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Performance Evaluation of a Tracking Total Station as a Position Reference forDynamic GNSS Accuracy Testing

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PERFORMANCE EVALUATION OF A TRACKING TOTAL STATION AS A POSITION REFERENCE FOR DYNAMIC GNSS ACCURACY TESTING

M. P. Sama, T. S. Stombaugh

ABSTRACT. *The dynamic accuracy of a tracking total station (TTS) was evaluated using a rotary test fixture to determine the viability of using a TTS as a position reference for dynamic global navigation satellite-based system (GNSS) accuracy testing. Tests were performed at angular velocities ranging from 0 to 3.72 rad/s at a radius of 0.635 m. A technique was developed to determine the average latency of the TTS measurement serial data output. TTS measurements were interpolated at a GNSS sampling interval to provide a method for direct comparison between TTS and GNSS position measurements. The estimated latency from the TTS serial data output was shown to be consistently near 0.25 s for all angular velocities and less variable when using a reflector-based machine target versus a prism-based target. Average positional error in the TTS position measurement increased with angular velocity from 3 to 90 mm, partly due to internal filtering which caused the magnitude of the TTS position measurement to decrease under stead-state sinusoidal motion. The standard deviation of error ranged from less than 1 to 20 mm as angular velocity increased. Sight distance from the TTS to the target was shown to have very little effect on accuracy between 4 and 30 m. The TTS was determined to be an adequate benchmark for most dynamic GNSS and vehicle auto-guidance testing but is limited by relatively large position measurement errors at high angular velocities.*

Keywords. *Dynamic error, GPS, GNSS, Precision agriculture, Tracking total station.*

The evaluation of dynamic global navigation satellite-based system (GNSS) and auto-guidance accuracy has been accomplished using several methods. One method used a test fixture to physically restrict the motion of a GNSS receiver to a known open track (Taylor et al., 2004) or closed track (Stombaugh et al., 2008). Another method used a highly accurate measurement system to determine the reference path from which performance characteristics were derived (Easterly et al., 2010). Up to this point, dynamic GNSS and auto-guidance testing have focused on off-track error, which is the lateral deviation from a reference path. While this may be sufficient for many field operations including harvesting and tilling, it fails to address performance characteristics relevant to variable-rate applications, section control and precision planting where precise placement of materials along a track are required.

The use of GNSS-based technology to prescribe, control, and measure agricultural operations is well documented for various spraying applications. Al-Gaadi and Ayers (1999) demonstrated a system where GIS and GPS were used to spatially prescribe application rates based on site-specific needs. They used a laptop computer as a control interface between a GPS receiver and a chemical pump to adjust the application rate based on the current position and the desired application rate. Luck et al. (2011) estimated that off-rate errors from GNSS position data due to turning movements resulted in up to 24% of a field receiving the wrong application rate for typical fields in Central Kentucky. Zandonadi et al. (2011) developed a computation tool for estimating off-target application areas for a given field boundary. Results from nine representative field boundaries showed that off-target application area for larger chemical application equipment varied from 9% to 24% but could be reduced to less than 1% when using individual section control. In all of these studies, the along-track error of the vehicle was ignored. This can be attributed to not having a viable method for measuring or predicting along-track error. Along-track error may significantly change the interpretation of field data or predictions of application rate in simulations. For example, GNSS latency in a section control scenario will cause the system to incorrectly apply material near boundary transitions. A measurement system is needed that can provide an assessment of GNSS position accuracy under dynamic conditions that includes both off-track and along-track error.

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A tracking total station (TTS) is a survey grade instrument capable of precisely tracking and measuring the relative location of a mobile prism or other reflective target. Sama et al. (2009) showed that a TTS can be accurately tied in to the local coordinate systems used in standardized (ISO, 2010) GNSS and vehicle guidance testing to within several millimeters. These features make a TTS a possible candidate for a position reference device for dynamic GNSS accuracy and auto-guidance performance testing. Krischner and Stempfhuber (2008) identified that the accuracy of a TTS under dynamic conditions was limited by varying latency, lack of internal synchronization between measurement subsystems, and the quality of the target. Some of these limitations have been addressed by modern systems and the authors concluded that a TTS can perform kinematic measurements up to 50 m with an accuracy of a few millimeters. Testing was limited to a straight path and only off-track error was measured, which may not describe how a TTS will perform when the target is travelling at higher velocities or along a curved path. Other issues such as the latency between the TTS measurement and when that measurement is transmitted limit the usefulness for evaluating along-track error. Time discrepancies of a few milliseconds could result in several centimeters of additional error. The amount of latency as well as the variability in latency must be known to better understand how accurately a TTS can track a moving target.

Using a TTS to assess GNSS accuracy and auto-guidance performance requires synchronizing two independent measurement systems. A GNSS device computes position at a consistent interval that is accurate to within a microsecond of universal coordinated time (UTC) (Daly et al., 1991). A TTS on the other hand operates independently of any external clock source or reference. This creates an issue where GNSS and TTS measurements do not line up temporally. Calculating the error of a GNSS measurement requires a reference that can be sampled synchronously with GNSS time. Therefore, an interpolation method is needed to synchronize TTS measurements with GNSS time. Many GNSS devices include a pulse-per-second (PPS) output that indicates the exact moment of each GNSS second. This signal can be used to determine when a TTS measurement has been made relative to GNSS time. Researchers at the University of Kentucky developed a signal timing device capable of synchronizing the serial data stream from at TTS with the PPS signal from a GNSS receiver to within a standard error of 47 μs (Sama et al., 2013). This timing error would result in less than 1 mm of position error at speeds typical of most agricultural operations.

OBJECTIVES

- Determine the latency present in a TTS position measurement.
- Determine the horizontal measurement error when compensating for TTS latency.
- Develop an interpolation method for calculating the TTS target position at the GNSS time interval.

MATERIALS AND METHODS

ROTARY TEST FIXTURE

A rotary test fixture was designed to evaluate the performance of a TTS (model SPS 930, Trimble Navigation Ltd, Sunnyvale, Calif.) under steady-state dynamic conditions. Angular velocity and acceleration criteria were used to specify the fixture drive train. Velocities similar to those used in standardized GNSS testing, 0.1 to 5.0 m/s, were used as minimum and maximum criteria, respectively. A conservatively high mass for the rotation components was estimated to be 45 kg. A 1-m radius circular hoop model was used to calculate the moment of inertia (1).

$$I = mr^2 = 45\,kg\,(1\,m)^2 = 45\,kg\,m^2 \tag{1}$$

An angular acceleration criterion of 10 seconds from 0 to 5 rad/s (2) was used to determine the torque required by the fixture (3) and the motor power (4).

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{5\ rad/s}{10\,s} = 0.5\ rad/s^2 \tag{2}$$

$$T = I\alpha = 45\ kg\,m^2\left(0.5\ rad/s^2\right) = 22.5\ N\,m \tag{3}$$

$$P = T\,\omega = 22.5\,N\,m\,(5\ rad/s) = 112.5\ W \tag{4}$$

A design factor of two was added to account for unknown mechanical inefficiency as well as the reduction in torque when operating the motor at slower speeds. The resulting motor specification was determined to be 225 W (0.3 hp). To achieve the velocity criteria, a 3-phase inverter-duty AC motor was selected along with a 30:1 gear reduction. The motor had a rated speed of 1720 RPM which was reduced to 57.3 RPM through the gear reduction. A speed of 57.3 RPM corresponded to an output angular velocity of 6.00 rad/s, and an instantaneous velocity of 3.81 m/s at a 0.635-m radius. Powering the motor with a variable frequency drive (VFD) enabled the output angular velocity to be reduced to nearly 0.1 rad/s (fig. 1).

The rotary test fixture was controlled using a microcontroller. A 3-wire RS232 interface (19200-8-N-1) connected the microcontroller to a PC. Two commands were used to update the speed and direction of the rotary test fixture. The speed command was a fixed-width string formatted as "$V,####*". The "$V" characters were used as an identifier and the #### characters were decimal numbers between 0000 and 4095, which were used to represent analog output voltages to the VFD between 0 and 5 V. The "*" character was used as a terminating character along with the non-printable carriage return and line feed characters. The direction command was a fixed width string formatted as "$M,#,#*". The "$M" characters were used as an identifier and each # character was a decimal 0 or 1, which corresponded to the FWD and REV signals on the VFD. The "*" character was used as a terminating character along with the non-printable characters carriage return and line feed.

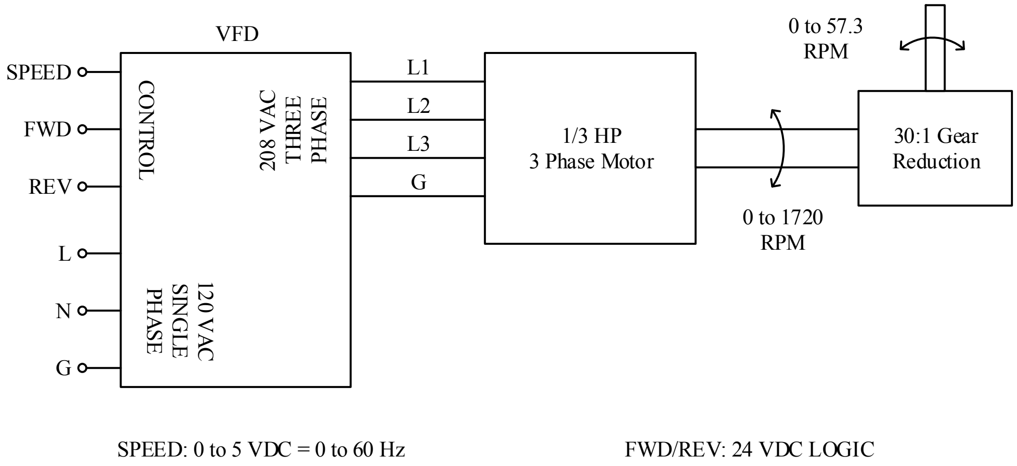


Figure 1. Fixture drive train and control.

An optical encoder (model E6-2500-625-IE-S-H-D-1, US Digital, Vancouver, Was.) with 2,500 counts per revolution was mounted to the bottom of the output drive shaft. The encoder had two incremental pulse outputs, A and B, which were 90° out of phase. The microcontroller had the ability to track a pulse sequence of both the A and B pulses, voltage transitions in the A pulse (×2 measurement mode), or voltage transitions in both the A and B pulses (×4 measurement mode). When operating in ×4 measurement mode, the encoder generated 10,000 transitions between the A and B phases, combined. This resulted in 10,000 counts per revolution or an angular resolution of 6.28×10^{-4} radians. The A and B phases, along with an index pulse that provided an absolute position reference, were connected to the microcontroller hardware quadrature encoder interface. Any transitions or pulses automatically incremented, decremented, or reset the quadrature encoders counter without the need for a software routine to track pulses.

An illustration of the rotary test fixture is shown in figure 2. A welded steel frame was fabricated to house the rotary test fixture drive train and control system. The structure consisted of 3.8-cm (1.5-in.) tube with 0.30-cm (11-gauge) sheet metal welded to the top, middle, and bottom surfaces. The remaining sides were covered with 0.12-cm (18-gauge) sheet metal and secured using socket head cap screws (not shown). A self-adhesive silicone gasket was adhered to all removable surfaces to minimize water infiltration. A rotating armature with mounting points at 0.000, 0.635, and 1.000 m, relative to the point of rotation, was attached to the drivetrain. A steel stand was fabricated to mount the rotary test fixture structure to the roof of the Charles E. Barnhart Building in Lexington, Kentucky.

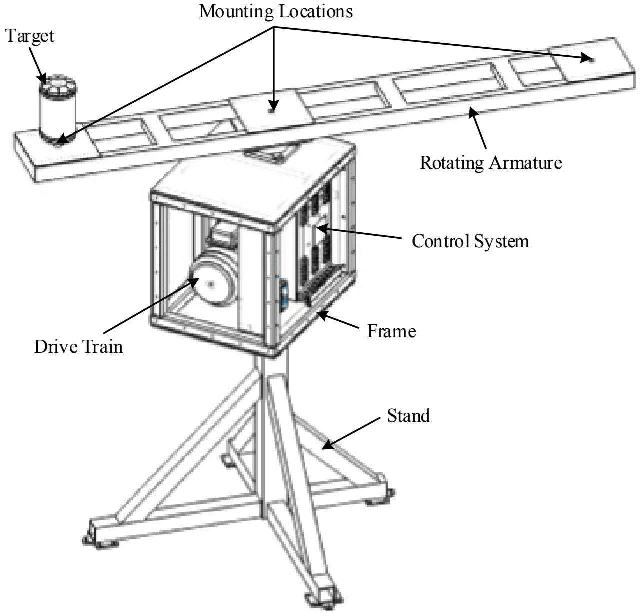


Figure 2. Rotary test fixture.

Figure 3. TTS, reflector target, and prism target.

TEST PROCEDURES

Latency of the TTS measurement relative to the test fixture was evaluated using two different targets (fig. 3). The first target was a prism-based device (Multitrack Target, Trimble Navigation Ltd., Sunnyvale, Calif.) with eight individual prisms for tracking in any direction. The second target was an active reflector-based machine target (MT900, Trimble Navigation Ltd., Sunnyvale, Calif.) which was designed for position control of construction equipment.

Seven data sets were recorded for both targets at varying angular velocities. Each data set consisted of 256 individual measurements. Horizontal position error of the TTS measurement relative to the test fixture was evaluated using only the active reflector-based machine target. Thirty-three data sets were recorded for eleven varying angular velocities at three sight distances from the TTS. Tests were conducted in order of increasing angular velocity and increasing sight distance. All measurements were taken at a 0.4-Hz sampling rate (TTS output rate) with the fixture rotating in the counter-clockwise direction. A summary of the test procedures is show in (table 1).

The high angular velocities used in this study exceed angular velocities in typical agricultural operations. The justification for using a rotary test fixture instead of a linear test fixture was due to the ability to precisely determine the relative position of the test fixture while moving at a constant speed.

DATA COLLECTION

The microcontroller that served as an interface between the PC and VFD also served as a signal timing device for time-stamping TTS position measurements and PPS events. Two RS-232 serial ports (19200-8-N-1) were used to send and receive command, timing, and position data. The first serial port was configured to receive speed and direction commands from the PC and send PPS event timestamps along with the fixture position. The second serial port was configured to receive position measurements from the TTS and retransmit each measurement to the PC along with a timestamp and fixture position. A program was written using Microsoft Visual Studio 2010 to record data into a comma-separated-value (CSV) file and allow the control of speed and direction (fig. 4).

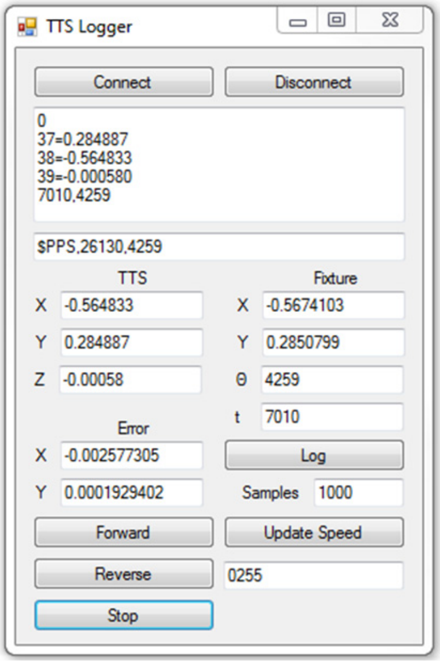
DATA PROCESSING

The data streams from the test fixture controller were compiled and stored in a CSV file format. Each data file contained nine elements (table 2).

The t_{TTS} column contained the result of a 16-bit timer running at 58.59375 kHz. The θ_{FIX} column represented the test fixture angle measured by the encoder where 0 represented 0 rad and 10,000 represented 2π rad. The x_{FIX} and y_{FIX} columns were the actual horizontal location of the TTS target in meters relative to the origin of the test fixture. The x_{TTS}, y_{TTS}, and z_{TTS} columns were the 3-D location coordinates measured by the TTS in meters. The t_{PPS} and θ_{PPS} columns were the 16-bit timer value and fixture angle at the most recent PPS event. The timer frequency was chosen to ensure that the timer rolled over in greater than one second to ensure that elapsed time between 1-Hz PPS events could be distinguished without having to count the number of complete timer cycles. There were only two possible outcomes for subsequent timer values in the t_{TTS} column – either the subsequent timer value was greater than or less than the previous timer value, within one timer cycle.

Table 1. Summary of test procedures.

	Latency Testing	Error Testing
Angular velocities	7	11
Targets	2	1
Sight distances	1	3
Replications	256	256



```
0
37=0.284887
38=-0.564833
39=-0.000580
7010,4259
```

$PPS,26130,4259

TTS
X -0.564833
Y 0.284887
Z -0.00058

Fixture
X -0.5674103
Y 0.2850799
Θ 4259
t 7010

Error
X -0.002577305
Y 0.0001929402

Samples 1000

0255

Figure 4. PC program for fixture control and TTS data logging.

The average TTS measurement latency was determined using a MATLAB script that read in the CSV file. The time stamp (5) and encoder angle (6) of two subsequent measurements were used to calculate an instantaneous angular velocity (7). The test fixture angle based on the TTS measurement was calculated from the x_{TTS} and y_{TTS} coordinates using a four-quadrant arctangent function (8). The latency of each measurement was calculated by taking the difference between the actual fixture angle and TTS measured fixture angle, and dividing by the angular velocity at that instance (9).

$$\Delta t_{TTS}[n]\,(s) = \begin{cases} \dfrac{t_{TTS}[n]-t_{TTS}[n-1]}{58{,}593.75}, & t_{TTS}[n] \geq t_{TTS}[n-1] \\[2ex] \dfrac{65536-t_{TTS}[n-1]+t_{TTS}[n]}{58{,}593.75}, & else \end{cases} \tag{5}$$

$$\Delta\theta_{FIX}[n]\,(rad) = \begin{cases} \dfrac{2\pi\left(\theta_{FIX}[n]-\theta_{FIX}[n-1]\right)}{10{,}000}, & \theta_{FIX}[n] \geq \theta_{FIX}[n-1] \\[2ex] \dfrac{2\pi\left(10{,}000-\theta_{FIX}[n-1]+\theta_{FIX}[n]\right)}{10{,}000}, & else \end{cases} \tag{6}$$

$$\omega[n]\left(\frac{rad}{s}\right) = \frac{\Delta\theta_{FIX}[n]}{\Delta t_{TTS}[n]} \tag{7}$$

Table 2. Sample data file.

n	t_{TTS}	θ_{FIX}	x_{FIX}	y_{FIX}	x_{TTS}	y_{TTS}	z_{TTS}	t_{PPS}	θ_{PPS}
1	49020	5264	-0.62628	-0.10485	-0.6321	0.002357	-0.00247	16098	4870
2	6963	5547	-0.59786	-0.21397	-0.62285	-0.10829	-0.00202	16098	4870
3	30298	5827	-0.55119	-0.31531	-0.59508	-0.21577	-0.00152	9953	5582
4	53880	6110	-0.48672	-0.40783	-0.54723	-0.3162	-0.00105	9953	5582
5	11745	6389	-0.40814	-0.48647	-0.48346	-0.40749	-0.00062	3825	6293

$$\theta_{TTS}[n]\,(rad) = \begin{cases} \operatorname{atan2}\left(y_{TTS}[n], x_{TTS}[n]\right), & y_{TTS}[n] \geq 0 \\ \operatorname{atan2}\left(y_{TTS}[n], x_{TTS}[n]\right) + 2\pi, & else \end{cases} \tag{8}$$

$$Latency[n]\,(s) = \begin{cases} \dfrac{\theta_{TTS}[n] - \theta_{PPS}[n]}{\omega[n]}, & \theta_{TTS}[n] \geq \theta_{PPS}[n] \\ \dfrac{2\pi - \theta_{PPS}[n] + \theta_{TTS}[n]}{\omega[n]} & else \end{cases} \tag{9}$$

TTS measurement error was evaluated using a MATLAB script that interpolated the location of the total station at a PPS event while taking TTS latency into account. First, the t_{PPS} and θ_{PPS} columns were processed for changes in content. A change in PPS values indicated that a PPS event had occurred before the current TTS measurement. There were typically 102 PPS events for every 256 TTS measurements as a result of the 2.5-Hz data output from the TTS. Four TTS points and their respective timestamps were used to calculate a third-order interpolation functions in the horizontal directions, two before the PPS event and two after (10). Each interpolation function resulted in four coefficients, *a* through *d*, that relate the time at which a total station measurement was made and the corresponding location. Indices n_1 though n_4 were the sequence of four samples used in each interpolation. The time at which the PPS event occurred was then used as an input to the interpolation functions for estimating the total station position (x_{INT}) at the exact time of the PPS event (11). The process was repeated for every PPS event in the data set with at least two TTS measurements before and after the PPS event.

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} t_{TTS}[n_1]^3 & t_{TTS}[n_1]^2 & t_{TTS}[n_1] & 1 \\ t_{TTS}[n_2]^3 & t_{TTS}[n_2]^2 & TTS[n_2] & 1 \\ t_{TTS}[n_3]^3 & t_{TTS}[n_3]^2 & t_{TTS}[n_3] & 1 \\ t_{TTS}[n_4]^3 & t_{TTS}[n_4]^2 & t_{TTS}[n_4] & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_{TTS}[n_1] \\ x_{TTS}[n_2] \\ x_{TTS}[n_3] \\ x_{TTS}[n_4] \end{bmatrix} \tag{10}$$

$$x_{INT} = a\left(t_{PPS}[n]^3\right) + b\left(t_{PPS}[n]^2\right) + c\left(t_{PPS}[n]\right) + d \tag{11}$$

RESULTS AND DISCUSSION

LATENCY RESULTS

The average latencies were determined to not differ significantly between the prism and reflector targets for all angular velocities tested based on a single factor ANOVA (α=0.05). However, there was a significant difference in the average latency for each target with respect to angular velocity. The prism target had a P-value of 0.016 while the reflector target had a P-value less than 0.001. More importantly, the variability in latency measurements between the prism and reflector targets was not the same. The prism target exhibited an increasing trend in the standard deviation of latency, ranging from 0.0131 to 0.0731 s. The reflector target standard deviation of latency measurements were consistently smaller and had a range from 0.0017 to 0.0100 s (table 3). The average latency of both targets was slightly larger than 0.25 s. The primary source of latency was assumed to be due to the wireless transmission between the TTS and the serial interface. The source of variability in latency measurements could not be determined directly from the data. However, a potential root of the perceived change in latency may simply have resulted from errors in position measurement, which could not be separated from latency using the techniques in this study.

INTERPOLATION RESULTS

Single factor ANOVA (α=0.05) was used to test for significant differences in the magnitude of position error with respect to sight distance from the TTS at varying angular velocities when accounting for TTS latency. Magnitude of position error was the magnitude of the vector component of error in both horizontal directions. There was a statistically significant difference in the average error for angular velocities of 0.000, 0.441 and 0.847 rad/s, but the actual average amount of difference was less than 1.5 mm. There was no significant difference in the average error for all other angular velocities (table 4).

Table 3. Summary of latency results.

Angular Velocity (rad/s)	Prism Target Latency Mean (s)	Prism Target Latency Standard Deviation (s)	Reflector Target Latency Mean (s)	Reflector Target Latency Standard Deviation (s)
0.442	0.2583	0.0131	0.2617	0.0100
0.847	0.2522	0.0182	0.2543	0.0060
1.251	0.2486	0.0282	0.2521	0.0017
1.660	0.2478	0.0346	0.2514	0.0026
2.069	0.2508	0.0435	0.2520	0.0032
2.482	0.2589	0.0710	0.2483	0.0063
2.894	0.2485	0.0731	0.2464	0.0066
Mean	0.2522	0.0402	0.2523	0.0052

Table 4. Mean and standard deviation of position error magnitude for varying sight distances and angular velocities.

Angular Velocity (rad/s)	4.255 m	14.689 m	30.184 m	P-value
0.000	0.0030 *0.0005*	0.0029 *0.0002*	0.0015 *0.0003*	< 0.001
0.441	0.0041 *0.0018*	0.0038 *0.0013*	0.0046 *0.0020*	0.004
0.847	0.0069 *0.0021*	0.0079 *0.0029*	0.0081 *0.0029*	0.006
1.251	0.0104 *0.0024*	0.0107 *0.0027*	0.0111 *0.0023*	0.114
1.660	0.0164 *0.0033*	0.0170 *0.0024*	0.0164 *0.0025*	0.205
2.069	0.0243 *0.0054*	0.0245 *0.0033*	0.0242 *0.0035*	0.868
2.481	0.0343 *0.0062*	0.0351 *0.0052*	0.0353 *0.0046*	0.377
2.893	0.0477 *0.0094*	0.0490 *0.0091*	0.0500 *0.0060*	0.163
3.303	0.0651 *0.0159*	0.0663 *0.0141*	0.0680 *0.0098*	0.335
3.781	0.0880 *0.0195*	0.0881 *0.0184*	0.0900 *0.0176*	0.708

Mean (m) *Standard Deviation* (m)

Both the mean and standard deviation of error tended to increase as angular velocity increased. The larger amount of variability in error at higher angular velocities was expected as any variation in latency is directly reflected to position error and vice-versa. There is evidence that filtering in the TTS may have introduced additional position error. The horizontal position measurement tended to shift towards the point of rotation as angular velocity increased (fig. 5). This may be due to low-pass filtering inside the TTS for noise reduction and resulted in an attenuation of the magnitude of the TTS output with no apparent change in phase. The data at 0.441 rad/s was from a single revolution while the data at 3.781 rad/s was from multiple revolutions to better illustrate the effect of angular velocity on magnitude of error. The patterns in the spacing between data points, particularly at the higher angular velocity, are not a result of varying latency. Rather, they are due to the fact that the sampling rate (0.4 Hz) does not line up exactly with the period of test fixture at either angular velocity.

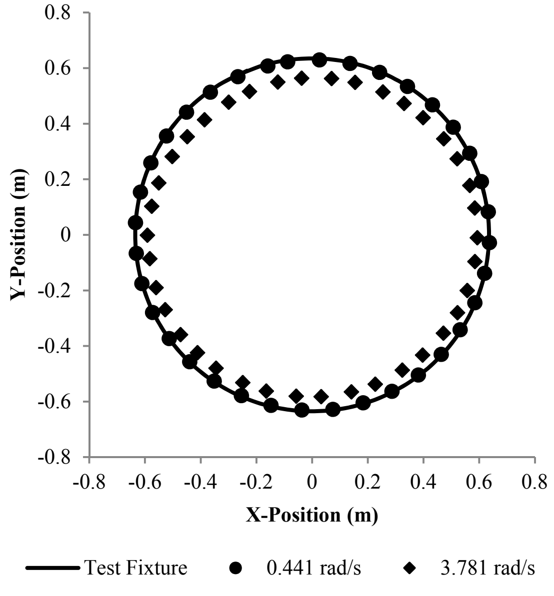


Figure 5. Horizontal position error vs. angular velocity.

CONCLUSION

Testing has shown that the prism and reflector targets had a similar average latency. The variability in latency for the prism target was several times greater than the reflector target. Since averages cannot be used for position measurements made on-the-fly, it is recommended that the prism target not be used for dynamic applications where millimeter resolution is required. There is a distinct and significant trend in average latency for the reflector target with respect to angular velocity. However, this may have resulted from TTS measurement error and not actual latency. As angular velocity increased, position error increased, which may have had an effect on the calculated phase shift between the TTS and rotary test fixture.

Distance from the TTS to the reflector target was shown to not have a significant effect on measurement error for most angular velocities tested. In the cases where there was a significant difference, that difference was less than 1.5 mm, which fulfills the order-of-magnitude accuracy requirement prescribed by the ISO 12188-1 standard. At higher angular velocities, the accuracy of the TTS is at a similar level to the static accuracy specified for most RTK GNSS devices. It is not known whether or not this level of accuracy will suffice for dynamic GNSS at angular velocities because no data on dynamic GNSS accuracy at high angular velocities has been published. Furthermore, no comparison has been made between angular velocity and actual speed. It was assumed that constant change in direction was one of the worst case scenarios for the TTS because the system was marginally stable. Both the TTS, and the interpolation method used to calculate TTS position at PPS events are expected to perform better when travelling in straight paths or around larger radii.

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