

# A Comparative Study on Testing of Wide-Range Angles Precision 2-axis Digital Angular Measuring Instrument

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*Abstract – 2-axis precision digital leveling instrument has greatly simplified the task for installation, setting up and maintenance of high precision CNC machines, angular measuring instruments and alignment-sensitive equipment to attain maximum positional stability. This paper presents a comparative study on using rotary table, sine bar and fixed angle jigs to test precision wide-range angle 2-axis digital leveling instrument. Literature review is presented focusing on identifying sources of measuring errors for these test equipment and their respective testing methodology. The findings demonstrate that a set of high precision fixed-angle jigs is a relatively reliable test apparatus as it has least variable affecting the uncertainty of the entire test system and well-understood material properties. In contrast, rotary table has the merit of its ability to generate large number of precise incremental angles within the full-range of 360° for testing wide-range precision digital angular measuring instruments.*

*Keywords – Sine Bar, Rotary Table, Fixed-angle Jig, Precision Digital Leveling Instrument*

## 1. Rotary Table Mechanism and Angular Measuring System

### 1.1 Direct-drive Servo motor used in Rotary Table

A rotary table is the core component of an angular motion system that exhibits one degree of freedom (rotation about one axis). The basic construction of a rotary stage consists of a platform and a base, where the platform is restricted to rotate within single axis with respect to its base.

Figure 1 illustrates the direct drive rotary motor used in a typical rotary table structure. Direct drive rotary motors develop high torque and enable precision servo control over very small step of angles within 360°. Their dynamic response is excellent as load is coupled directly to the drive, eliminating the need for transmission components that introduce backlash, hysteresis, gear-tooth error or belt stretch <sup>[1]</sup>.



Figure 1 Direct Drive Motor Application <sup>[1]</sup>

### 1.2 Air Bearing Mechanism of a Rotary Table System

The limitation of plain bearing technology represents one of the age-old problems for mechanical engineers. Plain and rolling element bearings developed in the last century have been subjected to radical improvement and follow the emergence of air bearings in recent decades. Bearing technology is further pushed to their technical limits by the stringent demands of applications in the semiconductor manufacturing test instruments, high resolution medical equipment, and high-speed precision CNC machinery. The key technical performance of air bearings such as near zero friction and wear, high speed

and high precision capabilities, and no oil lubrication requirements are advantages for applications in the precision equipment and instrumentation [2, 3].

Air bearings utilize a thin film of pressurized air to provide a ‘zero friction’ load bearing interface between surfaces to create the physical separation of the two surface areas as depicted in Figure 2. Being non-contact, air bearings avoid the traditional bearing-related issues of friction, wear, and lubricant handling, and offer distinct advantages in precision angular positioning and high speed motion applications [2, 3].

The fluid film of the bearing is achieved by supplying a flow of air through the bearing face and into the bearing gap. This is typically accomplished through an orifice or a porous media that restricts the flow of air into the gap as referred as R1 in Figure 2. The restriction is controlled such that, although the air is constantly escaping from the bearing gap, the flow of pressurized air as specified is adequate to match the flow through the gap. It is the restriction through the gap, R2 that maintains the pressure under the bearing and supports the working load. When air pressure was introduced to the gap without restriction R1, the flying height would change and thus the air consumption and the stiffness would vary accordingly [2]. This restriction is referred to as air bearing compensation and is used to optimize the bearing performance with respect to lift, load, and stiffness for a particular application as described subsequently.

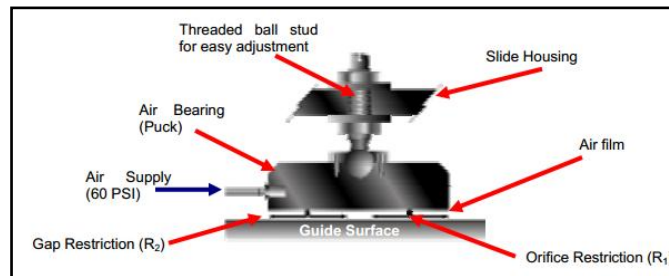


Figure 2 Flat Air Bearing [2]

Because of their advantages over conventional bearings, air bearings are a natural choice for numerous applications in precision linear and angular positional measurements, diagnostic and precision engineering that especially require clean room operating environments and high speed performance. The main advantages of air bearings are listed below.

No.	Merits	Descriptions
1	Zero Friction	Infinite resolution and very high repeatability are possible to be achieved due to zero static friction.
2	Zero Wear	Non-contact means virtually zero wear between surfaces which results in consistent machine performance and low particle generation.
3	Straighter Motion	Conventional bearings subject to surface areas contact that are directly influenced by surface finish and irregularities on the guide for linear or angular motions. Air bearing being non-contact average these errors.
4	Silence and Smooth Operation	Roller and ball bearings generate noise and vibration during re-circulating as hard elements become loaded/ unloaded and change direction.
5	Higher Damping	Being fluid film bearings, air bearings have a squeeze film damping effect resulting in higher dynamic stiffness and improved controllability.
6	Eliminates Oil	Air bearings do not use oil lubrication and eliminating implications associated with oil.
7	High Speed	No balls or rollers to slip at high acceleration.

Table 1 The Advantages of Air Bearing over Conventional plain and Roller Bearings

1.3 Angular-Positional Accuracy of Rotary Table for Angular measurement

In order to quantify the compounded uncertainty of the entire angular measuring system using rotary table, the following describes some critical elements of errors that could affect the measurement accuracy of a typical single-axis digital leveling instrument.

1.3.1 Offset Error with reference to center of gravity (g)

Figure 3.a and Figure 3.b show the initial setups for a typical rotary table before and after offset error correction where the device under test (DUT) is loaded with a Digi-Pas® 2-axis precision master machinist level model DWL-3500XY. The top surface of the L-plate is positioned in perpendicular to the center of gravity. Hence, the offset error of the rotary table against the earth datum is eliminated (i.e. negligible with respect to the resolution of DUT's of  $0.001^\circ$ ) when the Granite table is leveled to 1 arc-second of accuracy for both X and Y axis.

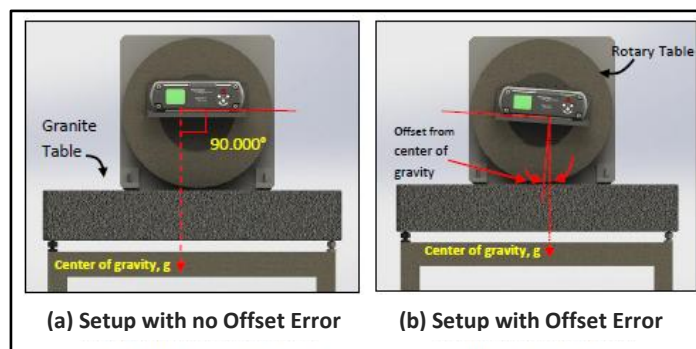


Figure 3 (a) Rotary Table Setups before and (b) after offset error correction [4]

1.3.2 Swash Error with reference to center of gravity (g)

Figure 4 illustrates the Swash error, the surface (Y-axis) plane of the L-plate, where the DUT is placed on, is not perpendicular to the center of gravity. Swash error occurs when the mounting plate contact surfaces to the Rotary Table is not in absolute parallel to the earth datum. Swash error is separately dealt in the JSB TECH Technical Paper “The Implication of Swash Error to Calibration System Uncertainty When Testing High Accuracy Inclinometer Utilizing MEMS Technology” [4].

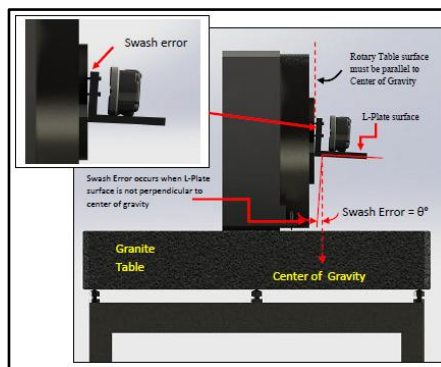


Figure 4 Swash Error with reference to center of gravity (g) [4]

1.3.3 Encoder Scale Errors

Encoder error is composed of three types: (i) quantization error, (ii) instrument error, (iii) cycle interpolation error [5]. Quantization error exists because the encoder cannot indicate motion occurring within one resolution quantum at transition points. This is the highest frequency error component and repeats every quantum of input motion. The quantization error is the deviation of the input shaft from the

mid position for a given readout, with the maximum error of  $\pm 1/2$  of the angular rotation between two successive bits.

Instrument error is the sum of disc and reticle pattern errors and mechanical imperfections within the encoder. Factors such as bearing types, line to space ratio tolerances, substrate flatness, optical setup, and encoder alignment contribute to instrument error.

Cycle interpolation error is due to imperfections in the analog signals from the photo detector due to phase shifts or dc offsets that cause position errors in the signals zero crossings, which affect the count produced by a given amount of movement, as zero crossings are counted as a measure of movement.

#### 1.3.4 Eccentricity Errors and Bearing Run Out Errors.

In order to achieve accurate angular measurement, a scale of uniform linear graduation must be positioned at a consistent distance from the axis of rotation. Variations in radius, as caused by eccentricity of a perfectly round rotary scale, generate errors that vary once per revolution<sup>[1, 6]</sup>. These combine with other errors within the system varying two or more times per revolution would result in scale distortion. When an angle encoder is removed and remounted on the same or a different mandrel, its accuracy would change and the error recorded could vary accordingly. The difference would correspond to the error caused by the change in eccentricity and higher order out-of-roundness of the encoder scale between its initial installation for graduation and its reinstallation for use.

Precision instrument demand high rotating accuracy of the bearing as it affects the performance of the instrument. Bearing run out error is often a key factor that affects rotation of encoder's axis in generating accurate and stable angle for measurement. Irregular encoder code disk motion due to bearing run out error could significantly degrade readout accuracy. The relationship between bearing run out, repeatability and angular position depend on: (i) the relative dimensions of the inner and outer bearing races, (ii) the number and diameter of its balls/rollers and (iii) the wear/adjustment of the bearing system<sup>[1, 6]</sup>.

## 2. Sine Bar Mechanism and Angular Measuring System

### 2.1 Sine Bar Mechanism

Figure 5 illustrates a typical sine bar consists of a hardened, precision ground body with two precision ground cylindrical shafts fixed at each end. The distance between the centers of the shafts is precisely controlled, and the top surface of the sine bar is parallel to a line through the centers of the two shafts. The dimension between the two shafts is chosen to be a whole number and forms the hypotenuse of a triangle when used in conjunction with a set of block gauge<sup>[7]</sup>.



Figure 5 Sine Bar<sup>[7]</sup>

When a sine bar is placed on a level surface (e.g. the surface of a granite table), its top face is required to be parallel to that granite table's surface. When one side of the sine bar is raised by a known distance, by utilizing gauge blocks, the top face of the bar is tilted by the same amount forming an angle that is calculated by the application of the trigonometric sine rule<sup>[7]</sup>.

As shown in Figure 6, two accurately lapped rollers are located at the extreme ends position<sup>[8]</sup>. The center to center distance between the rollers is available for fixed and precisely controlled distance of, for example,  $L=250 \text{ mm} \pm 2\mu\text{m}$ .

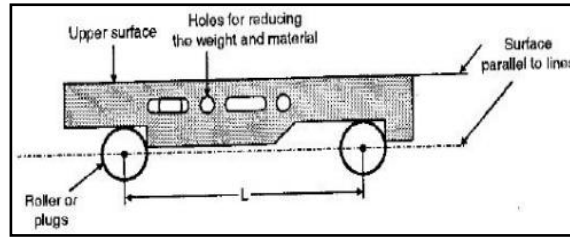


Figure 6 Position of two accurately lapped rollers with fixed center distance between the rollers [8]

## 2.2 Factors Affecting the Compounded Uncertainty of Sine Bar Angular Measuring System

The main contributing factors affecting measurement uncertainty of the entire sine bar angular test system are (i) the sine bar geometric dimension accuracy, (ii) the block gauge and granite table dimensional accuracy (iii) the test system initial positional set up and operating environment control.

- i. The sine bar geometric accuracy depends on (a) the inter-roller axis parallelism (b) the distance between the rollers center  $L$ , (c) the roller's diameter and roundness (d) the flatness of the top surface area of the sine bar, and (e) the parallelism of the sine bar top surface to the surface of the granite table [7].
- ii. The peripheral equipment used in conjunction with sine bar; (a) the block gauge dimensional accuracy (b) surface area flatness of the granite table.
- iii. The leveling of granite table surface and the alignment of its surface where the sine bar is placed to prevent offset error and Swash error. The testing laboratory environments fulfill the requirements of the test system on e.g. dust particle count, temperature and humidity.

IS 5359-1969 specifies the basic requirements for dimensional size limit and tolerance of sine bar that affect angular measurement error. The use of multiple block gauges in combination when measuring large angles introduces compounding errors that affect the accuracy of using sine bar for measuring large angle typically over  $45^\circ$ .

### 2.2.1 Example on the Effect of Block Gauge Height ( $H$ ) to measure angle ( $\theta$ )

Assuming that the length between roller to roller  $L = 200.0000\text{mm}$ , the combination block gauge required height ( $H$ ) of  $68.4040\text{mm}$  in order to generate an angle of  $20.000^\circ$ , as shown in Figure 7. By using grade zero block gauge with tolerance  $<0.5\mu\text{m}$ , the estimated maximum uncertainty value from the combination block gauge is  $H_{\text{uncertainty}} = 0.00014^\circ$ .

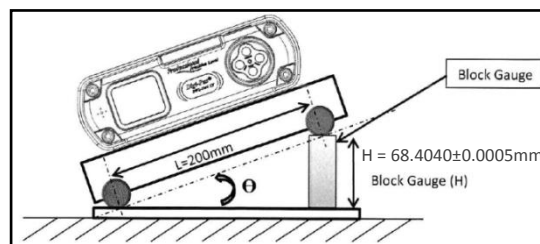


Figure 7 Effect of Block Gauge Height ( $H$ ) on uncertainty to measure angle ( $\theta$ )

### 2.2.2 Example on the Effect of Roller Center Distance ( $L$ ) to measure angle ( $\theta$ )

It was given that the roller-to-roller distance,  $L$  is  $200.000 \pm 0.003\text{mm}$  as shown in Figure 8. With largest angle measurement at  $20.000^\circ$  and  $H=68.4040\text{mm}$ , the estimated largest uncertainty of sine bar/ plate roller center distance is  $L_{\text{uncertainty}} = 0.00032^\circ$ .

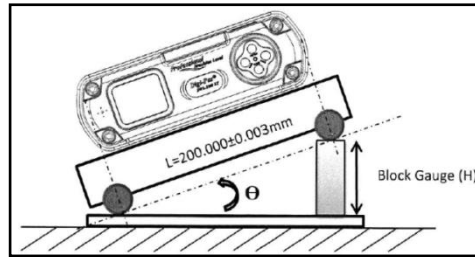


Figure 8 Effect of Roller Center Distance (L) on uncertainty to measure angle ( $\theta$ )

2.2.3 Example on the Effect of Sine Bar/ Plate Parallelism (P) to measure angle ( $\theta$ )

Given that the largest sine bar/ plate surface parallelism is  $2.5\mu\text{m}$  ( $H_0=0.0025\text{mm}$ ) and at  $L=200.000\text{mm}$ , as shown in Figure 9. It was estimated the initial offset angle from parallelism uncertainty of sine bar/ plate is  $\theta_{\text{Max, P}} = 0.00072^\circ$ .

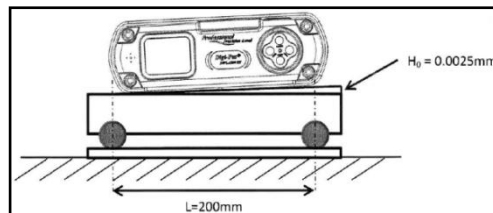


Figure 9 Effect of Sine Bar/ Plate Parallelism (P) on uncertainty to measure angle ( $\theta$ )

3. Precision Fixed Triangle Jigs

3.1 Utilizing Trigonometry Principal in Determining Precision Fixed Triangle Jig

Trigonometry is a well-known branch of mathematics that studies triangles and the relationships between the lengths of their sides and the angles between those sides. When one angle of a triangle is 90 degrees and one of the other angles is known, the third is thereby fixed. The two acute angles therefore add up to 90 degrees: they are complementary angles. The shape of a triangle is completely determined, except for similarity, by the angles. Once the angles are known, the ratios of the sides are determined, regardless of the overall size of the triangle. When the length of one side is known, the other two are determined. These ratios are given by the trigonometric functions of the known angle  $A$ , where  $a$ ,  $b$  and  $c$  refer to the lengths of the sides in Figure 10.

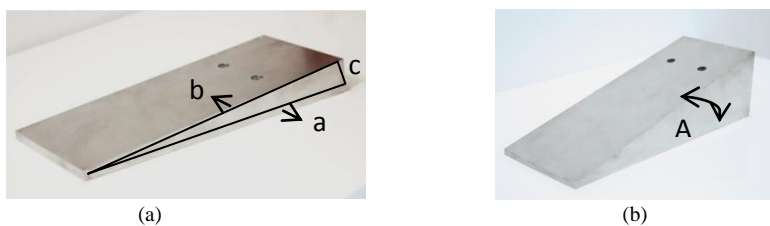


Figure 10 Precision Fixed Angle Jigs (a)  $4.993^\circ$  (b)  $15.001^\circ$

3.2 Utilizing the Coordinate Measuring Machine (CMM) to measure Surface Flatness of the Fixed Triangle Jig

CMM is measuring equipment for determining the physical geometrical shape of a physical object. Measurement points are defined by a probe attached to a moving z-axis in addition to the planar X & Y axis. Probes may be mechanical, optical image or laser.

Figure 11 below shows the Mitutoyo LEGEX series CMM claimed to be able to achieve exceptionally high dimensional accuracy among CMM family of  $0.2\mu\text{m}$  with a resolution of  $0.01\mu\text{m}$  [9].



Figure 11 Coordinate Measuring Machine (CMM)  
Mitutoyo LEGEX Series <sup>[9]</sup>

Multiple points of measurement on each surface area of the fixed triangular jig are obtained to determine the least square fit of surface plane and the geometric angle of each surface plane with respect to its base plane. The precise angle between the base and hypotenuse planes of the fixed triangular jig is then determined by applying sine function of the trigonometric principle.

### 3.3. Surface Flatness in Precision Measuring Instrument

In manufacturing of precision parts and assemblies, surface flatness is a critical quality of machining process to meet the required specification. Surface flatness is defined in terms of least squares fit to a surface plane and is also referred as statistical flatness. Granite, steel and ceramic surface plates are commonly used in precision geometrical measurements and the determination of surface flatness is an important basic task of dimensional metrology. The flatness of the surfaces plates is the angular variations of a predefined surface area and these angular variations can be determined using autocollimator, laser interferometer or CMM, depending on the required surface quality <sup>[10]</sup>.

Another variable affecting surface flatness resulting from interaction between machining tool and work piece is surface finishing quality. Several processes such as diamond turning, grinding, lapping, honing, polishing, ion- and electron-beam machining and chemical treatment are effective methods to enhance surface finishing quality <sup>[11]</sup>. Lapping technique is advantageous due to its ability to precise control of removing material from a targeted surface area and capable of producing high surface uniformity and dimensional accuracy. Lapping is a process that material is subtracted from a work piece by abrasion to produce a desired dimension and surface finish. The lapping plate typically rotates at a constant speed and operates in conjunction with abrasive material <sup>[12]</sup>. The process of lapping effectively removes subsurface damages on work piece such as cutting tool imprints and surface grinding traces. Surface finishes in the nanometer range can be achieved by lapping, thus makes lapping an attractive method for materials processing in precision machining for applications in high precision metrology.

### 3.4. Material Selection and Thermal Distortion in Precision Measuring Instrument

Appropriate choice of material with known thermal expansion coefficient for base structure of precision measuring instrument is critical in determining the accuracy performance. Physical dimension changes in accordance with its linear and nonlinear characteristics of material when subjected to machining processes and operating temperature variation. Compensation methods are able to minimize some negative implications of thermal distortion <sup>[13]</sup>; however stable material thermal properties of base material would contribute to improved reliability of an instrument.

Metal alloys material is commonly used in the instrumentation base structure, such as aluminium alloys, tungsten alloys, beryllium alloys, silver alloys and copper alloys, and is depending on the required performance level of a particular instrument. Among ceramic material, silicon carbide, tungsten carbide and in particularly graphite is of relatively low thermal distortion <sup>[13]</sup>.

#### 4. RESULTS AND DISCUSSION

##### 4.1 Digi-Pas® DWL3500XY Test Using Nanotech® 350FG, Ultra-Precision 3-Axis Freeform® Generator

Figure 12 shows the Nanotech® 350FG ultra-precision rotary machine with ultra-precision rotary axes utilized to test the DWL3500XY. The programmable linear resolution is 0.01 nanometer and rotary angle resolution of 0.0000001° (0.00036 arc sec) with built-in thermally insensitive linear scale feedback system of 34 Pico-meter resolutions. The Nanotech® 350FG allows swing capacity to 500mm diameter for off-axis and toric components, box-way hydrostatic oil bearing slides with 300mm of travel on Z, 350mm of travel on X, 150mm vertical travel on Y, and an adaptive air bearing counterbalance assembly on the vertical axis for optimal servo performance [14].



Figure 12 Nanotech® 350FG, Ultra-Precision 3-Axis Freeform® Generator

The DWL 3500XY has a specification of 0.000° to 2.000° is ±0.001°, while the angles within 2.000° to 20.000° is ±0.003°. Table 2 illustrates an incremental angle test generated by rotary table. The set angles and recorded readings from the DUT were taken for both positive and negative slopes from 0.000° to 20.000°. The recorded readings observed from DUT and the rotary table generated angles indicate that numeric deviation fall within the upper and lower limit of DUT specification.

Description	Set Standard (°)	Lower Limit (°)	Upper Limit (°)	Level Reading (°)	Deviation (°)
(+)-Slope	0.000	-0.001	0.001	0.000	0.000
	0.500	0.499	0.501	0.501	-0.001
	1.000	0.999	1.001	1.001	-0.001
	2.000	1.999	2.001	2.001	-0.001
	3.000	2.997	3.003	3.003	-0.003
	5.000	4.997	5.003	5.000	0.000
	10.000	9.997	10.003	10.001	-0.001
	20.000	19.997	20.003	20.003	-0.003
(-)-Slope	0.000	0.000	0.002	0.000	0.000
	0.500	0.499	0.501	0.501	-0.001
	1.000	0.999	1.001	1.001	-0.001
	2.000	1.999	2.001	2.001	-0.001
	3.000	2.997	3.003	3.003	-0.003
	5.000	4.997	5.003	5.002	-0.002
	10.000	9.997	10.003	10.002	-0.002
	20.000	19.997	20.003	20.003	-0.003

Table 2 DUT readings for Rotary Table

##### 4.2 Digi-Pas® DWL3500XY Test Using Micrometer Sine Bar

The DWL 3500XY is further tested using a micrometer sine bar for small angles range (i.e. 0.000° to 3.056°) as shown in Figure 13. Another independent single-axis digital level of manufacturer ‘L’ was also simultaneously placed on the sine bar for measuring comparison. Readings displayed on both DUT and device L were recorded against the micrometer sine bar set angles and tabulated as shown in Figure 14.



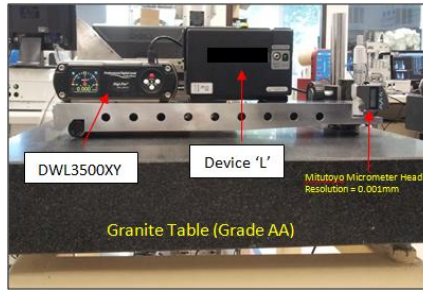


Figure 13 Setup Configuration of Sine Bar for DUT and Device L

The resolution of leveling instrument from manufacturer L is  $0.0001^\circ$ , which is 10 times more precise than DWL3500XY that has a resolution of  $0.001^\circ$ . Further, precise small angle incremental readings were also taken from  $0.0000^\circ$  to  $0.2800^\circ$  as shown in Figure 15. The observed readings of DUT fell within Upper and Lower Limits of  $\pm 0.001$ . The readings from instrument L were also in consistent with the micrometer generated readings.

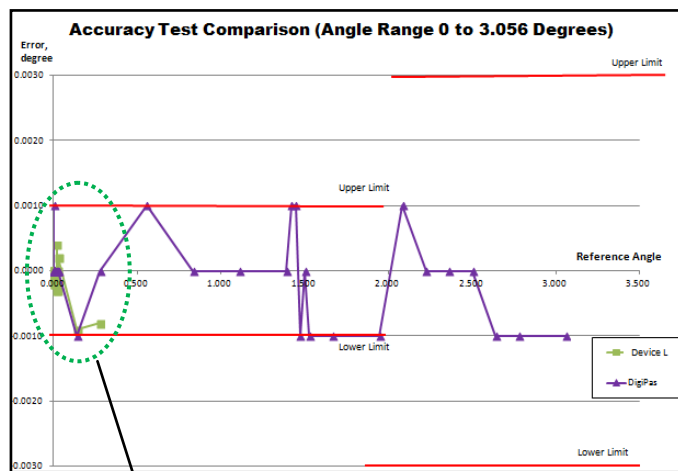


Figure 14 Accuracy Test Comparisons for Angle Measurement Range from  $0.0000^\circ$  to  $3.0560^\circ$

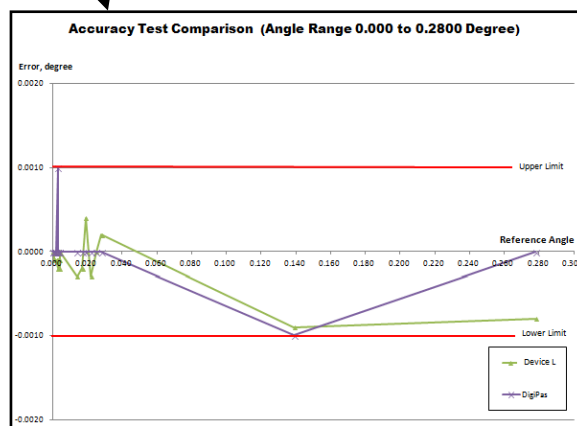


Figure 15 Accuracy Test Comparisons for Small Angle Measurement Range from  $0.0000^\circ$  to  $0.2800^\circ$

#### 4.3 Digi-Pas® DWL3500XY Test Using Precision Fixed-Angle Jig

A third party independent Singapore National Metrology Center calibrated precision fixed-angle jigs<sup>[15]</sup> of  $4.993^\circ$  and  $15.001^\circ$  were further utilized to test DWL 3500XY. The DUT was placed on top of the jig surface and displayed readings were taken and recorded as shown in Figure 16. The result illustrates that the measured values displayed by the DUT is within the specification of  $\pm 0.003^\circ$  for both jigs as shown in Figure 17 and 18.


Instruments	Precision Angle Jig		
	Calibrated by National Metrology of Singapore		
	Standard (Degree)	DWL3500XY (-) Slope (As found) (Degree)	DWL3500XY (+) Slope (As found) (Degree)
Measurement Readings 1	4.993°	4.993°	4.993°
Measurement Readings 2	15.001°	15.000°	15.000°
Repeatability		0.001°	0.001°
			

Figure 16 DUT readings for 4.993° and 15.001° fixed angle jigs, within tolerance of ±0.003°

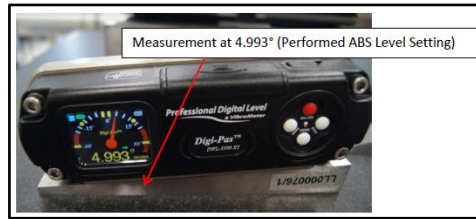


Figure 17 Measurement reading of DUT on 4.993° fixed angle jig



Figure 18 Measurement reading of DUT on 15.001° fixed angle jig

## 5. CONCLUSION

To ensure the mid-range (i.e. 0.01° to 0.001°) precision digital leveling instrument performs in accordance within the specified accuracy, a Digi-Pas® 2-axis precision digital leveling instrument model DWL3500XY was tested by using rotary table and sine bar. The accuracy performance of DWL3500XY was further laterally compared against an independent manufacturer ‘L’ leveling instrument and also tested with a third party independent National Metrology Center calibrated fixed-angle jigs.

This paper presents the literature review of a comparative study on using rotary table, sine bar and fixed angle jigs to assess precision wide measuring range angles of digital leveling instrument. The results from comparative tests utilizing the foregoing test methods showed that the DWL3500XY performed consistently within its accuracy specification. The findings provided substantive evidence to suggest that:

1. Conventional rotary table is single axis and suffers from compounding errors such as gear backlash, multiple gears, eccentric error and swash error. Direct-drive servo motor employing optical technology improves the test system uncertainty significantly.
2. The construction of Sine bar is constrained by numerous physical dimensions such as top-bottom surfaces parallelism, inter-round bar parallelism, surface flatness, inter-round bar distance tolerance, roundness/eccentric error compound to yield a considerable amount of uncertainty in the test system. This method is not suitable for testing wide-range angles of high precision angular instruments having stringent accuracy specification particularly when the angles under test becoming larger.
3. Fixed angle jig minimizes those limitations in Sine Bar and confines the sources for errors to (i) top-bottom surfaces flatness and (ii) the distance between top surface plane and bottom plane. Multiple measurement points of each surface and distance between the surfaces utilizing least square fit could further improve the test system uncertainty.
4. Rotary table are capable of generating a considerable number of incremental precise angles of 0.001° for a full 360° angles range. In contrast, fixed angle jig offered limited number of angles to test the 2-axis digital angular measuring instrument. All test methods described require to test the instrument one axis at a time.
5. The constraints of the foregoing angular test equipment are addressed and dealt in the accompanying JSB TECH technical paper [16], which tackles ultra-precision 2-axis angular leveling measurement of 1 arc sec or lower utilizing nano-technology dimensional and angular interferometer instruments.

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