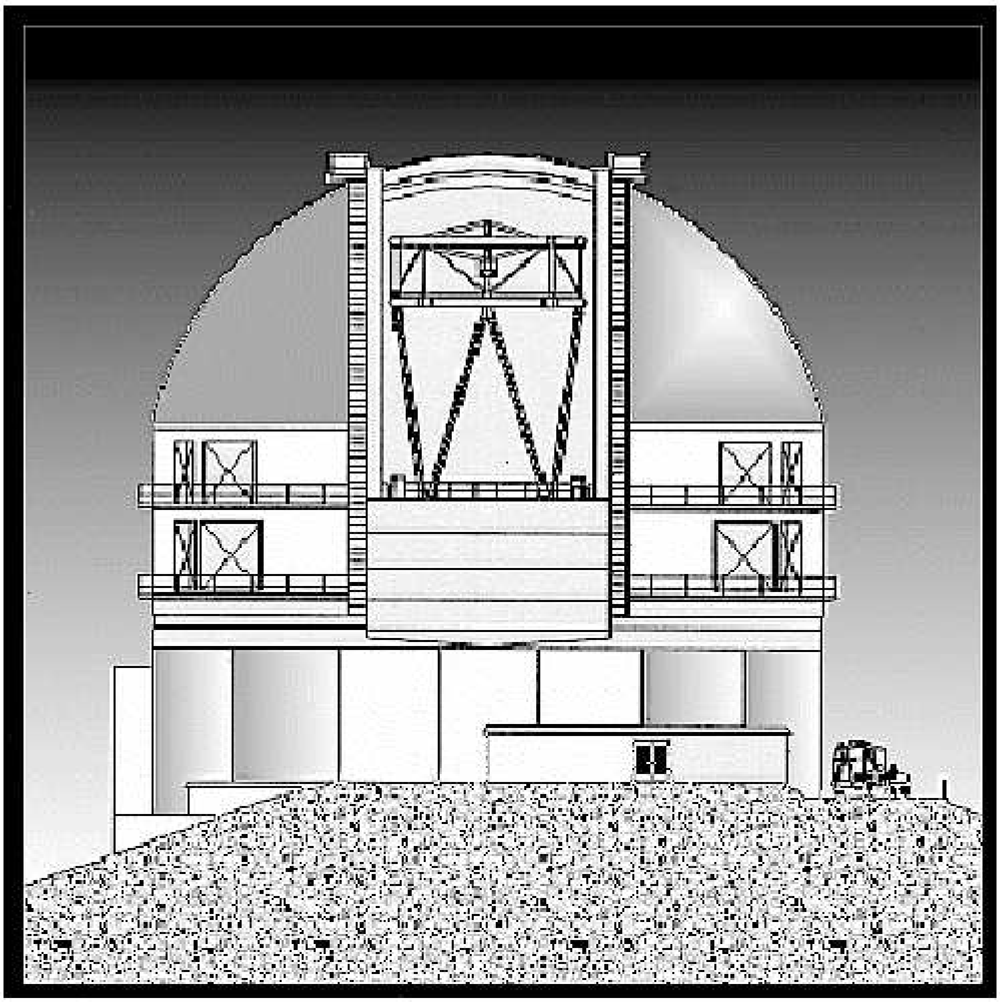
GEMINI
8-M Telescopes
Project

RPT-TE-G0028

Friction Driven Encoder Test Program Report



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1 INTRODUCTION

1.1 Purpose of document

This document describes tests carried out by the Gemini project, to evaluate the effectiveness of ground and disk referenced, friction driven encoder systems.

1.2 Scope of document

The document describes the test rig, test procedures and results, for the WIYN ground referenced encoder mount and the Gemini designed disk referenced encoder mount

1.3 Definition of key terms and abbreviations

The following list of terms and abbreviations are used throughout the document

FDE	Friction driven encoder.
Encoder	Device that accurately measures angular displacement.
Encoder mount	Mechanical device to hold encoder drive roller in contact with telescope drive disk surface.
Test rig	Device used to simulate telescope Altitude and Azimuth encoder wheel drive surfaces.
Drive Roller	Wheel connected to encoder mount that transmits telescope drive surface motion directly to encoder
On axis encoder	Encoder mounted on the test rig wheel rotation axis to provide feedback for closed loop motor control.

1.4 Test program, background

Friction driven encoder systems have been used on telescope axes for many years, and have proved very effective in providing accurate telescope position feedback information. This type of encoder system has been selected for use as one of the position feedback devices used on both axes of the Gemini 8m telescopes, for offsetting, pointing, and tracking operations. The principle concern with FDEs used on other large telescopes however, have been problems associated with slippage, and skipping of the roller, and the critical alignment required between the encoder mount and the telescope drive surface. Consequently, this test program has been initiated to help select the most promising FDE mount design, and to quantify their performance under a variety of operational conditions. The test program is a collaborative effort among four telescope design groups: Gemini 8m, Magellan, MMTO (now withdrawn), and WIYN 3.5m. As a result of discussions among the four groups, two FDE systems have been selected as the most promising candidates for investigation and possible use on the Gemini telescopes: a conventional ground referenced encoder, based on the WIYN telescope FDE design, and a new disk referenced FDE mount designed by the Gemini project.

2 DESCRIPTION OF ENCODER TYPES

2.1 Ground referenced Friction Driven Encoder mount

The ground referenced FDE tested is an actual end-item that will be used on the WIYN 3.5m telescope on Kitt Peak. The design is based on a modified "conventional" FDE mount; ie. The encoder mount is rigidly connected to ground and constrained in all degrees of freedom accept radially. The single most common source of errors in this type of FDE is due to yaw (or steering) angle misalignment between the roller and the telescope's drive disk. In theory, this yaw misalignment causes a helical 'drifting' of the roller away from it's intended path. As a result, an axial restoring force occurs and eventually exceeds the coefficient of friction between the roller and the disk. When this friction force is exceeded, the roller skips back to its correct axial location on the disk and an encoder position error occurs. In an attempt to minimize this error, the WIYN mount incorporates a steering, or alignment mechanism, and load cell (used to measure axial force). As the encoder begins to drift due to misalignment, the load cell is able to detect the corresponding build up of restoring force. During setup and initial alignment of the encoder mount, it measures this axial force, and by adjusting the steering mechanism, an accurate fine adjustment of roller alignment is provided.

2.2 Disk Referenced Friction Driven Encoder mount

In contrast to the ground referenced mount, the disk referenced mount is not fixed to ground in all degrees of freedom. By incorporating guide bearings that contact the disk drive face, just behind the encoder drive roller, and a perpendicular axial surface (disk drive side), the drive roller is constrained to follow disk runnouts and irregularities. It is believed that these guide bearings will cause a misaligned encoder roller to continually 'micro-slip' at a level that is undetectable in the encoder electronics. In contrast to the WIYN encoder design, the tangent arm that connects the encoder mount to ground is relatively 'soft' in all degrees of freedom except tangentially. This allows the entire mount assembly to follow axial and radial disk runouts. The other two guide rollers are designed to resist angular rotation of the encoder; this rotation would directly result in an encoder rotation. Note that both the ground and disk referenced mounts use the Heidenhain ROD-800 encoder with 25x interpolation.

3 TEST FACILITY

3.1 Overview

The test facility consists of a rig designed to simulate the altitude or azimuth drive surfaces found on today's large telescopes. The moving axis of the rig is controlled using a computer and can be moved to any angular position. Data logging is provided to gather and store test results. Figure 1.0 shows the encoder test rig. Figure 1 shows the encoder test rig.

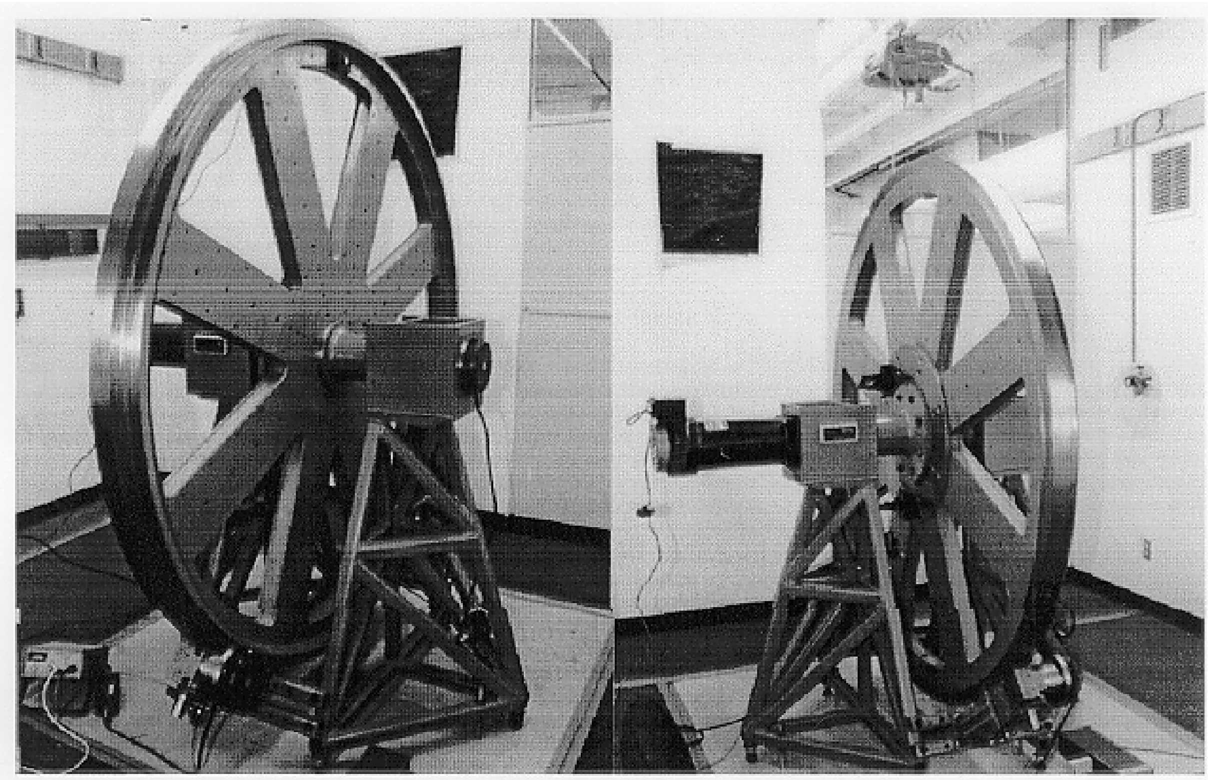

Figure 1 Encoder Test Rig.

3.2 Construction

The encoder test rig consists of an eighty inch main wheel mounted on a flanged shaft. Shaft and wheel bridge a pair of support structures each capped by a bearing housing. One end of the shaft is driven by a DC motor connected through a spiral misalignment coupling. The other end drives an encoder (referred to as "on axis") through a plate coupling. Four two inch square tubes connect the base of the support structures. The test encoder fastens to the rig using two of the four cross tubes.

3.3 Fiducial Point

A fiducial or reference point is incorporated on the test rig. This consists of an electronic autocollimator, mounted to one of the rig support structures, and a reference mirror or mirrors mounted on the test rig wheel. The system provides a resolution of one hundredth of an arcsec. Figure 2.0 shows the fiducial system.

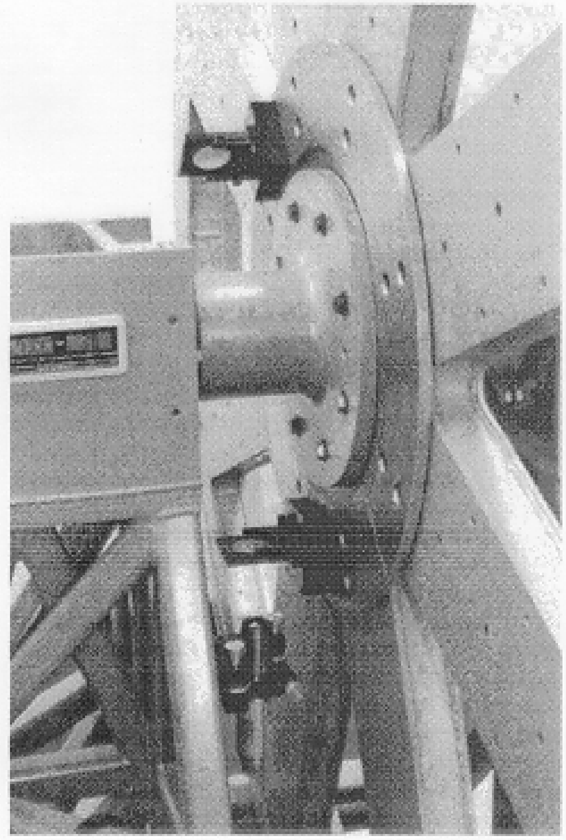

Figure 2.0 Fiducial System

3.4 Test rig wheel control

The test rig wheel is controlled by an electronic servo system. This comprises a personal computer (486) linked by serial line to a DC motor control board. The system reads data from the on axis encoder to provide closed loop servo control. Other data gathered includes, test encoder counts, load cell voltage and autocollimator output.

3.5 Test rig wheel, angular resolution

The test rig wheel can be driven to any position, with a repeatable accuracy of one count, or 0.36 arcsec, measured at the "on axis" encoder. Using the fiducial system, repeatable angular positioning of 0.01 arcsec have been achieved, however, this level of accuracy can only be verified at the fiducial point, or between this and a second reference mirror placed on the wheel. With a test rig wheel to encoder drive roller ratio of 20.5:1, count errors read at the test encoder are measured to an accuracy of 20 FDE counts or 7.2 arcsec. In all tests carried out manually, i.e. not using the fiducial system, count errors below 20 are assumed to be 20.

3.6 Test facility environment

To reduce the effects of external vibration, the test rig is mounted on a concrete block isolated from the surrounding floor. Temperature and humidity control in the test lab is provided by the standard air conditioning system found in the building. This arrangement gave a range of temperature over the duration of all tests not exceeding 1 degree Fahrenheit, at a nominal level of 72 degrees. Humidity remained within 20% over the testing period. Variations in temperature and humidity over the period of a typical test (1 hour) stayed within 0.2 Deg and 1% respectively.

4 DESCRIPTION OF TESTS

4.1 Swing Test

The aim of this test is to determine count error at the test encoder, when the test rig wheel is moved through various angular increments. The procedure that follows was used for all swing tests.

- The test rig wheel is driven to the zero position.
- Reset test encoder reading to zero.
- Drive the test rig wheel to a pre-defined positive position, bring to rest.
- Return wheel to zero, bring to rest.
- Record test encoder error.
- Each test is repeated ten times

To assure consistency and repeatability the tests are executed by a motion control program. The program executes the steps described above, in addition, at the beginning and end of the test cycle the test wheel is driven through the zero fiducial point of the autocollimator. During this time, data is continuously gathered from the autocollimator, on axis encoder and test encoder. The instance the autocollimator fiducial point is encountered the test encoder count value is recorded. These values, gathered at the beginning and end of the test are compared. The difference being equal to counts lost during the test.

4.2 Pre-Load Test

The aim of these tests is to determine the optimum contact force or "pre-load" between the test rig wheel and test encoder roller. The pre-load must be high enough to maintain consistent drive between the wheels with the lowest amount of "slip." However it must be low enough to maintain a safe level of contact or "Hertzian" stress. Stress is a limiting factor due to the very small area at the wheel to wheel point of contact. The safe upper limit of pre-load is found by calculating a suitable contact stress value. The Lower limit of pre-load must be found by testing. The following method was used to obtain this limit.

- Set pre-load to upper limit value. (11lb giving a contact stress of 35000lb/in^2)
- Drive test rig wheel to zero point .
- Set test encoder count value to zero.
- Move test rig wheel through 360 degrees, bring to rest.
- Return wheel to zero point, bring to rest.
- Record test encoder count value.
- Repeat the test, decrementing the pre-load setting at the end of each cycle, and record results.

A marked increase in lost counts should be observed at the point where the contact force is no longer sufficient to provide accurate wheel to wheel tracking. A word of caution, the test rig wheel has a measured radial runout, because the pre-load is provided by a compression spring that is referenced to ground, the pre-load will vary with radial runout. For example, if the radial runout of the wheel is equal to 0.005" and the pre-load spring has a rate of 1001b/in. The pre-load will vary by 0.51b. It is very important that this variation does not allow the wheel to wheel contact stress to exceed the materials yield point. Compressive yield for structural steel can be as low as 350001b/sq in. For this reason it is highly recommended that the pre-load be set at the point of high radial runout.

Use of a low spring rate pre-load spring reduces this effect.

4.3 Misalignment test

The aim of this test is to determine the level of lost counts at the test encoder, at various skew angles with respect to the test rig wheel. The following procedure was used.

- Set test rig wheel to zero.
- Reset test encoder value to zero.
- Drive test rig wheel through 360 degrees and bring to rest.
- Return wheel to zero, record encoder count value.

Repeat the cycle, each time setting the test encoder roller to a different skew angle. Perform tests with both positive and negative angles. A graph of the data taken during this test should show a minimum value of count errors and a corresponding "best" skew angle setting.

4.4 Contamination test

This test is designed to investigate the effects of surface contamination, of the test rig wheel telescope drive disk surface), on the performance of the test encoder mount. In the interest of preserving the integrity of the test encoder drive roller, soon to be installed on the WIYN telescope, only oil was used as the contaminant. Tests using particulate contaminants were not performed. Test procedures used are identical to the misalignment tests described earlier, to prove comparison.

4.5 Swing tests with axial runout (disk referenced encoder mount only)

This test is similar to that described in section 4.1, with one major difference. The test rig wheel is tilted with respect to its bearing axis to produce axial run out at the wheel periphery. This tilt was achieved by placing shim stock between the test rig wheel and its mounting flange. See results section for specific runout data.

5 INITIAL TEST ENCODER ALIGNMENT TO TEST RIG.

5.1 Ground referenced encoder mount:

5.1.1 Gross Alignment (test rig wheel to encoder mount drive roller)

Gross alignment was achieved by measuring the angle between the side of the test rig wheel and the side of the WIYN Mount. Measurements were taken at two adjacent points on the mount, using a depth micrometer placed on the test rig wheel. The readings were compared and the angle adjusted using the adjustment screws provided on the WIYN mount, until both measurements were the same.

5.1.2 Fine Alignment (test rig wheel to encoder mount drive roller)

Fine alignment was achieved using the following technique. Monitor output from the side thrust load cell on the WIYN encoder mount. Rotate the test rig wheel through one full revolution. Note the maximum value shown by the load cell. Using the micrometer adjuster, Skew the WIYN encoder roller. Repeat the test and record the maximum load cell value. Repeat this process rotating the test rig wheel in both directions until the load cell reading is at a minimum, indicating minimum side thrust and hence optimum alignment angle.

5.2 Disk guided encoder mount:

5.2.1 Gross Alignment (test rig wheel to encoder mount drive roller)

A straight edge is placed on the surface of the side guide bearings. The angle between this straight edge and the encoder drive roller is adjusted to zero, by measuring between the side of the encoder drive roller at two adjacent points, and the edge of the straight edge.

5.2.2 Fine Alignment (test rig wheel to encoder mount drive roller)

Fine alignment is achieved by recording encoder count errors over a constant angular movement of the test rig wheel and adjusting the "skew" angle of the test encoder until the error count is at a minimum. No load cell or other device is incorporated to measure side forces that may be used as an alignment aid.

6 RESULTS - INTRODUCTION

Wherever possible, the tests outlined in section 5.0 where performed on both, ground and disk referenced encoder mounts in the same way, to provide direct comparison of errors. However, due to differences in design and finished hardware this was not possible in every case. Differences in procedure are highlighted in the text where appropriate.

6.1 Ground referenced encoder

6.1.1 Pre-load test

The ground referenced encoders pre-load is controlled by a compression spring, mounted in a housing with an adjustable screw device, that allows various spring loads to be applied. The results were obtained using the procedure outlined in section 4.2. The table shows the mean and standard deviation of counts recorded at the test encoder, during the application of various spring pre-loads. The spring rate of the pre-load spring was measured at 98.36lb/in.

Table 1 Pre-Load test results

Pre-load setting (lb)	Test rig wheel rotation (Deg)	Mean count error at test encoder (WIYN)	SD of count error at test encoder (WIYN)
11.000	0 -360 - 0	49.000	59.000
10.200	0 -360 - 0	63.000	120.000
9.400	0 -360 - 0	221.000	313.000
8.600	0 -360 - 0	9.000	11.000
7.800	0 -360 - 0	168.000	641.000

The results show the best pre-load position as 8.6lb and a high count loss due to slippage at 7.8lb and 9.4lb values. It can be seen from the data that the relationship between pre-load and count error is not linear. This may be due to movement within the encoder mount assembly or disk surface effects. Further tests could be done with a pre-load spring of a lower spring rate mounted in a housing, providing fine calibrated adjustments, this would provide a wider range of test results. The 11lb setting was chosen for use in all results that follow. This value does not induce high contact stress levels, but is high enough to comfortably avoid slippage.

6.1.2 Misalignment test

The following results were obtained using the procedure outlined in section 4.3. The start condition for these tests is with the encoder mount aligned to the test rig wheel, following the methods outlines in the "Initial encoder alignment" section. The encoder roller is skewed with respect to the test rig wheel, using a micrometer adjuster with a range of + - 0.025" and a resolution of 0.00001". The adjuster is positioned 6.25" from the roller pivot point. This arrangement gives an angular resolution for the adjuster of 0.33 arcsec.

Adjuster increments of one rev (41.25 arcsec) were used in the test.

Test rig wheel movements for all results were 0 - 360 - 0 (Deg).

Figure 3.0 shows the results of the misalignment tests. The zero point on the x axis (test encoder roller skew angle) shows the error present at the beginning of the test, with the roller angle set using the procedure outlined in section 4.0. The arrow indicates the optimum skew angle of 82.5 arcsec (relative to starting angle). This data may be used to set the optimum skew angle for the encoder roller. It also gives an indication of the allowable skew angle error for a given range of encoder errors. It is important to perform this test after the final encoder mount pre-load is set, as any subsequent change of pre-load would produce a totally different set of data.

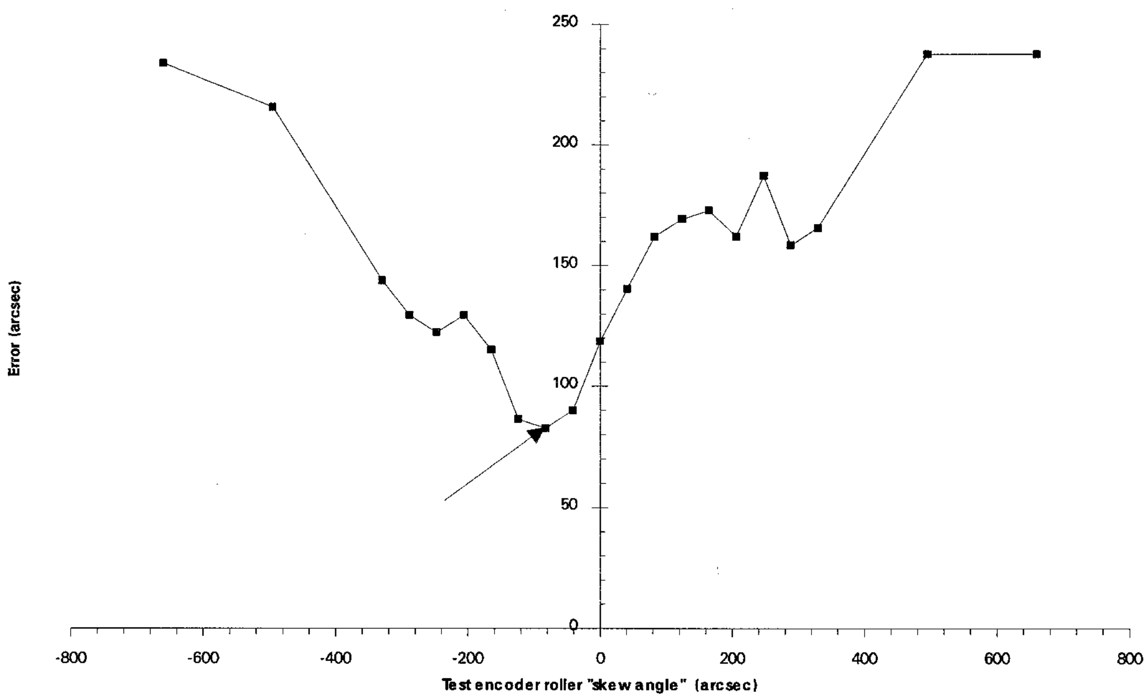

Figure 3. Misalignment test results (ground referenced encoder)
Note: Vertical axis is count errors in arcsec.

6.1.3 Contamination test

The following results were obtained using the procedure outlined in section 5.4. The misalignment test was repeated with the contaminant present (light, clean machine oil) to show the effect of oil contamination on the test encoder count error.

Figure 6.3 shows encoder roller skew angle against test encoder error, plotted over the previous uncontaminated data. In general the oil contamination had only a small effect on performance. Undoubtedly prolonged oil contamination in the field would attract airborne particulate and give rise to more significant errors.

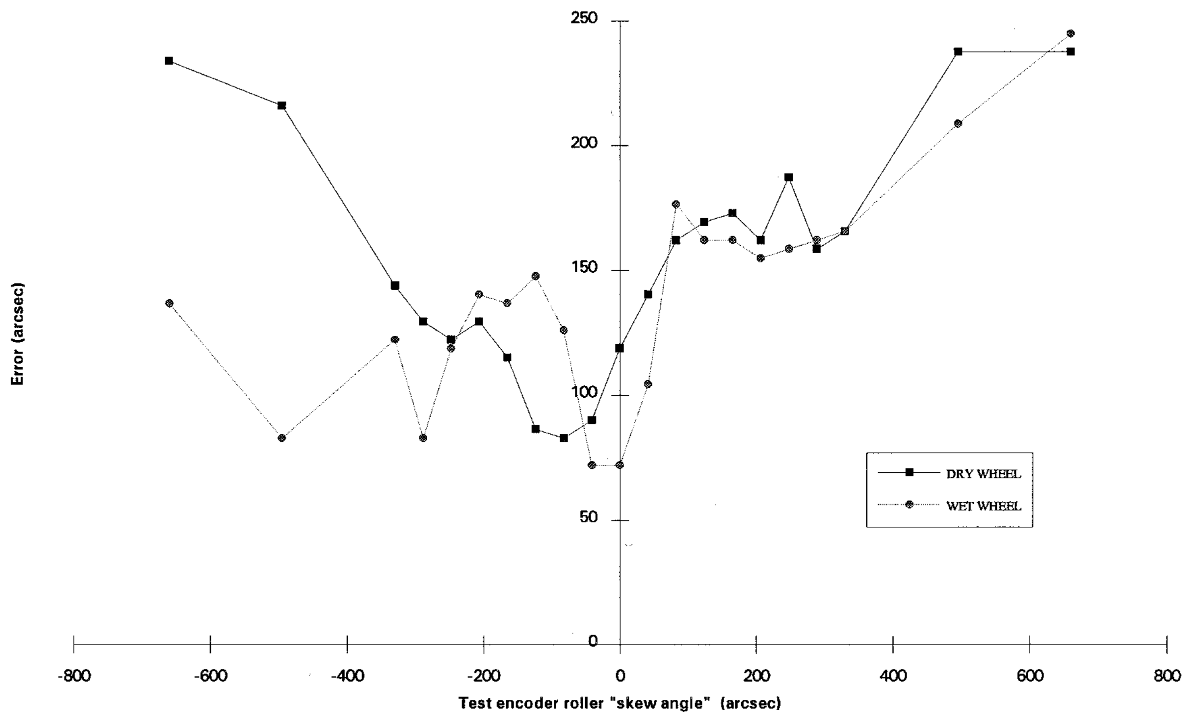

Figure 4. Contamination test (ground referenced encoder)
Note: Vertical axis is encoder count errors in arcsec.

6.1.4 Swing test

The following results were obtained using the procedure outlined in section 4 5.1 and are presented in the tables as they apply to both Gemini and WIYN telescope azimuth axes.

Table 2 Ground referenced encoder.
Swing test results related to *(WIYN Azimuth Axis)*

WIYN Azimuth Rotation (Deg)	**FDE Encoder (Standard deviation) Counts**	**FDE Encoder error (RMS Counts)**	**FDE Encoder error (RMS ARCSEC)**	**WIYN Azimuth Error on sky (ARCSEC)**
0.016	0.000	10.000	3.600	0.100
1.000	3.000	11.400	4.100	0.110
90.000	24.800	27.680	9.960	0.280
180.000	15.600	22.800	8.210	0.230
360.000	39.000	45.270	16.290	0.450

Table 3 Ground referenced encoder. Swing test results related to *(Gemini Azimuth Axis)*						
Gemini Azimuth Rotation (Deg)	FDE Encoder (Standard deviation) Counts	Error on FDE Encoder axis (RMS counts)	Error on FDE Encoder Axis (RMS arcsec)	Gemini Azimuth Error on Sky *Before pointing correction* (arcsec)	Target Specification *After pointing correction* (arcsec)	Goal *After pointing correctio n* (arcsec)
0.016	0.000	13.300	4.780	0.049	--	--
1.000	15.000	15.800	5.690	0.059	0.200	0.150
90.00	11.000	13.030	4.690	0.050	--	--
180.000	114.280	314.500	113.200	1.180	--	--
360.00	311.000	1,051.000	378.400	3.950	1.410	0.424

6.2 Disk referenced encoder

6.2.1 Pre-Load test

The ground referenced encoder design uses a magnet to pull the encoder assembly on to the test rig wheel in the radial direction. This method was employed during the tests to replace a spring device that is itself connected to ground and might provide resistance to movement of the encoder assembly in the axial direction. The magnet is clear of the disk surface by a small amount, and offers no resistance to axial movement, this clearance or gap can be adjusted to vary the radial pre-load. Due to the similarity between encoder drive wheel contact on both mount designs no pre-load tests were undertaken on this mount design, the pre-load was set to 11lb as in previous tests.

6.2.2 Misalignment test

The following results were obtained using the procedure outlined in section 4.3. The start condition for these tests is with the encoder mount aligned to the test rig wheel, following the methods outlines in the "Initial encoder alignment" section. The encoder roller is skewed with respect to the test rig wheel, using a micrometer adjuster with a range of + - 0.1mm and a resolution of 0.0005mm. The adjuster is positioned 100mm from the roller pivot point. This arrangement gives an angular resolution for the adjuster of 1.03arcsec. Adjuster increments of one division (1.03 arcsec) were used in the test. Test rig wheel movements for all results were 0 - 180 - 0 (Deg).

Figure 5 shows the results of the misalignment tests. The zero point on the x axis (test encoder roller skew angle) shows the error present at the beginning of the test, with the roller angle set using the procedure outlined in section 4.0. The optimum skew angle is around 3.5 arcsec (relative to starting angle). This data may be used to set the optimum skew angle for the encoder roller. It also gives an indication of the allowable skew angle error for a given range of encoder errors. Some hysteresis was present in the tested mechanism indicated by the erratic data points in the zero to ten range, however the over-all trend indicates the ideal skew angle.

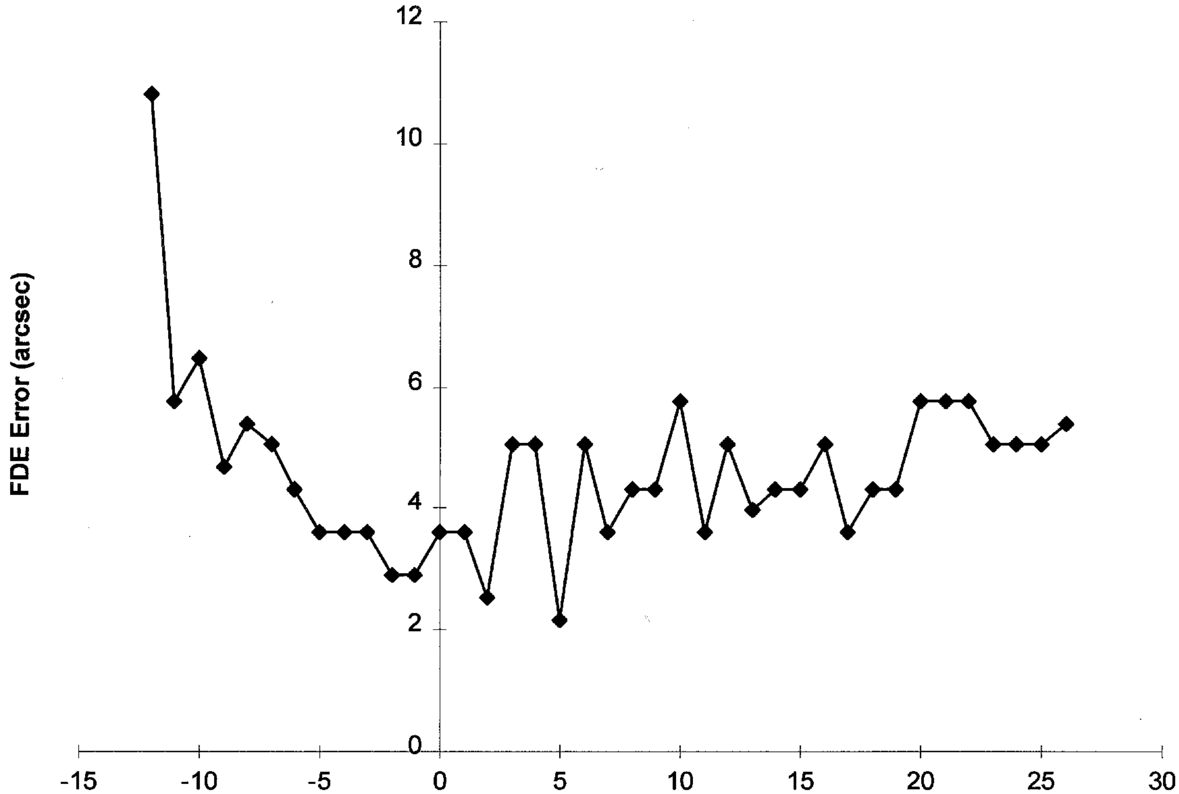

Figure 5 Misalignment test results (Disk referenced encoder)

6.2.3 Contamination test

Due to the similarity in encoder drive wheel to test rig wheel contact properties between both types of encoder mount. This test was not performed for the disk referenced mount.

6.2.4 Swing test

The following results were obtained using the procedure outlined in section 4.1 and are presented in the tables as they apply to the Gemini azimuth axes.

Table 4 Disk referenced encoder. Swing test results related to *(Gemini Azimuth Axis)*							
Gemini Azimuth Rotation (Deg)	Test rig rotation (Deg)	Error on FDE encoder axis (Standard deviation counts)	Error on FDE encoder axis (RMS counts)	Error on FDE encoder axis (RMS arcsec)	Gemini Azimuth Error on Sky *Before pointing correction* (arcsec)	Target Specification *After pointing correction* (arcsec)	Goal *After pointing correction* (arcsec)
0.660	3.150	11.900	12.600	4.530	0.047	--	--
1	4.720	0.000	20.000	7.200	0.074	0.200	0.150
90	425.190	93.000	98.000	35.300	0.364	--	--
180	850.390	8.400	20.000	7.200	0.074	--	--
360	1,700.780	200.000	772.000	277.900	2.867	1.410	0.424

The above values can be derived using the following constants:

- Diameter of Gemini azimuth drive surface = 9600mm
- Diameter of test rig wheel = 2032mm (80")
- Diameter of test encoder drive wheel = 99.06mm (3.9")
- One count error at the FDE encoder = 0.36 arcsec

6.3 Swing test with axial run out

Two tests were performed to measure the effectiveness of the disk guided encoder mount, with different axial runout settings. The first test had a wheel axial run out of 0.889mm (0.035"), the second 3.81mm (0.150"). It should be noted that prior to the tests the nominal test rig wheel axial runout was measured at 0.1016mm (0.004"). For comparison both tests repeated the 90 deg Gemini azimuth axis (425.19 deg test rig wheel rotation) tests outlined in Table 3.

Table 5 Disk referenced encoder Swing test with axial run out related to *(Gemini Azimuth Axis)*						
Axial runout (mm)	Gemini Azimuth Rotation (Deg)	Test rig rotation (Deg)	Error on FDE encoder axis (Standard deviation counts)	Error on FDE encoder axis (RMS counts)	Error on FDE encoder axis (RMS arcsec)	Gemini Azimuth Error on Sky *Before pointing correction* (arcsec)
0.889	90	425.190	27.600	33.600	12.090	0.125
1.400	90	425.190	70.730	1,504.500	541.620	5.580
1.520	90	425.190	59.000	1,446.400	520.700	5.370
3.810	90	425.190	127.400	1,543.400	555.620	5.733
4.320	90	425.190	110.000	560.600	201.800	2.080

7 CONCLUSIONS AND COMMENTS:

7.1 Encoder mount design: General

The following text describes design criteria thought to be important in an effective encoder mount assembly, in most cases they apply equally to both ground or disk referenced systems.

- Mount the encoder drive wheel in a stiff pre-loaded bearing assembly with zero axial play.
- Provide a calibrated, radial pre-load device.
- Apply a crown to the periphery of the encoder drive wheel. Ensure that a hardened and around, high quality surface form, and finish are present.
- Include a calibrated, coarse and fine, rotation adjustment of the encoder drive wheel.
- Encoder mount stiffness, in the direction tangential to the drive surface is paramount, to minimize errors.

7.2 Encoder drive wheel angular adjustment:

It has been established through the tests carried out by this project and information gained from the astronomical - engineering community, that fine angular adjustment mechanisms must be incorporated into any high performance encoder mount design. The resolution of this adjustment should be in the, one to five arcsecond range for fine adjustments. A coarse adjustment range should also be provided of around +two deg. this will allow inaccuracies between the encoder assembly telescope mount, and the telescope drive disk surface, to be eliminated prior to fine adjustments. It is also important to lock the assembly to avoid unwanted rotation, once adjustments have been made. It is imperative that this "lock" does not impart further rotation to the encoder assembly.

7.3 Encoder assembly stiffness

Having established that the encoder drive wheel be mounted in a stiff pre-loaded bearing arrangement, and that angular adjustment of this assembly is required, it is important to ensure, that the angular adjustment mechanism, does not compromise the overall stiffness of the encoder assembly or mount.

7.4 Axial load measurement

Direct measurement of friction induced axial loading of the FDE encoder drive wheel can be incorporated within the encoder assembly (as in the WIYN design) using suitable load cell's. The output from such a load cell may be used as an alignment aid when setting up the encoder assembly on the telescope. This method can be useful, but only if its implementation does not compromise the encoder assembly stiffness. This route was not taken in the Gemini encoder design, as alignment using the direct count error readout was though to give satisfactory results, without the added complication of the load cell and associated mechanical assembly.

7.5 Radial pre-load

None of the encoder mounts tested provided adequate radial pre-load adjustments. The WIYN ground referenced mount came close, by providing a compression spring mounted in a tube, with an adjustment nut that allowed the applied spring force to be varied. The Gemini disk referenced mount originally provided an adjustable compression spring mounted from ground that provided radial pre-load. This arrangement proved ineffective as it impaired the free axial movements necessary for correct encoder assembly operation, and was replaced by a magnetic device. This device consisted of a simple rectangular magnet, fixed to the underside of the encoder assemble, and arranged to clear the test rig wheel by a small amount. The magnet's distance from the test rig wheel was adjusted using a simple fine pitch bolt. This adjustment allowed the pre-load to be set, and offered no resistance to axial movements of the encoder assembly.

Radial pre-load is an important factor in the operation of the encoder mount. It must be restricted to limit the Hertz contact stresses at the wheel to wheel contact point to ensure that plastic deformation does not take place. It also has an effect on the level of errors generated by the encoder mount system and must be high enough to prevent slippage.

The ideal radial adjuster should provide a good range of calibrated load adjustment. The upper limit of this adjustment can be calculated to limit contact stress. The lower limit may be found by experimentation. The provision to use various springs of similar dimension, but differing spring rates would be a useful addition. Ideally the adjustment of the spring should be calibrated to allow accurate force measurement and repeatability.

7.6 Comparison of test results:

Table 6 Disk and Ground referenced encoders.
Comparison of swing test, count results
Note: Test rig wheel "best " axial run out = 0. l mm

Test rig rotation (Deg)	Error on encoder axis **With 0.1mm** axial runout (Counts) *Disk referenced*	Error on encoder axis **With 0.1mm** axial runout (Counts) *Disk referenced*	Error on encoder axis **With 0.889mm** axial runout (Counts) *Disk referenced*	Error on encoder axis **With 3.81mm** axial runout (Counts) *Disk referenced*
3.150	12.600	13.300		
4.720	20.000	15.800		
425.190	98.000	13.030	33.600	1,543.000
850.390	20.000	314.500		
1,700.780	772.000	1,051.000		

Table 6 lists the comparisons of test results taken in all swing tests, in terms of lost counts at the encoder axis.

The data shows for rotation values of 3.15 and 4.72 degrees. The performance of both mounts is comparable with a maximum count difference of 5.

For the 425.19 degree rotation the ground referenced mount shows a far superior reading, being some 85 counts lower than the disk guided mount.

The final two angular movements of 850.39 and 1700.78 show the disk referenced mount to be superior with 294.5 and 279 counts less, respectively.

A comparison of the 425.19 degrees (90 deg of Gemini azimuth axis) swing tests between the disk referenced encoder with adjusted axial runout of 0.889mm, shows a gain in performance, and a decided loss in performance at the 3.81mm axial run out setting as compared to the 0.1mm nominal runout. This may suggest some resistance to axial movement in the encoder ground connecting link, which is inducing these high errors.

7.7 Conclusions:

The tests support the theory that an encoder mount designed to follow disk axial runout can improve overall performance in cases where axial runout are unavoidable. It is important however to ensure that the mechanisms incorporated to allow axial movement tracking, do not in themselves, add to the inaccuracies of the system. There is no doubt that the ground referenced mount is inherently simpler in design, this increases reliability, and system stiffness, and should be considered as a design priority in cases where axial runout is acceptably low. In cases where axial runout is a concern, a hybrid system may be considered that is attached to ground but allows some controlled movement in the axial and radial directions only.