be under co-focusing control. And each segment surface has to be corrected by active force for better image quality. Moreover, during the observation the corrector mirror has to be driven on both azimuth and altitude axes. The combination of these three control modes applied on the corrector mirror is unprecedented among all known astronomical telescopes in the world. However, it has given LAMOST control engineers a headache technically. In the beginning of the new millennium LAMOST teem set up a model telescope at the campus of Nanjing Institute of Astronomical Optics & Technology (NIAOT) to better understand and predict to some degree the telescope's performance in reality. The test setting simulates the way of the star ray coming, through the model telescope and finally forming an image on the focal plane. The optical configuration is illustrated in figure 1. In the test only one segment is taken as the corrector mirror, and one spherical segment mirror is taken as the primary, which in the reality also consists of 37 segment mirrors. The distance between the corrector mirror and the primary is 40 meters with the focal plane in the middle of the two. The primary is stationary on the foundation, presenting another distinguishing feature from conventional ones.

The corrector mirror rests on the model mount, an alt-azimuth structure, and follows the star passage during the observation. Primarily the test is meant to demonstrate the active force correction of the corrector while tracking. However, in this paper we focus on the tracking. Many factors contributing to the tracking performance in the test will come to play too for LAMOST under future circumstances. The major test progress, starting from scratch to date, has been recorded in this paper. The measures taken for structure optimization and tracking performance improvement are analyzed too. Finally the summary of lesson and experience drawn from the test is given as useful information for future reference. The tracking accuracy has been dramatically improved up to 0.35"-0.42" RMS, demonstrating a very good sign to fulfill future LAMOST tracking requirement given more reliable mount and sophisticated control system.


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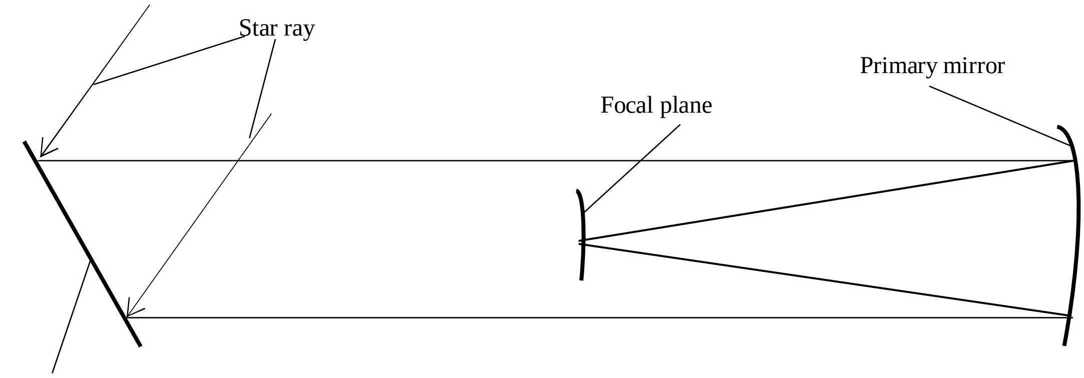


Figure1: Optical configuration

## 2. MODEL MOUNT STRUCTURE

Initially in order to reduce the test cost we took a model mount, which was a leftover more than 10 years ago from another project. The model mount schematic is shown in figure 2. The azimuth disk is supported by a number of supporting rods and propelled via friction by a pair of cylindrical rollers each driven by a coaxial motor distributed $180^0$ apart around the circumference of the disk. Underneath the supporting rods is the azimuth bearing, around which the disk can rotate in horizontal plane. For balancing horizontally the disk 3 small rollers are pressing against the cylinder of the disk. They are distributed around the circumference of the disk with$120^0$ apart. The altitude axis is driven by twin leading screw-nut drive system plus connecting rods. Either leading screw is again driven by a step motor. The rotation angle of the altitude is determined by how the 2 step motors rotate, which is so called two-motor-differential drive.

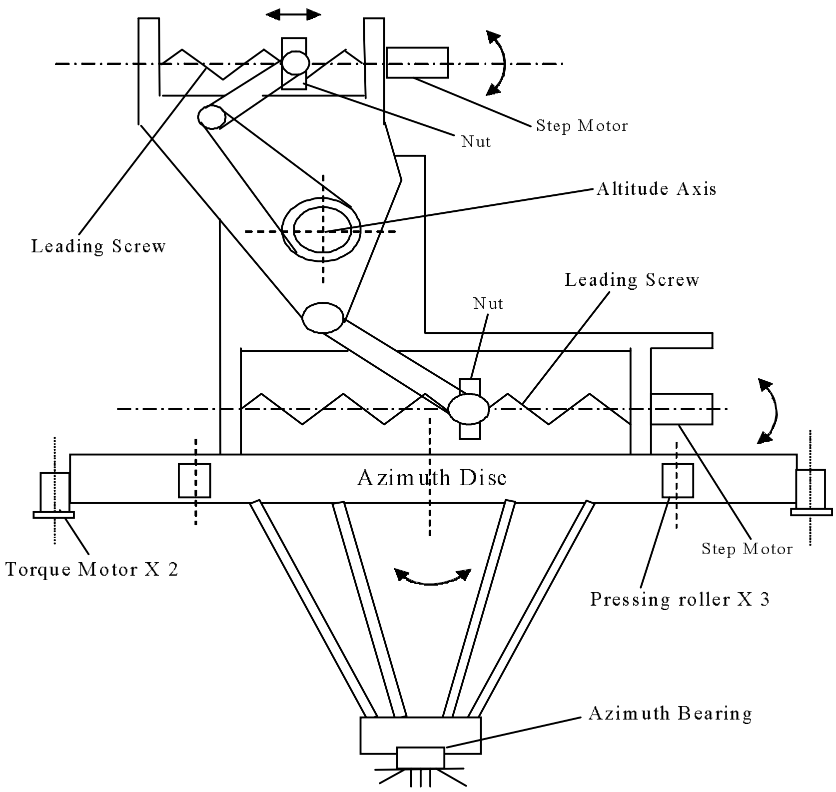


Figure2: Model mount schematic

This model mount was fine more than 10 years ago for a then project with less technical demand has a number of weaknesses for our demanding test today. Aiming at a high tracking accuracy with a better rigid mechanism the model mount experienced a series of small modifications in its structure until one day the overhauling of the model was proved necessary. The renovated model after the face lifting, as it stands now, has replaced the azimuth bearing with oil pads, and also replaced the twin leading screw-nut drive system with a friction drive simulating the real case for the altitude drive of LAMOST.

## 3. IMPROVEMENT: STEP BY STEP

The test is still being conducted for the final result of active force correction of the corrector in tracking process. However, as long as the tracking alone concerned the following table records chronically the tracking test events associated with problems coming along, actions taken and effects.

| Date | Events & Problems | Measures taken | Effects & Remark |
|---|---|---|---|
| Early spring of 2000 | Drive system encountered unknown disturbance | A copperplate and 2 angle irons of 2.5 meters each were buried under the site soil to make a good earth connection | Earth resistance was reduced to less than 1 ohm, and unknown disturbance was much subdued |
| Spring, 2000 | The friction velocity ratio seemed to be too small, and the direction of the pressing force applied by the friction rollers was not aligned towards the azimuth disk centre | The friction velocity ratio was increased to 15 from 10. The direction of the pressing force applied by the friction rollers was re-aligned more accurately towards the azimuth disk centre | The azimuth disk rotation seemed to become more stable |
| August, 2000 | When power was off suddenly the azimuth disk rotated too much because of the inertia | Add an energy consumption brake, meaning the excess mechanical motion turned into electricity and dissipated as heat | The overshoot was much reduced |
| August, 2000 | More efficient and precise time ticking was needed | GPS time receiver was successfully installed on the test site | The time system became more efficient and accurate |
| September 13, 2000 | Started the trial night observation | A plane mirror of 300mm in diameter was provisionally installed in stead of the corrector, which was not ready yet | First light of North star was received successfully in the field with some jitter. Note that The load inertia was much less than what it would be with the real corrector |
| End of 2000 | A CCD camera for trial night observation was expected | A CCD guider ST-7E from SBIG was installed on the test site | Since then it has been possible to frame the star and make exposures while tracking |
| From winter, 2000 to summer, 2001 | A corrector mirror replaced the small plane mirror, and tens of force actuators were put on the back of the mirror plus a huge bundle of cable dragging from them. Tracking became very poor with severe stick and | Two new Heidenhain incremented encoders RON905 with 0.2" accuracy were coaxially assembled on the axes, one for each axis. The home-made PWM electronics driver without velocity feedback was replaced with a commercial driver. A cascaded feedback driver (current, velocity and position) was | For azimuth it was apparent that the coaxial assembled RON905 was better than the old encoder of lower resolution. The old one used to be assembled against the cylinder of the disk with less measuring accuracy than coaxial installation. For altitude the coaxial RON905 was also better |

| | | | |
|---|---|---|---|
| | slip phenomenon | put in place with a newly bought tachometer as the velocity sensor. The friction velocity ratio on one of azimuth motor was increased to 30 from 15. The PID algorithm was improved | than the original inductance encoder of lower resolution. The cascaded feedback performed much better, and the stick and slip phenomenon disappeared. The CCD exposures of star images showed the azimuth tracking with accuracy of around 1" RMS |
| From winter of 2001 to July of 2002 | The altitude tracking remained a dominated factor hurting the overall tracking accuracy. The torsion rigidity of the altitude appeared very poor | Painstaking effort was made on the PID parameter determination. Counterweight of the altitude was re-adjusted. The huge bundle of actuator cable, which apparently hindered the altitude movement was rearranged with light cable | No remarkable improvement was gained. However the zero pulse of the two incremented encoders were fully utilized to ease the initial finding of a star during the night observation |
| From August of 2002 to January of 2003 | The backlash of the altitude leading screw-nut system was found to be as big as 8'. The altitude encoder was found to be mechanically poor assembled | Another motor was bought and began to try the so called two-motor-differential drive with intent to subdue the backlash effect for the altitude. The altitude encoder was re-assembled with better mechanical support. A pointing system-error correction was developed | The gain was dramatic on the altitude tracking. The combine tracking accuracy examined from the framed star images showed about 1.5" RMS |
| From spring of 2003 to October of 2003 | No site test was conducted since the old model mount was dismantled for a new model mount to replace | Azimuth bearing was replaced with oil pads, and the twin leading screw-nut drive system was replaced with a friction drive simulating the real case for the altitude drive of LAMOST. After investigation and sizing a brushless motor was purchased from Parker for the altitude friction drive | The rigidity on both axes has obviously been further improved. |
| From November of 2003 to date | The new model mount was erected on the site. After series of adjustment night observation began | Control software adaptation was done for the new brushless motor. A spiraling searching method of a nearby star was developed | Night observation shows the tracking accuracy on both axes reached 0.35"-0.42" RMS |

## 4. MAIN FEATURES OF THE NEW MODEL MOUNT SERVO

After the face lifting the new model mount made its debut, and the control system was up and running by the end of 2003. The distinguishable optimization is that the azimuth bearing has been replaced with oil pads, and the twin leading screw-nut drive system has been replaced with a friction drive. These two new features are exactly the same as the ones for future LAMOST. The bottom line is that the rigidity on both axes has obviously been improved. We have got rid of the annoying 8 arcminutes backlash in the old transfer chain of the altitude axis with the friction drive being used. For the azimuth the support of oil pads is much better than the mechanical bearing because of the hoist supporting mode of the azimuth disk used before seemed to be unstable. Finally both radial run-out and end face run-out have been much reduced.

Here are the highlights for the current drive servo. The azimuth disk is propelled via friction by a pair of cylindrical rollers each driven by a coaxial DC torque motor distributed $180^0$ apart around the circumference of the disk. The velocity ratio between the roller and the disk is 25. On one of the motor coaxially assembled is a tachometer as the velocity feed back sensor. An industrial computer gives a velocity command, an analogue voltage signal after a D/A convert card, to the motor microprocessor-based driver. The azimuth velocity loop is closed on the azimuth driver. On the other hand, for the altitude axis friction drive is implemented too. A friction cylindrical roller with velocity ration of 25 propels the altitude disk. A brushless motor from Parker Dynaserv DM series is coaxially assembled on the altitude friction roller. An integral optical encoder is coaxially on the shaft of the motor and gives 655360 steps/rev after interpolation. The industrial computer gives velocity commands, digital pulse signals, through a counter card to the proprietary motor driver. The altitude velocity loop is also closed on the motor driver

On both axes each coaxially installed is a ROD905 incremented encoder with 36000 line count/rev from Heidenhain as the axis angle sensor. The signals from both encoders are interpolated by an IK220PCI card with factor of 4096, producing the resolution of 0.0088". The industrial computer reads in axis position signal, with which compared is the target position. The error signal is processed with PI algorithm. The position feedback is closed in the industrial computer. A classical position loop PID algorithm is implemented. The formula is

$Y = k_p e + k_i \int edt + k_d \frac{de}{dt}$, or $Y(k) = k_p e(k) + k_i \sum_{j=0}^{k} e(j) + k_d [e(k) - e(k-1)]$ expressed in discrete data. In the above two formulas $Y$ is output, $e$ is error, $k$ is number of iteration, and $k_p, k_i, k_d$ are proportional, integral and derivative respectively. In our practice a variable parameter PID algorithm is used in order to avoid too much overshoot, lessen the number of oscillation during transient and reduce the settling time.

The mount servo block diagram is illustrated in the figure 3. The application software is developed under Windows 98 operating system, programming language in VC++6.0. The basic functions of application software are:

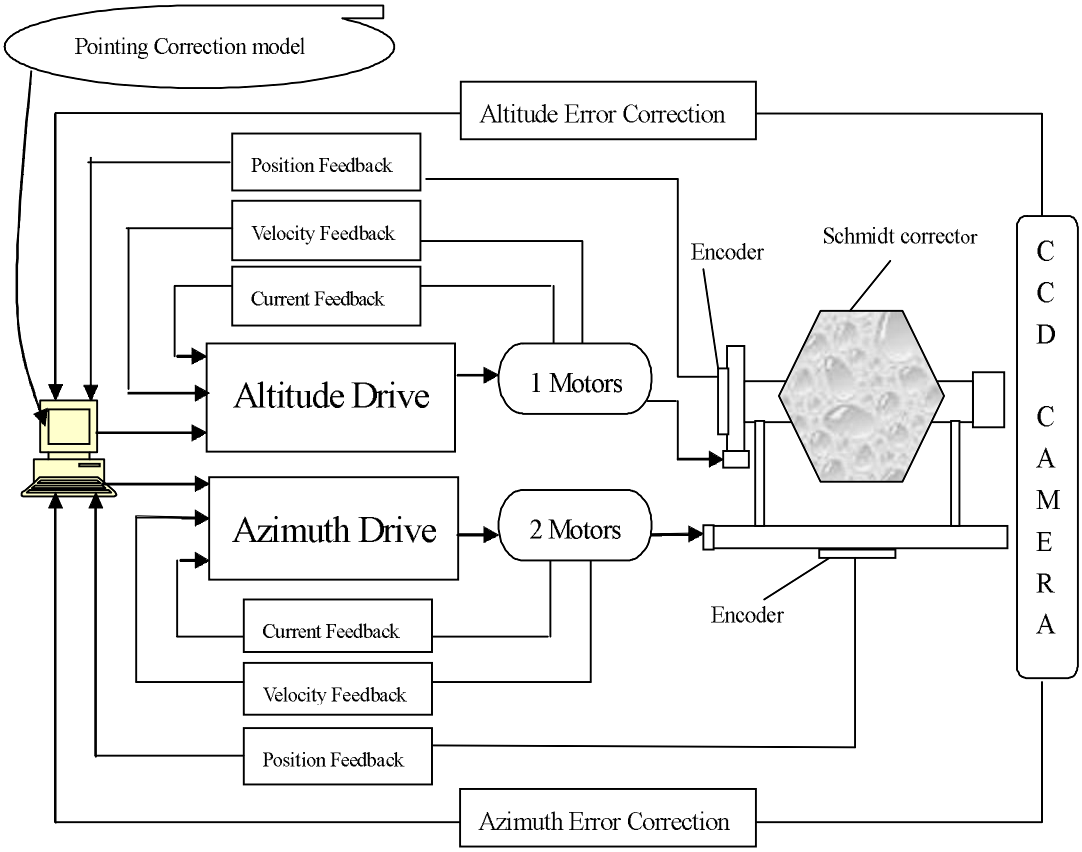


Figure3: Model mount servo block diagram

- Rotate the mount with various predefined velocities.
- Rotate the mount to any target positions and keep it still there under the servo.
- Pointing, tracking, guiding and searching.
- Pointing system-error correction model.
- Motion status monitoring and software safeguard.

The pointing system-error correction model corrects some system errors, such as the pointing error of azimuth axis deviating from zenith and non-perpendicular error between the azimuth axis and the altitude axis, etc. There are a number of approaches to establish a pointing model, such as formulas based on experience, special fitting, etc. The most popular and widely implemented is probably the TPOINT. If only 6 basic physical terms are taken into consideration the formula is expressed as below. In our current pointing correction model we have merely taken the 6 terms too.

$$\Delta A = IA + CA\sec(E) + NPAE\tan(E) + AN\tan(E)\sin(A) - AW\tan(E)\cos(A)$$
$$\Delta E = IE + AN\cos(A) + AW\sin(A)$$

In above two formulas the parameters are listed in the following table with their meanings respectively.

| | |
|---|---|
| A | Azimuth position |
| E | Elevation position |
| IA | Indicated azimuth zero-offset |
| IE | Indicated elevation zero-offset |
| CA | Non-alignment of mechanical and optical axes |
| NPAE | Non-perpendicularity between azimuth and elevation |
| AN | Azimuth axis deviation from zenith in north-south direction |
| AW | Azimuth axis deviation from zenith in west-east direction |

In observation practice by measuring the pointing errors of tens of stars distributed evenly in the sky the above 6 terms can be obtained with least squared method. We have learnt and adopted the method in our recent night observation, and the pointing correction is evident. With the new model mount now we are able to reach tracking performance of

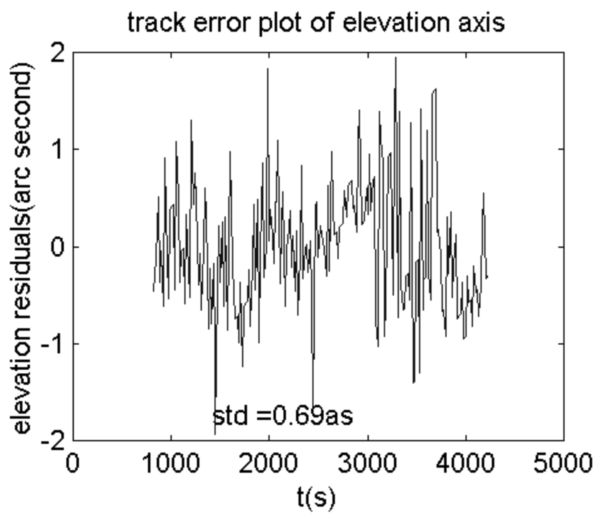


Figure4: Altitude tracking error taken from CCD exposures on May 6, 2004, which has not been converted to the mount altitude axis yet.

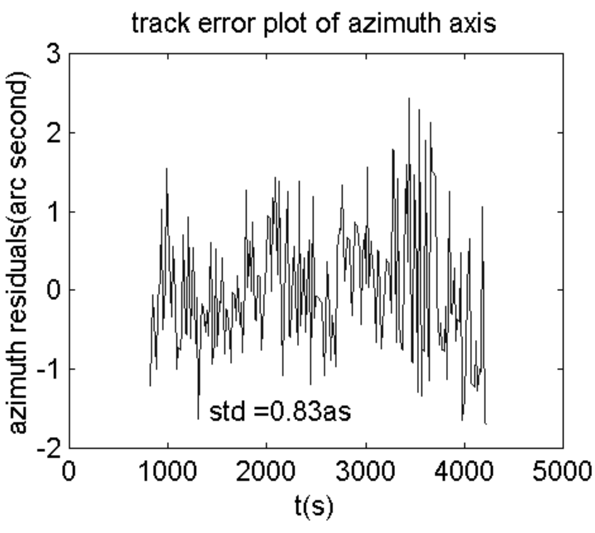


Figure5: Azimuth tracking error taken from CCD exposures on May 6, 2004, which has not been converted to the mount azimuth axis yet.

0.35"-0.42" RMS converted to both mount axes. Figure 4 and figure 5 shows the tracking error of azimuth and altitude respectively taken from the CCD exposures of night observations on May 6, 2004. Please note that because of the unconventional optics configuration of LAMOST the tracking error taken from CCD exposures is different from the error converted to the mount axes. Roughly speaking the former is twice as big as the latter. Please refer to figure 1, which simulates the LAMOST in this particularity.

## 5. SUMMARY OF LESSON & EXPERIENCE

The test has undergone off and on for 3¬4 years for various reasons. Painstaking efforts have been paid during the years' process, and useful experiences have been accumulated.

- In the budget phase it is important to carefully make performance-cost analysis. Blindly pursuing economy in the beginning often turns to be extra money investment in the end. It is especially true for those hi-tech projects. In our case, as the test preceding more and more weakness with the initially adopted model mount had come to surface. We had to solve all sorts of problems, which distracted our main attention greatly, until one day we realised that unless we abandoned the old mount of poor rigidity in the transfer chain and got a new one with overall face lifting for much higher rigidity we would not be able to reach our goal. However, this was proved more expensive than if we designed a new one with higher rigidity in the first place.
- A good earth connection is always one of most critical site conditions for all control tests. We had the lesson that at the first stage of the test a lot of abnormal and unaccountable encounters appeared. With a great effort, the earth resistance has been reduced to less than 1 ohm, and those unaccountable phenomena greatly subdued.
- Between the choices of commercial and home-made circuits we prefer the former. This is particularly true nowadays in the so called modern electronics century. General speaking, industrial products that are backed by a group of experts and have undergone survival of the fittest are better in many aspects, sometimes even more economy than the home-made unless you have no way to turn to or the home-made products have actually become your heirloom. For example, initially we developed in conjunction with a post-graduate program a home-made PWM circuit, which used to work fine fore the model mount without the heavy corrector mirror plus tens of actuators and a huge bundle of cables from them, proved unfit later on for those things in place producing heavy inertia. Eventually we purchased a commercial driver and added a velocity loop in the servo the creeping phenomenon disappeared.
- The electromechanical unification is crucial for any high-end drive system. This means that the performance of any drive servo depends on both electronics elements and mechanical elements in the drive chain. When problems arise both of electronics engineers and mechanical engineers should sit down and have a talk to solve the problems. Fighting and evasive attitude do not help. This is easy said than done. Frequently we do not know who is to blame, or who should be to blame more. In our experience, more often than not, the electronics engineers are more active in finding problems since the problems do not come to surface until the drive system is powered and electrically tested, but the mechanical engineers often play more vital role in the rigidity-associated drive system. A good example of this case is how to coaxially assemble the RON905 encoder on the altitude axis. At one time we had too many signal-too-weak warnings from the altitude encoder. At first we tried everything possible to look for the causes electronically such as a bad cable connection, too long cable and malfunction interface circuits, but failed. Finally we disconnected the encoder and then measured its output by means of a signal monitor from Heidenhain while manually turning the rotor of the encoder. We noticed the output was weak and unstable. The signal amplitude appeared severely disturbed even by a slight touch of the encoder supporting plates. Obviously the problem was mechanically improper installation of the encoder. The responsible mechanical engineer re-designed the assemblage of the encoder with rigid supporting structure. Since then we have never got the annoying signal-too-weak warning once again.
- Read product menu carefully before getting your hands on. This is particularly true when you have to try some products that you have never triad before. We got such a lesson with our purchased RON905 encoders. The problem arose when we were about to install them. The axial connection between the encoder rotor and the rotating disk should be rigid according to the menu from the supplier, yet instead we made it a flexible connection at first for fear of damaging the encoder rotor if rigid connection was employed. Later on during the tracking the performance was apparently not satisfactory. One day we calibrated the encoder readings against a mechanical

indicator, and found out the problem. After re-designing the connection strictly according to the menu the problem disappeared, and the tracking accuracy was clearly improved.

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