iGPS Used as Kinematic Measuring System

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Key words: iGPS, kinematic measurement system, large volume metrology, time-referencing

SUMMARY

iGPS is a measurement system which uses laser transmitters and sensors to determine the 3D position of static or moving objects. The technology is based on internal time measurements related to spatial rays that intersect at sensors in the measuring volume. The advantage of the iGPS system is the flexibility by using multiple transmitters and sensors. In this way the measurement volume can be configured to the size of the application, which can be scaled from small work cells to facility-wide installations. The typical applications are found in industrial manufactures, primarily in aerospace, automotive and shipbuilding industries.

The static iGPS accuracy is well known, but there is a lack of testing the tracking accuracy with the latest system developments. Due to the measurement principle of iGPS, tracking measurements can caused a delay time which will lead to deviations in spatiotemporal positioning. Utilizing the new Digital Input Module it is possible to examine the iGPS system with a time-referenced 4D test and calibration system.

In this paper measuring result examples are represented in order to show the iGPS performance under kinematic conditions (time and space). Velocities up to 3 m/s were reached and the 4D tracking deviations were less than 1.5 mm. At velocities lower than 1 m/s the 4D deviations decrease to below 0.5 mm. These results show that Nikon has reached to reduce the theoretical delay time and that iGPS is not only a static metrology system but also capable for tracking applications.

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1. INTRODUCTION

The measurement system iGPS is currently known under the corporate name Metris, and previously under ArcSecond. Since November 2009 Metris was acquired by Nikon Metrology NV. The system is based on internal time measurements of spatial rays that intersect at the sensor. The system is mainly used by industrial manufactures, primarily in aerospace, automotive and shipbuilding industries and enables a high flexibility and accuracy.
There are only few academic experimental studies of the technology in the literature (e.g. Wang et al., 2009) and the rapid development of the iGPS system in the previous two years makes it important to understand which system and software version is used for testing. Of special note is the kinematic measurement mode in which Nikon has made advancements. With the new Digital Input Module there is now the possibility to examine the kinematic mode by the time-referenced 4D test and calibration system. First results will be represent in this paper.
To use kinematic optical measuring systems in spatiotemporal positioning it is nescessary that all sensors of the measuring systems must be synchronized. Any existing delay times in a measuring system will lead to deviations in space-time position. These delay times will be determined with a developed time-referenced 4D test and calibration system, which is qualified for tracking optical measuring systems of any kind.

2. CONCEPT AND EQUIPMENT OF iGPS

2.1 iGPS Technology

The iGPS technology is a laser-based indoor system with optical sensors and transmitters. The typically components of an iGPS network are at least two transmitters, a mini-vector bar with two sensors, an amplifier as analog-digital converter and the position calculation engine (PCE) that measures the arrival time of each signal with an internal clock and manages the communication with the PC (Fig. 5). The transmitters surround the volume in which the location of the sensor may be calculated using the process of triangulation in an analogous fashion to a theodolite network.
Each iGPS transmitter emits two different types of signals, the strobe signal and two fan-shaped beams which are projected from the rotating head of the transmitter (Fig. 6). Photodiodes in the body of the transmitter flash the strobe signal into the whole working volume at the beginning of every second rotation to distinguish precisely from fan beam signals. The fan beams are emitted continuously and each transmitter has its own rotational speed with a frequency between 40 and 50 Hz and as a unique identification. The fans, with a beam width of ±30°, are arranged in a way that they are separated in a horizontal plane by an angle of about 90° and they are tilted at 30° to the spin axis (Fig. 1). As a result of this assembly, the angle between the two fan beams is greater than 90° above the horizontal plane

and less below. Individual values for each angle, the rotation speed and the spin axis biases are quantified by a calibration method and stored in data files for each transmitter.
Each sensor in the working volume receives signals from each visible transmitter and the arrival time is measured. The time of the strobe signal (t_{ref}) and the interpolated signal (t_0) define the beginning and end of each transmitter cycle (Fig. 2). t_1 and t_2 are time measurements when the two fan beams pass the sensor.
Based on these time measurements and the fan beams geometry, the angle values from transmitter to sensor are determined. With increasing time interval between the signal peaks of fan beam 1 in respect to fan beam 2 the elevation angle increases. The azimuth is determined using the reference time of the strobe and the mean between fan beam 1 and fan beam 2 in respect to one cycle rotation (Fig. 3).

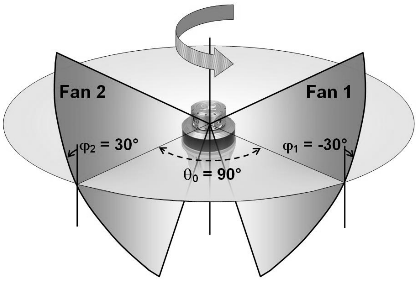

Fig. 1: Fan beam geometry of the transmitter

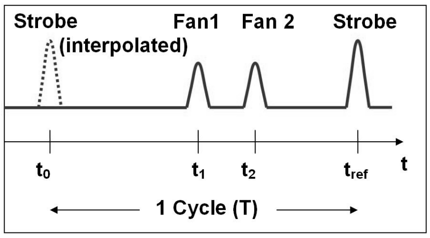

Fig 2: Signal sequence of one transmitter

The elevation and azimuth angles define a line in space or the so-called ray from the transmitter through the sensor (Fig. 4). When measuring with two transmitters (with known position), the sensor position is the closest point of intersection between two skew rays. A connecting line can be established which represents the minimum distance between these two rays and the sensor position is then the mean point of this connecting line. With more than two transmitters a redundant number of observations can be obtained and different methods of adjustment can be applied.
For the iGPS system to work, the location of the transmitter relative to each other must be established. One method for doing this is the free space network or bundling. To get the scale for the network a scale bar with two sensors of precisely know separation distance is used (Fig. 10, 14). This setup process can be very quick (two minutes) and is used to take data in the volume in which the transmitters are placed.
iGPS can be used for static or kinematic measurements. The range of a transmitter is between 2 and 40 m and the static accuracy is about 0.08 mm depending on numbers of transmitters and geometry used. Some effects and influences iGPS, like multipath or signal registration are explained in (Depenthal, Schwendemann, 2009). In this paper the focus is on the kinematic effect of iGPS. The measurement principle of iGPS is based on time measurements of non-synchronous signals and therefore the kinematic measurements can cause delay times for the azimuth and elevation determination. The sensor moves during a time measurement depending on the angular velocity relative to a transmitter. A first theoretical delay time can arise between the time of data request and the time the strobe signal requires to reach the sensor. Delays can also exist between the strobe signal and the first fan beam that passes the sensor and also between the strobe and the second fan beam. These delay times have a direct influence on azimuth and elevation determination. Another delay time in kinematic

measurements can be caused by the lack of synchronization of the different transmitters. This means that for a spatiotemporal position determination, the respective first fan beams of the transmitter arrive at the sensor not at the same time and the sensor has moved away. To eliminate these effects, it is necessary to have a good internal time base and interpolation method.
The heart of iGPS and iSpace systems is the software Surveyor. It connects to PCEs, collects data from sensors and calculates the location of the transmitters and any frames in the system. Surveyor presents a lot of detailed information that can be useful to experienced users and of course for troubleshooting by support staff. Surveyor contains functionality for bundling the system, can also be uses as a basic measurement application and displays the most important system health metrics. For experimental measurements it is very helpful that Surveyor collects all raw data and that this data can be reprocessed.

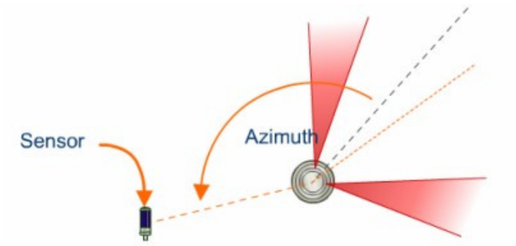

Fig. 3: Fan beams and azimuth

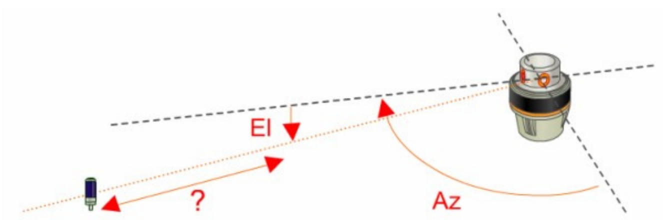

Fig. 4: Azimuth and elevation define a ray

2.2 Digital Input Module

Since summer 2009 the PCE Digital Input Module (DIM) has been available (Fig. 7). With the DIM it is possible to synchronize an external digital input signal with iGPS data. External events such as a trigger signal are time stamped in iGPS time base. In the newest Surveyor version (1.2.40) the DIM time stamp is available with coordinates information. The DIM has four input channels for the external event source and connects to a G5 DIM capable PCE. All events are automatically stored in the measurement log files. Only the DIM enable time-referenced measurements (see 3.2 and 4.2) and these kinds of measurements allow the examination of 4D kinematic performance of iGPS.

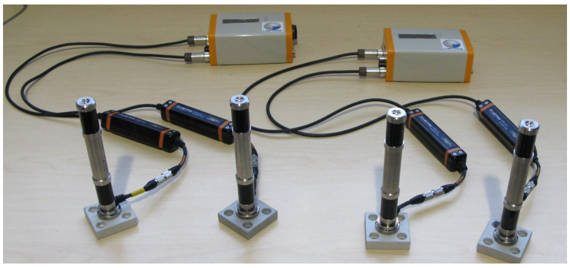
Fig. 5: Mini-vector bar, amplifier and PCE

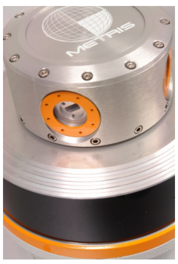
Fig. 6: Transmitter


Fig. 7: DIM and PCE

3. 4D TEST AND CALIBRATION SYSTEM

3.1 Technical Realization

The time-referenced 4D test and calibration system consists of a tiltable rotating arm with a length of 2 m. At the end of the arm a prism or sensor can be fixed and balanced by a weight on the opposite end. A rotary direct drive with an integrated rotary encoder is used as prime mover of the rotating arm. The encoder has a resolution of 0.36" and the grating disk has a reference point, the so-called homepoint, for a defined orientation. After a calibration of the direct drive a measurement uncertainty for any angular position of $U_{k=2} = \pm 4.2''$ is achieved (Depenthal, 2006). The direct drive can produce angular velocities up to 550°/s. However, up to now only 6 m/s at the arm's end has been used in default of a measuring system, which can follow objects moving with this high velocity. Depending on the rotating arm position, a calibration function for eccentricity or rotating arm bending is used.
The main item of the test and calibration system is the direct drive and the control system with the real-time multi-axis servo motion controller PMAC (Programmable Multi-Axes Controller), which is used for the position and velocity control of the direct drive. The position-capture function latches the current encoder position at the time of an external event into a special register. The actual latching is executed in hardware, without the need for software intervention. This means that the only delays in a position capture are the hardware gate delays (less than 100 ns) thereby providing a very accurate capture function (Depenthal, 2009a, 2009b).

3.2 Time Referencing

Time referencing means that specific procedures have to be assigned to a given time scale. For time referencing only, real-time systems can be used. A system is said to be real-time if the total correctness of the result of a real-time data processing depends not only upon its logical correctness, but also upon time in which it is performed. A real-time system also has to have a guaranteed temporal deterministical behavior.
Time referencing is ensured with two different procedures, either an external trigger or a serial interface. The communication between the calibration system and a test item – measurement system –is created with a function generator using the rising edge of a rectangular signal as trigger. Figure 6 shows a TTL (transistor-transistor-logic) circuit for a rising edge with a steepness of 1 µs. Within the high level both, the measurement system (t_1) and calibration system (t_2), detect the trigger, but not at the same time. A time lag Δt within the referencing arise from the gate delay of both systems and can be calculated by the difference (1) of the trigger point, which are shifted by the gate delay.

$$\Delta t = t_4 - t_3 \quad (1)$$

The gate delay of a measurement system is rarely known. The gate delay of the calibration system is less than 100 ns. The reference point for the delay time determination is the trigger point detected by the calibration system.

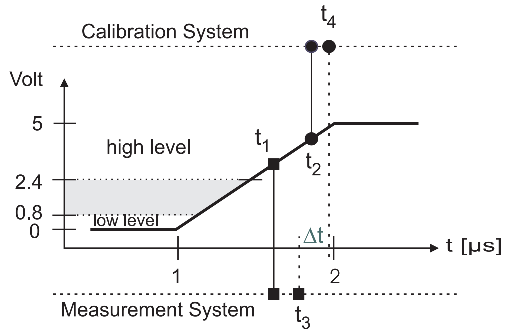

Fig. 8: Time-referencing with external trigger

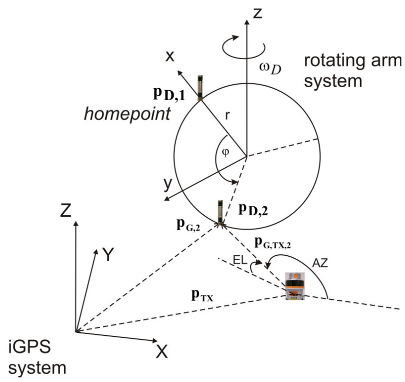

Fig. 9: Rotating arm and iGPS system

3.3 Modeling

The test and calibration system can assign an exactly defined rotation angle in respect of the homepoint and the associated time for the spatiotemporal position of a prism or sensor on the rotating arm. The aim of modeling is the determination of the delay time for every measurand of a test item. Kinematic measurements are characterized by non-repeatable measurements and therefore the kinematic model must bear the delay time for each measurand at a discrete measurement point as a unique unknown. If the measurand itself is expressed as a function of the delay time, then the solution can be found e.g. by the Newton Iteration. To reach this aim, the modeling is developed on quaternion-based rotations. The advantage of using quaternions is the efficient concatenation of multiple rotations and that only one rotation axis with one rotation angle will be used in the trigonometric form.
The theory of quaternions is given, for example, in (Kuipers, 1999) and a detailed representation for the modeling is given in (Depenthal, 2009a, 2009b). For all developed models, a coordinate transformation must be executed to combine the coordinate system of the rotating arm with the coordinate system of the test item. This transformation will be calculated using quaternions also and the algorithm based on (Horn, 1987).

The development of the model starts in the rotating arm system with the homepoint as starting point $\mathbf{p_{D,1}}=(r,0,0)^T$, with r as known radius of the rotating arm (Fig. 9). The x-axis and y-axis of the rotating arm system always lie in the rotating arm plane and the z-axis is taken to be planar to this plane. The rotation axis for the first quaternion q_1 is equivalent to the z-axis of the rotating arm system. The rotation angle will be replaced by the relation of angular velocity ω_D and time t. For a new position $\mathbf{p_{D,2}}$ in relation to the homepoint a triple product will be used and with q_1 and $p_{D,1}$ as a pure quaternion, the result of (2) is also a pure quaternion

$$p_{D,2} = q_1 p_{D,1} q_1^* \quad . \tag{2}$$

In this way all positions on the rotating arm can be defined.
The next step is the transformation from the rotating arm system to the iGPS system. With a coordinate transformation the quaternions q_R and p_{tr} are determined for the rotation and translation between both coordinate systems. The result of the coordinate transformation for (2) is the same position, but now in the iGPS coordinate system

$$p_{G,2} = q_R p_{D,2} q_R^* + p_{tr} = q_R q_1 p_{D,1} q_1^* q_R^* + p_{tr} = q_R q_1 p_{D,1} (q_R q_1)^* + p_{tr} \, . \tag{3}$$

The azimuth and elevation for the sensor position is produced from each transmitter-sensor pair (Fig 9). In order to calculate these angles equation (3) must be expanded by the vector $\mathbf{p_{TX}}$ as a pure quaternion

$$p_{G,TX,2} = p_{G,2} - p_{TX} \; . \tag{4}$$

The quaternion $p_{G,TX,2}$ is again a pure quaternion and can be directly assigned as a vector $\mathbf{p_{G,TX,2}}$ in Y^3. From this vector the azimuth and elevation can be calculated and the only unknown in this non-linear equation is the delay time t. For the iterative solution by Newton's method the initial value for the delay time is the time of measurement event. iGPS delivers only the coordinates of the sensor and transmitter and therefore the azimuth and elevation has be calculated.

4. MEASURING RESULT EXAMPLES

4.1 Equipment and Measurement Procedure

The measurements were executed in July 2009 in the Geodetic Laboratory of KIT. Four iGPS transmitters were arranged around the rotating arm and a scale bar was used for bundling (Fig. 10, 14). A mini-vector bar was fixed on one end of the rotating arm and the PCE in the center (Fig. 11, 12). Instead of cables, a wireless D-Link 802.11 wifi network was used. The DIM was connected to the frequency generator and the static scale bar PCE. The Surveyor software version 1.2.30 was used. For independently measurements a Leica laser tracker LTD 500 (measurement uncertainty ±10 ppm static and ±40 ppm kinematic) was employed. The laser tracker was also connected with the frequency generator to get trigger signals for the measuring.

The rotating arm was placed in three different positions: horizontal, slant and vertical (Fig 10, 14). Each new transmitter positions in the network are calculated through a bundling procedure and for this the scale bar is moved slowly throughout the working volume to collect bundle points. For the coordinate transformation a static reference measurement with both systems – iGPS and laser tracker – was carried out. In the kinematic mode angular velocities up to 160°/s (3 m/s) could be reached.

Within the kinematic mode the laser tracker could only follow at vertical rotating arm position, because of the visibility of the CCR. The iGPS could follow at all positions. But the vertical rotating arm position was a real challenge for the system due to detector visibility and hardware limits. Due to the vector bar position at the rotating arm the transmitters had to be arranged in the vertical rotating arm plane with a range of about 1 m out

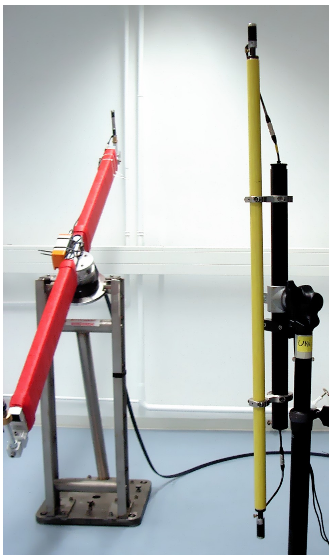

Fig. 10: Scale bar and slant rotating arm

of plane and three transmitters on one side and only one on the other side of the rotating arm (Fig. 13). These transmitter positions are not optimal for a free network and therefore it could be critical for position determination. Also the slant rotating arm position was a hard test for transmitter and sensors.

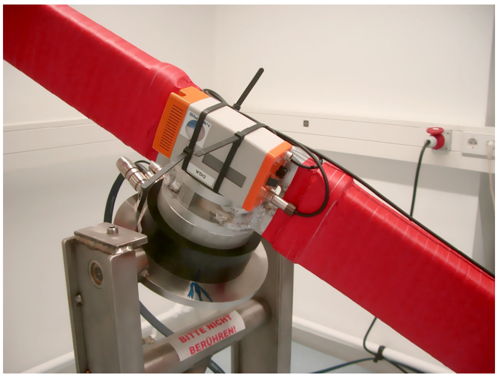

Fig. 11: PCE, center of rotating arm (slant position)

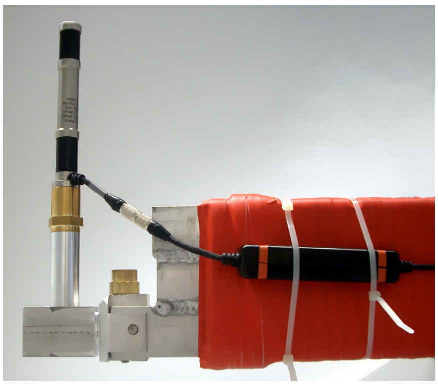

Fig. 12: Mini-vector bar and amplifier (rotating arm end)

Fig. 13: Transmitter at the highest position

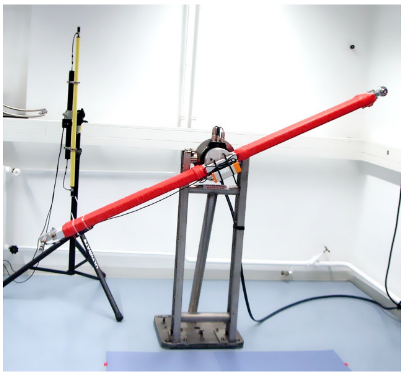

Fig. 14: Vertical rotating arm position, scale bar

4.2 DIM and Time-referencing

The DIM can be used for synchronization (see 2.2) but not in the sense of time-referencing with a trigger signal as explained in 3.2. In order to create the time-referencing, a function generator was used as an external trigger with a clock frequency of 5 Hz. That means that DIM and PMAC get a trigger signal every 200 ms with high accuracy. iGPS reports positions with a frequency of about 40 Hz (25 ms) and therefore there are about 8 measurements between two trigger signals. Each iGPS position value has an accurate internal iGPS time stamp (range µs).
The angular velocity of the rotating arm is known within 0.36"/ms and together with the PMAC encoder angle corresponding to the trigger signal, an encoder angle for each iGPS time stamp can be calculated. The iGPS time base has been controlled and there was observed a time drift of 200 µs after 72 s and therefore there is no significant time drift expected inside of the trigger period of 200 ms.

4.3 Reference Comparison

The 4D calibration system delivers the reference values: the angles in relation to the homepoint, the angular velocity and the time reference. For every revolution of the rotating arm a 3D circle fitting can be calculated using the least-square method. In the following the results as planar deviations (perpendicular to the circle plane) and radial deviations will be shown. After the coordinates of iGPS and laser tracker are transformed into the rotating arm system, the angles in relation to the homepoint are calculated. In the best case these angles are the same as the time-referenced angles of the PMAC-encoder. Due to the known angular velocity the differences between both angles are calculated as well as time deviations and tangential deviations with the known radius of the rotating arm. The delay time for the azimuth and elevation will be calculated using the modeling (3.3).

4.4 Static Measuring Results

Every static measuring starts at homepoint and than the position changed with steps of 15°. The result is the top and bottom sensor position of the mini-vector bar from iGPS and the CCR position from laser tracker. The measurement uncertainty will be deduced from the determined coordinate transformation and the residuals include the measurement uncertainty of the rotating arm as well as the measurement uncertainty of the iGPS system or laser tracker. From these residuals the measurement uncertainty for the delay time for every measurand can be deduced, more details in (Depenthal, 2009a).
For the horizontal rotating arm position the planar deviations (Fig. 15), the radial deviations (Fig. 16) and the tangential deviations (Fig. 17) represented nearly the same deviations < ±50 µm for the iGPS sensors and laser tracker. This shows that there is only a small difference between the both systems in the static condition. The standard deviations of the residuals of the coordinate transformation are less than 40 µm. Figure 18 represent the radial deviations of the vertical rotating arm position and the increased deviations for the top and bottom sensors point out the critical configuration of the iGPS network. The planar and tangential deviations are in the same order as in the horizontal position. The slant rotating arm position shows for the laser tracker the same behavior as the horizontal position and for the iGPS the deviations increase to ±120 µm.

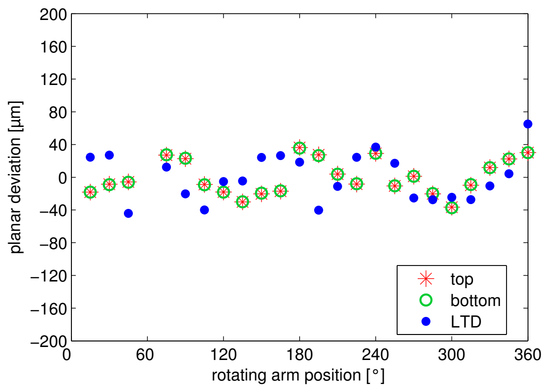

Fig. 15: Horizontal position, planar deviations

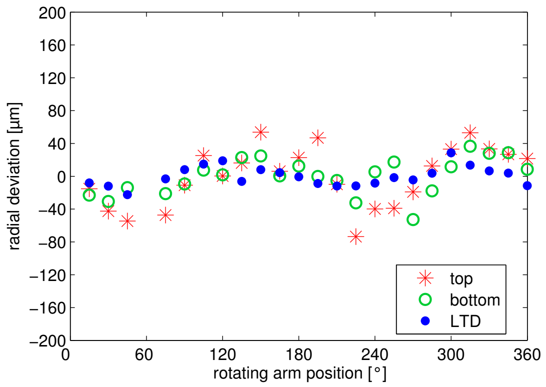

Fig. 16: Horizontal position, radial deviations

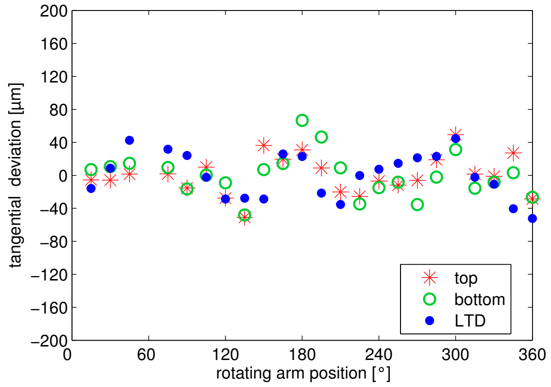

Fig. 17: Horizontal position, tangential deviations

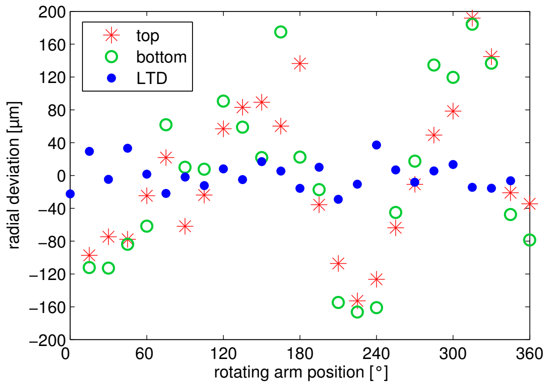

Fig. 18: Vertical position, radial deviations

4.5 Kinematic Measuring Results

The kinematic measuring are executed with different angular velocities incipient with 20°/s (0.36 mm/ms). With each new measurement the angular velocity was increased until the iGPS could not collect anymore data. To ensure an unbiased data set, the rotation direction of the rotating arm was changed for each measurement. The next figures will represent example results which are calculated as described in 4.3.

For the horizontal rotating arm position at velocity of 20°/s the planar deviations are less than ±80 µm and the radial deviation ±150 µm in spatiotemporal positioning. Figure 19 shows the tangential deviations for top and bottom sensor and they are both less than -0.5 mm (-1.4 ms). The negative deviations can be interpreted as run ahead of the iGPS sensor. Normally it would be expected that the sensors run after. There is no explanation until yet for this behavior, but it has been reported to Nikon and is being investigated. However the deviations are very small and the iGPS system is better than expected for the measuring principle employed. Figure 20 shows the tangential deviations for an angular velocity of 160°/s (2.9 mm/ms) in counterclockwise revolution. The deviations rise up to -1.3 mm (-0.5 ms) and this is a very good result for such a high velocity. Fig 21 shows the tangential deviations at the same velocity, but now in clockwise revolution. The deviations are positive that means that the sensor runs ahead again. The radial and planar deviations are remaining in the same order as at lower velocity.

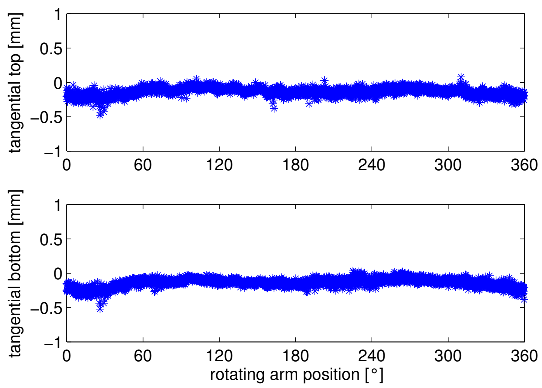

Fig. 19: horizontal, tangential deviations, 20°/s (cc)

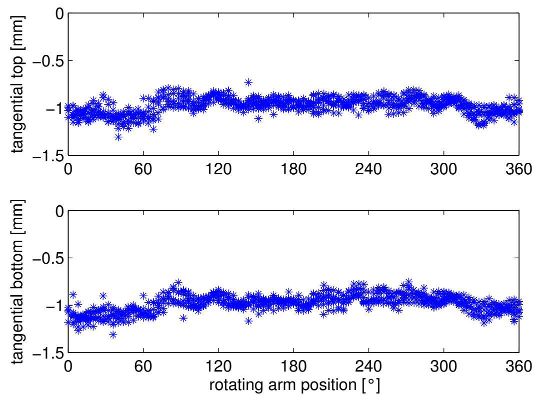

Fig. 20: horizontal, tangential deviations, 160°/s (cc)

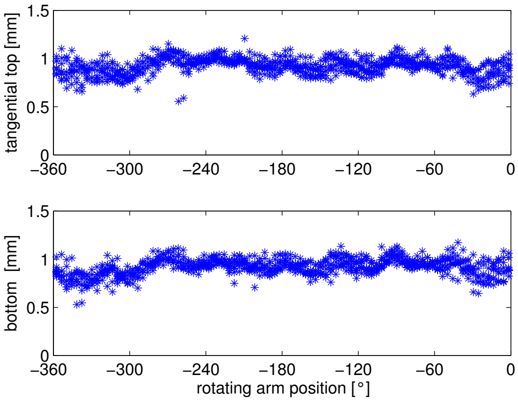

Fig. 21: horizontal, tangential deviation, 160°/s, (cw)

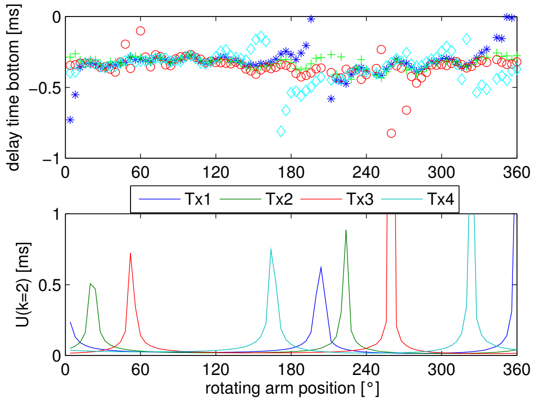

Fig.22: horizontal, delay time azimuth, 160°/s (cc)

Figure 22 shows the delay time determination for azimuth of the four transmitters – bottom sensor pairs and figure 23 the delay time for the elevation. Due to the geometrical restrictions, there are angular ranges which are not suited to derive delay times and this can be seen by the measurement uncertainty. The delay time is less than 1 ms for both measurands.

The vertical rotating arm position has the advantage that both systems – iGPS and laser tracker – can be used simultaneously, but it should be noted that the iGPS transmitter network configuration was regarded as poor and at the limits of the hardware functionality. Figure 24 shows the planar deviations at an angular velocity of 120°/s (2.2 mm/ms) about 13 revolutions of the rotating arm. The laser tracker and the top and bottom sensors show nearly the same deviations, most being less than ±100 µm. The radial deviations represent another result. The deviations for the top and bottom sensors rise up to ±350 µm (Fig. 25) however the systematic behavior remains the same about all revolutions. The increasing values could be expected due to the critical transmitter network. The tangential deviations are less than -1.3 mm (-0.6 ms) (Fig. 26). The comparison with the tangential deviations of the laser tracker, which are less than ±50 µm, point out, that the deviations are only a result of the iGPS system. The delay time determinations are in the same range as the horizontal results. The results show that to achieve acceptable results, a good transmitter network is required.

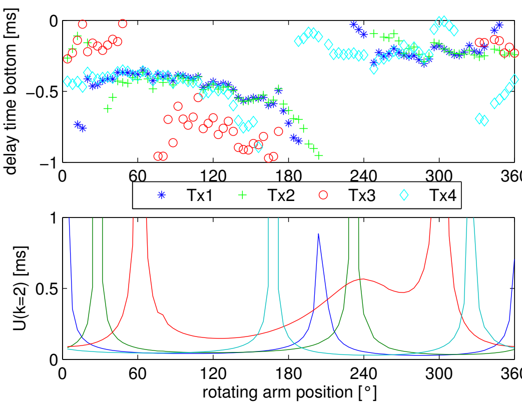

Fig. 23: horizontal, delay time elevation, 160°/s (cc)

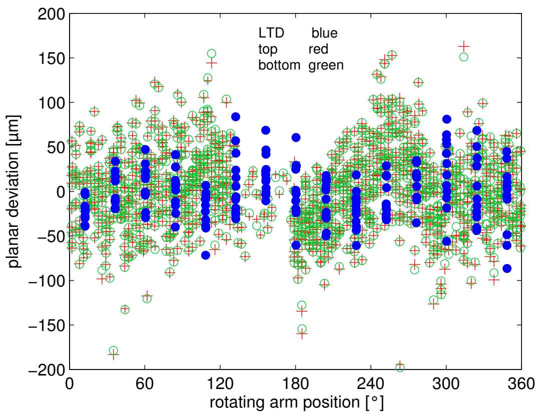

Fig. 24: vertical, planar deviations, 120°/c (cw)

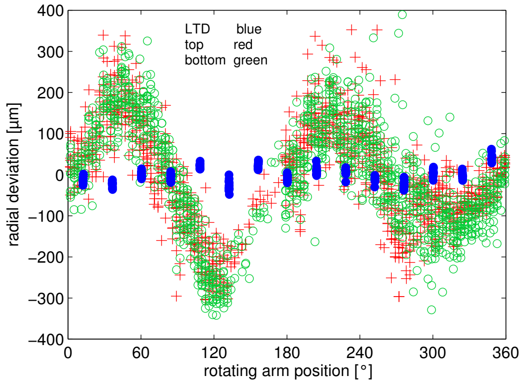

Fig. 25: vertical, radial deviations, 120°/s (cw)

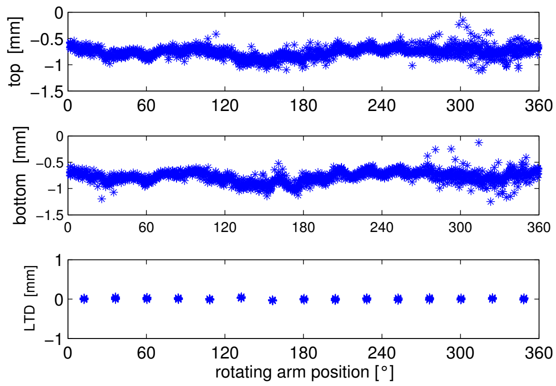

Fig. 26: vertical, tangential deviations, 120°/s (cw)

The slant rotating arm position is also a critical position for the iGPS system in this configuration. Until an angular velocity of 120°/s the system collects nearly all data. The planar deviations reach values up to ±200 µm and the radial deviations remain also in this range and do not show the systemic attitude seen in the vertical test. Figure 27 shows the tangential deviations for an angular velocity of 120°/s (2.2 mm/ms) and the result was less than -0.5 mm (-0.2 ms) which was not expected by this configuration. Figure 28 represent again the delay time for the azimuth for the different transmitter – bottom sensor pair and the result is less than 1 ms.

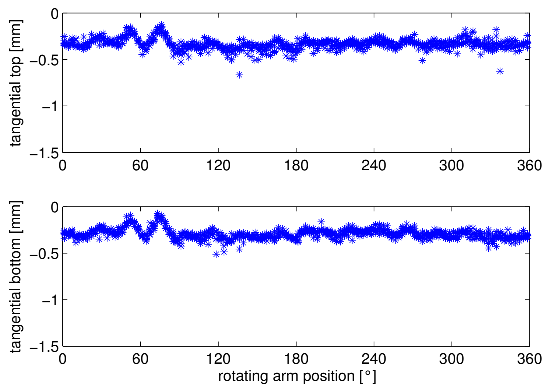

Fig. 27: slant, tangential deviations, 120°/s (cw)

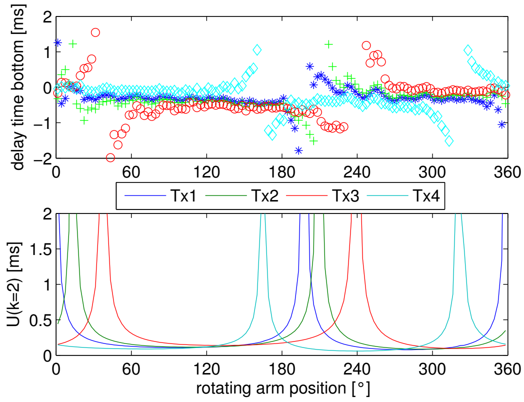

Fig. 28: slant, delay time azimuth, 120°/s (cw)

5. CONCLUSIONS

The aim of the measurements which are represented in this paper was to analyze the kinematic performance of the iGPS metrology system. The original question was to determine if there exists a theoretical delay time and to determine the maximum velocity the system can work. By usage of latest equipment and Surveyor software it was possible to show that the iGPS system has done great steps of development. A part of the experimental conditions were a hard test for the system because the critical limits for transmitter and sensors were reached.

The system could collect and process data up to velocity of 3 m/s in this experimental set-up. At 1 m/s a tracking deviation of less than 0.5 mm is reached (spatiotemporal) and at the highest velocity the deviation can be on the order up to 1.5 mm. An interesting fact is that the "sensor" seems "to run ahead" and further examinations will be done for clearing this effect. Altogether show the results that the development of the latest iGPS system has reached to reduce the theoretical delay time. For this reason iGPS can be used as well as static or kinematic measuring system and due to the flexible measuring performance it provides an interesting range of applications.

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BIOGRAPHICAL NOTES

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