

# *Let's Talk Accuracy*

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Written by Gerald S. Gordon

In the world of encoders, the terms **resolution**, **accuracy** and **repeatability** are often confused, and sometimes even thought to be synonyms. Before we can talk sensibly to each other, we need a common language, so we'll start with some definitions. This article refers to rotary encoders because they're much more common than linear, but the interested reader can easily extend this discussion to linear encoders as well.

**Resolution** is a measure of how many counts per unit distance the encoder generates, or, inversely, the size of the measuring step. With rotary encoders, resolution is expressed in either units of angle (degrees-minutes-seconds, decimal degrees, grads, or radians) or in number of measuring steps per revolution (e.g., 10,000 counts/rev). [PPR, or pulses per rev, is quite common, but we avoid this term on purpose. Often, when a binary number of measuring steps per revolution is required, the term "bit" is used to indicate the resolution's highest power of 2; for example, a 16-bit encoder generates  $2^{16} = 65,536$  counts/rev. Resolution is the most basic encoder parameter; you cannot specify an encoder without stating its resolution.

**Accuracy** is a measure of where the encoder says it is vs. where it actually is, or where the counts are compared to where they should be. It is almost always expressed in units of angle, although some components of the error may sometimes be expressed in electrical degrees, which must then be translated to angular measure before summing with other sources. The use of that other term, error, is almost always a tip-off that the accuracy of the encoder is being discussed. Accuracy and error are both expressions of the difference between indicated and true position, but with slightly different connotations: accuracy is how close the indicated reading is to true position, while error is how far the indicated is from true. Thus, higher accuracy is better, but higher error is not.

While the resolution of the encoder is permanently fixed at the time of manufacture by what code disk is installed, and what kind of sensing and processing electronics are built in, encoder error can vary as a function of environmental factors like temperature, shaft loading, and service life. This does not mean that the number of counts per revolution changes. That would occur only as a result of severe damage or contamination of encoder components such as the code disk or bearings. Although accuracy is an attribute of all encoders, not all customers specify it, and you won't even find commonality among the various encoder vendors' data sheets. Some, like us, go into considerable detail when specifying accuracy, some touch on it lightly, and some don't even mention it! In all fairness, many customers assume any encoder offered for sale will be accurate to not worse than  $\pm 1$  count, including quantization error, and in the case of low-resolution devices (up to about 10,000 counts/rev), it's pretty hard to build a self-contained encoder that's not at least that accurate. However, resolution and accuracy are not directly related. In higher performance encoders, the error may sometimes equal many counts, or may be a tiny fraction of a single count, depending on the needs of the application.

**Repeatability** is a measure of what the reading is this time, compared to what it was last time, for travel in the same direction. Depending on the application, it may be important to distinguish between long-term and short-term repeatability. Like accuracy, it is expressed in units of angle. The repeatability of a rotary encoder of conventional construction is usually 5-10 times better (smaller) than the manufacturer's quoted total accuracy (error) specification. You have to understand the application to know what to specify. If you're tracking an aircraft, for example, accuracy will be critical, but if you're teaching a robot to perform a repetitive task, repeatability may be more important to you than accuracy.

**Total Optical Encoder Error** is the algebraic sum of **Instrument Error + Quadrature Error + Interpolation Error + Quantization Error**. In reality, these error sources sum to a value statistically less than the theoretical maximum, but if you use the sum, you'll have a conservative worst-case value. (Before you add the errors, make sure they're all in the same unit of measure.)

**Instrument Error** is the sum of code disk eccentricity, pattern errors, bearing run-out and other opto-mechanical imperfections within the encoder. This error tends to vary slowly around a revolution. We usually express it in either seconds or minutes of arc. In applications where the user's apparatus is operating over a limited rotation angle, it's often possible to assume a significant part of the instrument error will be in effect outside the arc of interest. If you think this may be the case in your application, please consult with us. We know how to estimate (or measure exactly, if necessary) how much of the instrument error over a given angle can be ignored for each of the encoders we produce.

**Quadrature Error** is the combined effect of phasing and duty-cycle tolerances and other variables in the basic analog signals. This error applies to data taken at all four transitions within an optical cycle (the "4X quadrature decode" that is so common among encoder users). If data are extracted from 1X square waves on a 1X basis (i.e., at only one transition per cycle), this error can be ignored. It is expressed on most vendors' data sheets in electrical degrees; you can convert it to angular measure with one of these formulas:

$$\text{Error in arcsec} = (3600) \times (\text{error in elect degrees}) / (\text{disk line count})$$

$$\text{Error in arcmin} = (60) \times (\text{error in elect degrees}) / (\text{disk line count})$$

$$\text{Error in milliradians} = (17.45) \times (\text{error in elect degrees}) / (\text{disk line count})$$

**Interpolation Error** is present only when the resolution has been electronically increased to more than four measuring steps per optical cycle. It is the sum of all the tolerances in the electronic interpolation circuitry, and on our data sheets it is expressed in quanta. ("Quantum" is the final resolution of the encoder; it's also called measuring step or count.)

$$\text{Error in arcsec} = (1296000) \times (\text{error in quanta}) / (\text{final counts/rev})$$

$$\text{Error in arcmin} = (21600) \times (\text{error in quanta}) / (\text{final counts/rev})$$

$$\text{Error in milliradians} = (6283.2) \times (\text{error in quanta}) / (\text{final counts/rev})$$

**Quantization Error** is not an encoder error *per se*, but is an inherent characteristic of any digital instrument. It is the measure of uncertainty stemming from the fact that there is no information between transitions; its value is always  $\pm 1/2$  quantum. Since encoder vendors' data sheets typically define accuracy at the signal transitions, quantization error is not included, but it should not be overlooked when determining the total error budget for your application. Since simply increasing the resolution of the encoder can reduce this error source, servo system designers often specify higher resolutions than they "need" with full knowledge that the final accuracy of the system is nowhere near the resolution of the feedback device. That's one reason why it is helpful to remember that encoder errors occur in such a way that the encoder never loses count; it always produces exactly the correct number of measuring steps per revolution unless it has been badly contaminated or damaged.

One way to **measure** encoder accuracy is to rotate the encoder at a very precisely controlled speed, and measure the time interval between successive transitions of the encoder's output. Modern electronics allow this time interval to be measured quite accurately, but it is impossible to separate speed variations in the test stand from the encoder's position errors. Present-day capabilities in speed control make this technique adequate for encoders of low to moderate performance, but better encoders need a method to measure position errors more directly.

The classic way to measure position errors is with an **autocollimator**. This is essentially a multi-faceted mirror that is mounted on the encoder's shaft. The angle between the facets is known to high degree of accuracy. By using reflected light from the mirrors, the encoder shaft can be turned this known angle, and the results compared to the encoder's electronic output. There are two severe disadvantages to this technique: it is very slow and labor-intensive, and it allows a very limited number of measurements per revolution. To overcome these drawbacks, Gurley Precision Instruments has developed a unique angle standard we call **METRA - Master Encoder for Testing Rotary Accuracy**. The heart of METRA is an optical encoder with a 20-inch diameter disk that is mounted to an air-bearing spindle. A multiple reading head technique eliminates virtually all errors. METRA has resolution of  $2^{21}$  counts/rev, or 0.62 arcseconds per count. Its NIST-traceable accuracy is better than  $\pm 0.1$  arcseconds; this certified accuracy is limited by available angle standards, and not by METRA itself. Because the accuracy is inherent in the master encoder, precise speed control is not necessary.

The electronic portion of the test stand works much like a logic analyzer or digital storage oscilloscope, but with the samples occurring at regular angle intervals dictated by the master encoder, rather than at regular time intervals according to a crystal-controlled clock. Also like a logic analyzer, the sample history of an entire revolution is stored in a high-speed RAM cache for subsequent computer analysis.

To measure accuracy, the **EUT (Encoder Under Test)** is coupled to METRA with precision fixturing. As the EUT and METRA are rotated together, the position information from METRA is used to interrogate the EUT 2,097,152 times per revolution. Thus, this test verifies the location of every single output state of the EUT. This method reveals all encoder errors, and does not depend on statistical assumptions based on an incomplete data set.

On the resultant plot, you see a gray band that represents the composite of the errors from all sources: instrument error, quadrature error and (if applicable) interpolation error. The band is composed of 512 vertical line segments, each of which includes the errors of all consecutive edges comprising 1/512th of a revolution. The top end of each line represents the maximum positive (lead) error from its group, and the lower end shows the maximum lag error. The solid dark line is the average of all errors for the group, and is a good approximation of the encoder's instrument error only, i.e., the error curve from data taken on a once-per-optical-cycle basis, excluding quadrature and interpolation errors. If the EUT has an index signal, it is used to initialize the test and is therefore located at  $0^\circ$  rotation angle.

The typical error curve will tend to have a generally sinusoidal shape, with its period related directly to the number of read stations in the encoder. As the number of read stations in the EUT is increased, there will be a corresponding increase in the number of sub-cycles, but their amplitude will be much less than in an encoder with fewer read stations.

Since its founding in 1845 as a producer of surveying instruments, Gurley Precision Instruments' engineers have always been preoccupied with the question of **accuracy** in all of its products. Today, our company is an ISO-9001 certified designer and manufacturer of precise measuring equipment and components applied in several fields besides encoders, including optical sights and reticles, digital machine tool readouts, hydrological instruments, and sophisticated machines for testing material stiffness, porosity, and other quality characteristics. If you have an application that demands high performance, give us a call, and **let's talk accuracy!**

For more information, please call (800) 759-1844, or visit [www.gurley.com](http://www.gurley.com).

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