Celera MOTION
A Novanta Company

Alignment of Rotary Scales

TN-1101 | REV 160602

PRECAUTIONS

Follow standard ESD precautions. Turn power off before connecting the sensor.
Do not touch the electrical pins without static protection such as a grounded wrist strap.

Do not touch the glass scale unless you are wearing talc-free gloves or finger cots. Refer to the Mercury Encoder installation manual for full instructions.

INTRODUCTION

Eccentricity error is the radial difference between the grating's axis of rotation and the center of the rotary grating, see figure 1.0 below. Eccentricity is also the largest controllable source of error in any rotary encoder systems. To achieve the highest level of long range accuracy, the eccentricity must be minimized. The run-out of the bearing shaft can degrade the long range rotary accuracy, making the selection of the proper bearing an important part of the integration process. In general, we recommend a Nema class 7 bearing or better for high accuracy applications. The effect of eccentricity and run-out has an increasing effect as the grating size decreases.

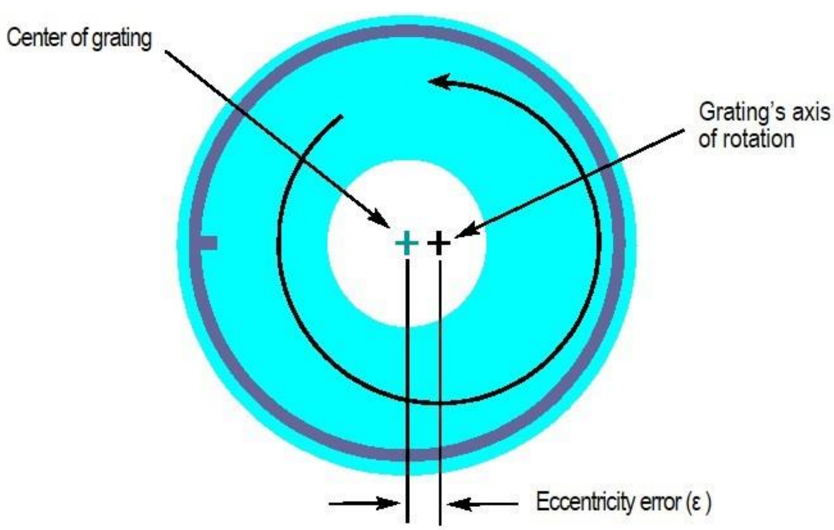
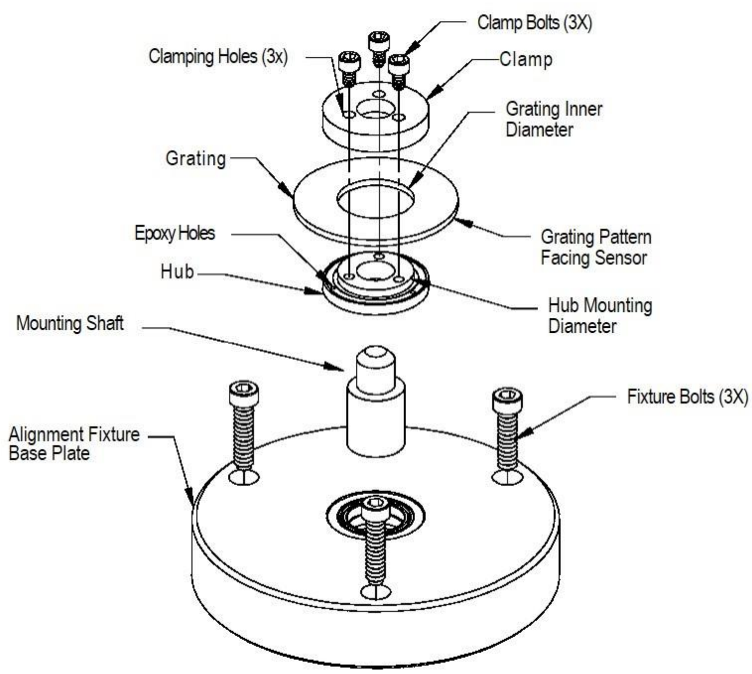


Figure 1.0

This document will cover two different methods of aligning rotary gratings; optically centering the grating pattern track using a CCD camera and using two sensors to "electrically" center the grating. Optically centering gratings requires less skill and training than the electrical method, but is not able to center the grating as well. The eccentricity can be reduced to approximately to 10 µm using the optical method and the electrical method can reduce eccentricity to better than 3 µm.

ALIGNMENT FIXTURE

The alignment fixture uses the inside diameter (ID) of the hub as the reference datum.
Once the grating has been aligned to this reference datum, alignment can be
"transferred" to the customer's application by remounting the hub/scale assembly in the customer's application using the same reference datum.



Mounting Clamp, Grating and Hub (Exploded View)

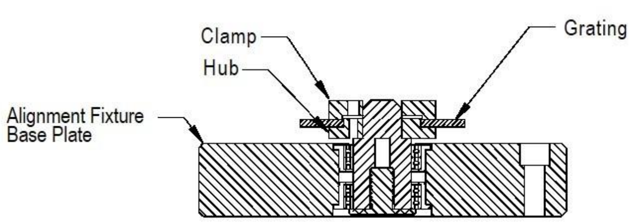


Figure 2.0 Exploded view of alignment fixture

OPTICAL ALIGNMENT

Optically aligning a rotary grating to the hub using a CCD camera relies on the fact that the outer edge of the grating pattern is essentially a perfect circle. The edge of the grating pattern will not shift radially if the center of the grating pattern is perfectly aligned to the assembly's axis of rotation. If the grating is not perfectly centered, the grating pattern will shift radially by twice the eccentricity error. The CCD camera must provide approximately 1 µm resolution to be able to accurately measure how much the edge of grating pattern is moving radially as the scale is rotated 360 degrees. A 0.5mm field of view is a good rule of thumb (25 lines for a 20µm pitch grating).

What you will need:

- Rotary Scale
- Hub
- Scale Clamp
- Mounting fixture for hub
- CCD camera or Microscope
- Hard Epoxy (TRA-BOND 2143D is recommended)
- Acetone (for cleaning scale)
- Lint free 100% optical cleaning cloths (Kimwipes)
- Power free finger cots or gloves for handling scales
- Stout wooden stick (~0.25 inch diameter)
- Light mallet for tapping

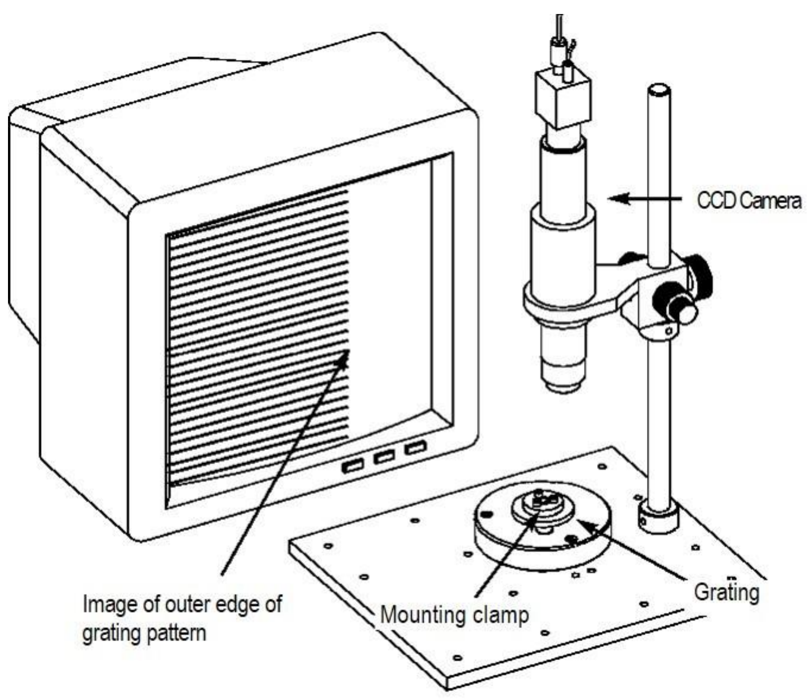


Figure 3.0: Setup of CCD camera and alignment fixture

PROCEDURE:

1. Secure the alignment fixture to a flat reference surface such as an optical bench.
2. Place the hub in the alignment fixture.
3. Place the scale on the hub being sure that the grating pattern is facing the correct direction.
4. Position CCD camera over the outer edge of the grating pattern.
5. Place the clamp over the scale and tighten the screws so that the scale can still move with respect to the hub with resistance.
6. Rotate the hub/scale/clamp assembly, and observe the movement of the pattern edge on the camera's monitor.
7. Note the peak-to-peak radial travel of the pattern's edge over one full rotation of the scale.
8. Locate the largest peak radial displacement under the CCD camera and gently tap the edge of the scale until the pattern's edge has moved 1/2 the peak-to-peak distance using the wooden stick and mallet.
9. Rotate the assembly again and repeat steps 6-8 until the peak-to-peak radial travel is minimized (typically less than ±10 µm)
10. Carefully tighten the clamping screws to secure the scale in position. Verify that the scale is still properly aligned.
11. Remove scale/hub/clamp assembly from alignment fixture.
12. Mix epoxy and inject it into the hub's epoxy groove using the epoxy holes.
13. Allow the epoxy to fully cure before removing mounting clamp. Consult epoxy manufacturer for information on appropriate curing schedules.

The images in figure 4.0 illustrates a scale with an eccentricity error of 5 µm. The eccentricity error is calculated by dividing the total radial movement of the scale pattern by 2 (10 µm/2 = 5µm).

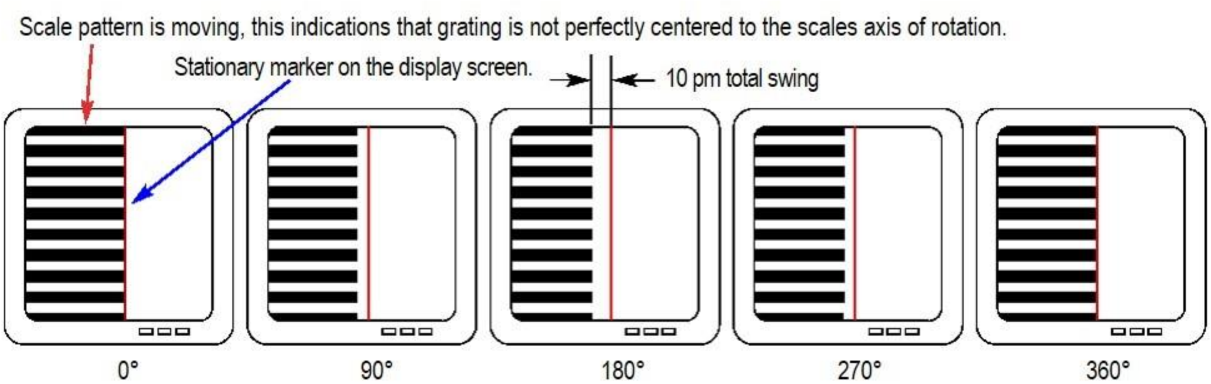


Figure 4.0: Screen images of edge of scale with eccentricity error with the rotary position of the scale under each image

When the scale is perfectly centered, the eccentricity error will be zero and the edge of the grating pattern will have no radial movement as the grating is rotated through 360 degrees. Figure 5.0 illustrates a scale that is perfectly centered.

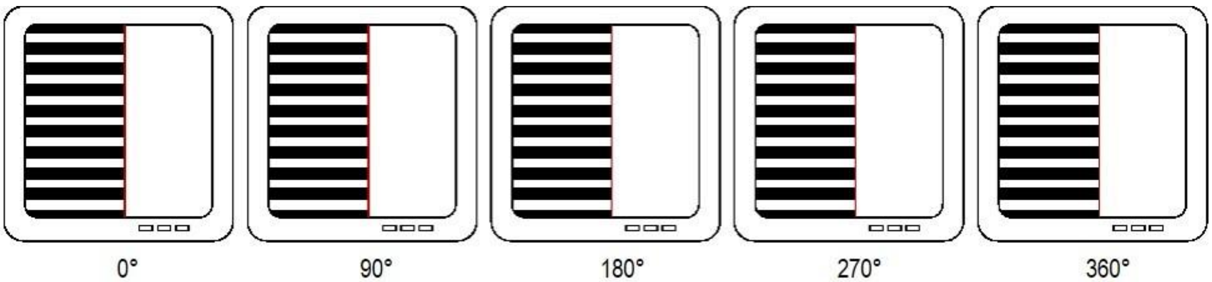
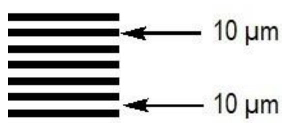


Figure 5.0: Close up of edge of scale without any eccentricity error or bearing runout with the rotary position of the scale under each image.

If the CCD camera does not have a scale, the chrome lines on scale can be used to calibrate the amount of movement radial of the grating pattern. The width of a single scale line or the space between the lines are both 10 µm.



Electrical Alignment

What you will need:

- Two (2) analog output sensors (ex: M05, M1200, MII1900)
- Breakout Board with power supply
- Two (2) standard oscilloscope cables
- Two channel oscilloscope (digital oscilloscope with storage is recommended)
- Hard Epoxy (TRA-BOND 2143D, recommended)
- Acetone (for cleaning scale)
- Lint free 100% optical cleaning cloths (Kimwipes)
- Power free finger cots or gloves for handling scales
- Motorized fixture to rotate scale at a constant speed(20 to 50 RPM)

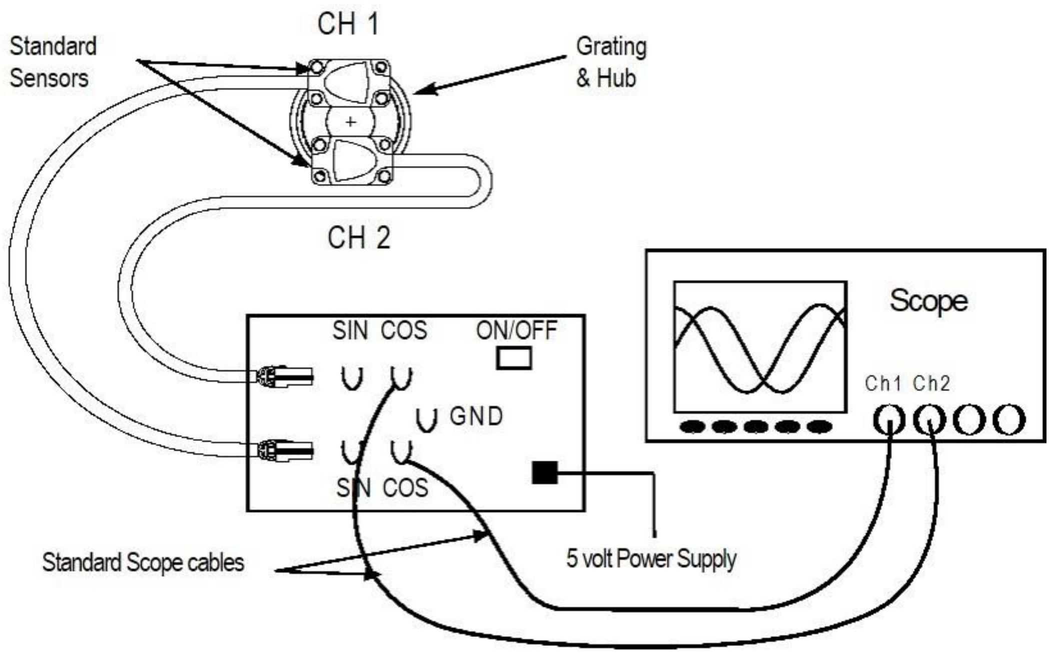


Figure 6.0: Setup for aligning Rotary scales using two sensors

Locate the sensors 180 degrees apart. Then align each sensor individually.

Once both sensors are aligned, connect the sin signal from each sensor to the oscilloscope. The oscilloscope should be in time based mode and set to trigger off the Channel 1 signal. It is important that the scale is rotating a constant speed during the alignment process. Variations in speed will cause both signals to expand and contract at the same rate making it very difficult align the scale. Both signals will remain stationary when the scale is perfectly aligned. If there is any eccentricity, the measurement signal (Channel 2) will move one direction then to the other direction as the scale completes one rotation. This movement is the total swing of the measurement signal and is used to calculate the eccentricity error using equation 1.0.

Equation 1.0: eccentricity error = 5 x Total Swing (number fringes)

See the Reference section on the Theory for Two Sensor Head Alignment Method for an explanation of how to calculate the eccentricity from the total swing of the measuring signal.

Note: Very small rotary gratings may not be able to be aligned using the 2 sensor head method because the scales are too small for two sensors to read the scale at the same time.

PROCEDURE:

1. Place scale on the hub without the epoxy.
2. Loosely clamp scale to hub using temporary clamp.
3. Placed hub and scale assembly on a motorized centering fixture to provide constant rotation.
4. Two sensors are placed 180 degrees apart on the scale and aligned.
5. One sine signal from each encoder is monitored on an oscilloscope.
6. The oscilloscope is triggered by one sensor, which forms a stationary sine wave on the oscilloscope.
7. The sine wave from the second encoder moves across the oscilloscope's screen in both directions with the motion of the scale relative to the triggered stationary wave. Using a clean tapping tool (wooden dowel), tap the edge of the scale close to the encoder that is used as the trigger until the measurement sine wave moves no more than +/- 1 cycle relative to the stationary wave. 8. Tighten the mounting clamps
8. Inject epoxy (Tra-Con 2143D) in to the epoxy injection holes on the hub.

Below are two oscilloscope images showing different levels of alignment.

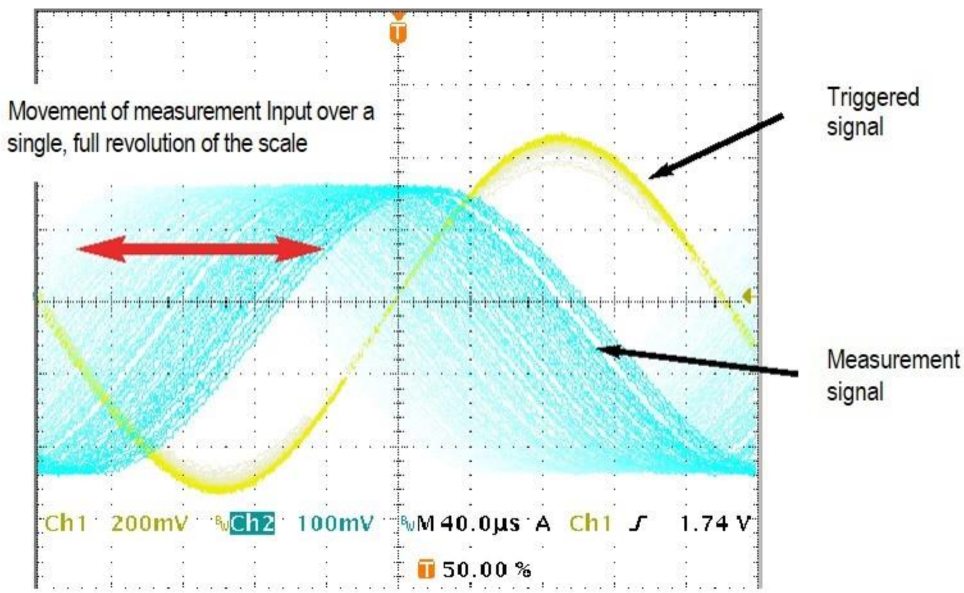


Figure 7.0: Oscilloscope trace showing alignment within 1/2 fringe

Oscilloscope trace showing the measurement signal moving approximately 1/2 of the display width as the scale moves through 360 degrees. Since the display is adjusted so the total display is equal to one fringe, it is clear that the measuring signal is moving 1/2 of a fringe. This translates to an eccentricity error of 2.5 µm (5 x number of fringes = 2.5 µm).

Refer to the reference section located at the end of this document for more information on how the 2 sensor method works and how to calculate.

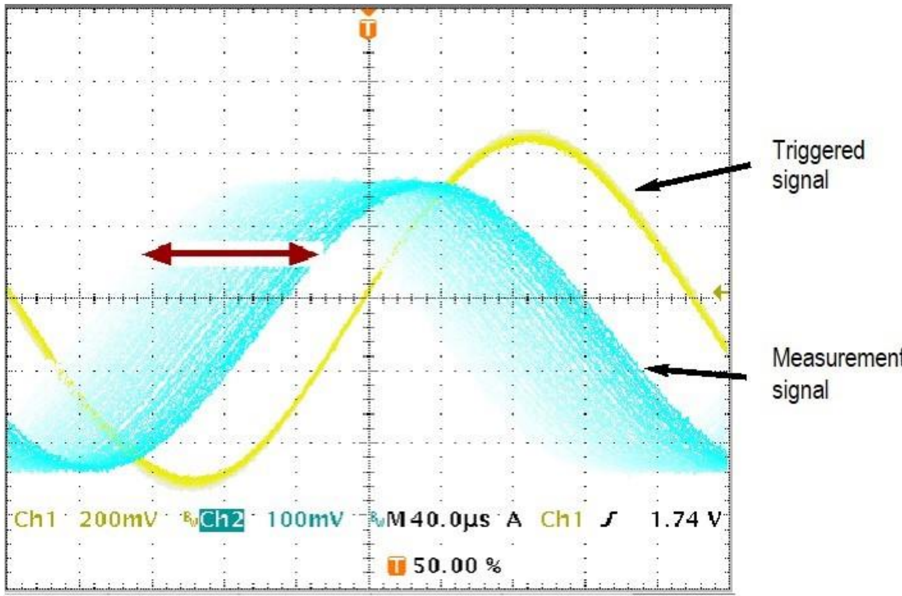


Figure 8.0: Oscilloscope trace showing alignment within 1/5 fringe

Oscilloscope trace showing the measurement signal moving approximately 1/5 of a fringe. The eccentricity error has been reduced to approximately 1 µm.

REFERENCE SECTION

Rotary Accuracy

Rotary accuracy can be divided into two different parts; long range and short range accuracy. The long range accuracy is typically measured over 360° and the short range accuracy is measured over a single fringe. The major error sources for long range accuracy are; eccentricity error and bearing runout. The major error sources for short range accuracy are; small imperfections in grating pattern, variations in the sensing components, and imperfection in signal corrections.

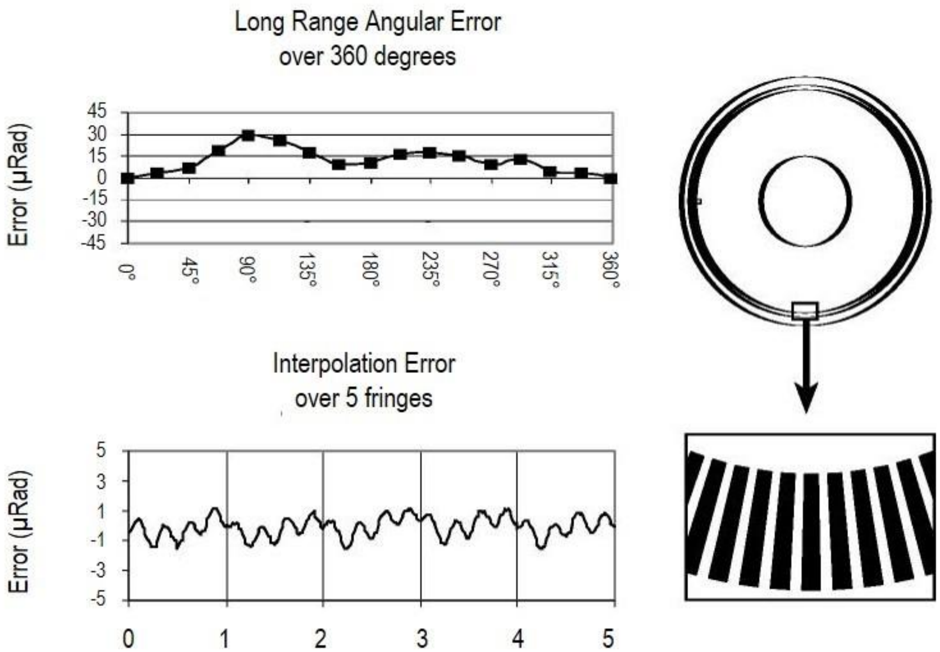


Figure 9.0: Short and Long range angular errors

Short Range Accuracy (Intrafringe Error)

The magnitude of the short range error varies with the optical radius and the type of processing electronics. Intrafringe error is based on the interpolation of cyclical error of a sensor head family. See MicroE data sheets for the error associated with your particular encoder model. See the Reference Section located at the end of this document for a sample of how the intrafringe errors were calculated.

Long Range Accuracy

Assuming perfect alignment of grating pattern to axis of rotation.

Table 1.0 lists the scale accuracy of each standard Mercury scale assuming perfect alignment of the scale to the axis of rotation.

Grating Model	Optical Radius	Angular Error
R1206	0.207 [5.25]	± 100 [21]
R1910	0.314 [7.96]	± 63 [13]
R3213	0.514 [13.04]	± 38 [8]
R5725	1.027 [26.07]	± 19 [4]
R10851	2.053 [52.15]	± 10 [2]
	inch[mm]	µRad[Arc-sec]

Table 1.0: Long range errors

Long Range Accuracy (Eccentricity Errors)

Figure 10.0 illustrates the angular error (θ) resulting from an eccentricity error.

The amount of allowable eccentricity error can be calculated from the maximum angular error desired.

$\theta = \tan^{-1}(\varepsilon/R)$

Given:

θ = angular error due to eccentricity.
ε = eccentricity error. R = optical radius of scale

For a R10851 with an eccentricity error of 3 µm $\theta = \tan^{-1}(\varepsilon/R)$

$= \tan^{-1}(0.003\text{ mm}/ 104.3*0.5\text{ mm})$
= 0.003296 deg
= 11.866 Arc-sec
= 57.5 µRad

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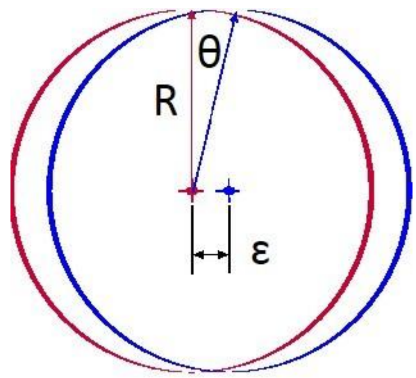


Figure 10.0

Effect of Eccentricity on Angular Accuracy over 360 degrees

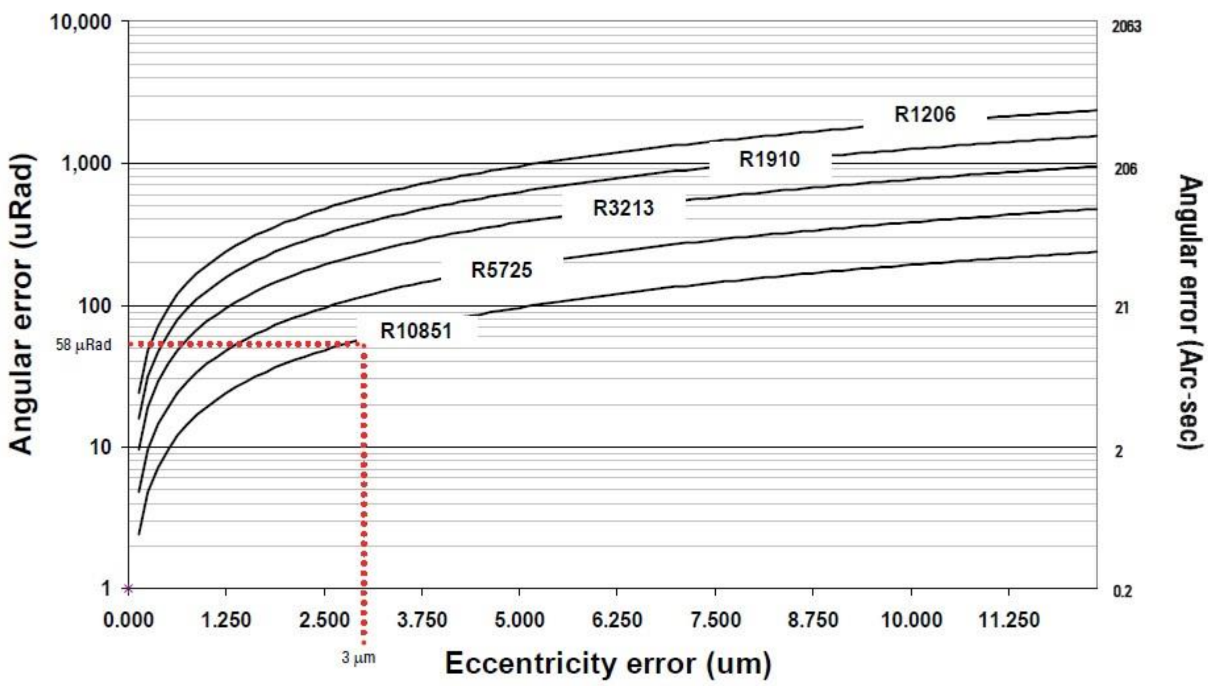


Figure 11.0: Chart relating eccentricity error to angular error for standard Mercury scales

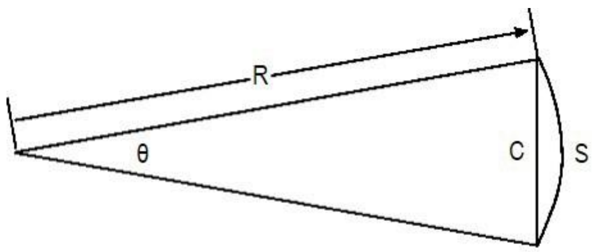
This chart can be used to find the angular error that would result from a given eccentricity error or to find what eccentricity corresponds to a given angular error.

In either case, first locate the curve for the scale in question then select either the maximum acceptable angular error on the Y-axis or select the eccentricity of interest then find the corresponding value on the other axis.

As an example, if the eccentricity error for a Mercury R10851 scale is reduced to 3.0 µm, the resulting angular error would be 58 µRad (see dotted line lines in Figure 11.0).

The total system accuracy for a rotary encoder will depend on the scale size, the intrafringe error, the eccentricity error, and the run-out of the shaft.

Method of Calculating Intrafringe Values



Given:

Θ = angular error due to intrafringe error C = cyclical (linear intrafringe) error
R = optical radius of scale

For a 4096 line disk and a Mercury programmable encoder
R = 13.04 mm
C = 0.12 µm*
*Note: This is the maximum deviation from expected value. Maximum peak to peak deviation value would be 0.24 µm

$\theta = 2 \sin^{-1} (C / 2 R)$

$\theta = 2 \sin^{-1} (0.00012 / 26.08 \text{ mm}) = 0.00052726 \text{ deg} = 9.2\ \mu\text{Rad}$

Check using small angle approximation (assuming C = ~ S)

$\theta = S / R$

$\theta = 0.00025 / 13.04 = 9.2\ \mu\text{Rad}$

Theory Supporting the Electrical Method

For Sensor$_n$, the Phase Error (Ψ) due to eccentricity is a function of the rotating shaft angle (θ) and can be represented by the following equation.

$$\Psi_n(\vartheta) = (360 / \lambda)\ \varepsilon \sin(\alpha + \vartheta)$$

Given: ε = Eccentricity of scale.
360 = The number of degrees in an electrical fringe.
λ = Electrical fringe period. α = Angular position of sensor. θ = Rotating shaft angle.

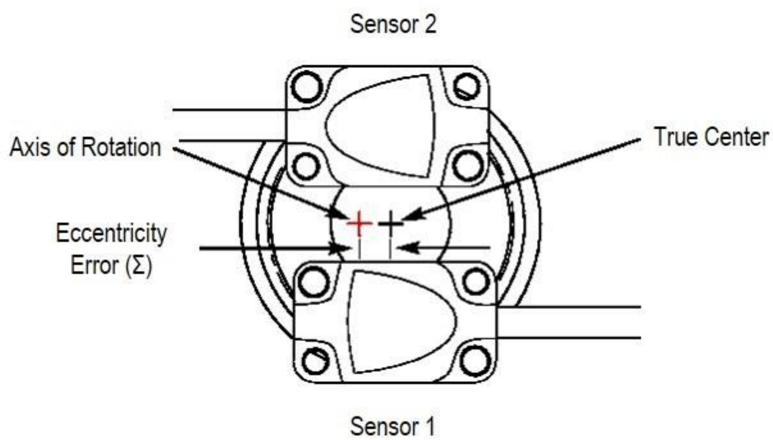


Figure 12.0

With Sensor$_1$ at α = 0°, its Phase Error (Ψ) is:

$$\Psi_1(\vartheta) = (360 / \lambda)\ \varepsilon \sin(\vartheta)$$

With Sensor$_2$ at α = 180°, directly opposite Sensor$_1$, its Phase Error (Ψ) is:

$$\Psi_2(\theta) = (360 / \lambda)\ \varepsilon \sin(180 + \theta) = -(360 / \lambda)\ \varepsilon \sin(\theta)$$

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By triggering of the signal from $Sensor_1$ we are observing the other sensor from a new reference frame; one that varies in phase with $Sensor_1$. From this new reference frame we see the Phase Errors varying as $\Psi_n'(\theta)$.

$$\Psi_n'(\theta) = \Psi_n(\theta) - \Psi_1(\theta)$$

$$\Psi_n'(\theta) = \Psi_n(\theta) - (360 / \lambda)\, \varepsilon \sin(\theta)$$

The signal from $Sensor_1$ appears to stand still since;

$$\Psi_1'(\theta) = \Psi_1(\theta) - (360 / \lambda)\, \varepsilon \sin(\theta) = (360 / \lambda)\, \varepsilon \sin(\theta) - (360 / \lambda)\, \varepsilon \sin(\theta)$$

And the phase error variation of $Sensor_2$ is given by:

$$\Psi_2'(\theta) = \Psi_2(\theta) - (360 / \lambda)\, \varepsilon \sin(\theta) = -(360 / \lambda)\, \varepsilon \sin(\theta) - (360 / \lambda)\, \varepsilon \sin(\theta)$$

$$\Psi_2'(\theta) = -2\, [\, (360 / \lambda)\, \varepsilon \sin(\theta)\,]$$

Now consider that l is a constant for a given scale (20 µm) and ε is a constant for a given alignment. Therefore, Ψ_2' is simply a sinusoidal function of the rotating shaft angle (θ) with amplitude.

$$\text{Amplitude} = 2\, [\, (360 / \lambda)\, \varepsilon\,]$$

Thus the phase error variation appears to oscillate with twice the actual amplitude of the eccentricity.

The total swing of the oscillation that appears on the oscilloscope is the peak to peak value of this equation, and it is twice the amplitude of $\Psi 2'$ or four times the actual amplitude of the eccentricity.

$$\text{Total Swing (number of fringes)} = 2 \times 2 \times [\, (360 / \lambda)\, \varepsilon\,] = 4\, [\, (360 / \lambda)\, \varepsilon\,]$$

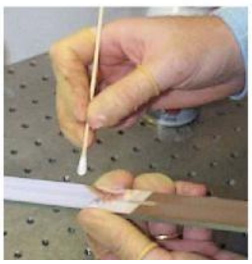
The eccentricity can be calculated from the total swing from $Sensor_2$.
$\varepsilon = [\, \lambda \text{ Total Swing (number fringes)} / (4 \times 360°)\,]$

Since one fringe is = 360 ° and λ is equal to 20µm for Mercury encoder the equation can be reduced to
$\varepsilon = 5 \times \text{Total Swing (number fringes)}$

Cleaning Scales


General Partical Removal

Blow off the contamination with nitrogen, clear air, or a similar gas.




Contamination Removal

Use a lint-free clean room wipe or cotton swab dampened with isopropyl alcohol or acetone only. Handle the scale by the edges. Do not scrub the scale.