METROLOGICAL COMPARISON BETWEEN TWO SENSOR-CONFIGURATIONS OF THE IGPS MEASUREMENT SYSTEM

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Abstract. *Currently, there are coordinates measurement equipments of large volumes that use laser and optical technologies providing accuracies up to tenths of a millimiter with a greater measuring.flexibility.One of these equipments is known as iGPS (indoor Global Positioning System), whose measurement system, among others, depends on the sensor-configuration used. The first sensor type is a bar with two sensors, known as mini-vector bar, which is attached to the measurand. A wireless probe, named iProbe, offering freedom and versality in the measurement of any measurand point, represents the second configuration. Thus, through an experiment in a predetermined volume work, this work compares the measurement characteristics of these two types of sensor-configurations. Where values obtained of repeatability lower than ± 0,1 mm and accuracies of ± 0,3 mm approximately, would address the iGPS use for measurements and control of robotic aplications.*

Keywords: *iGPS; measuring system, mini-vector bar, iProbe, metrological characteristics.*

1. INTRODUCTION

The iGPS (indoor Global Positioning System) is a system designed to large scale metrology. It is composed of transmitters emitting laser signal that is captured by a set of sensors located within a volume work. The final result of this data acquisition represents sensors positions with accuracy up to tenths of a millimeter. Up to now, few iGPS works have been published:Maropoulos *et al.* (2008) with the laser tracker metrological system have compared their tolerances in large volumes related to aerospace parts and subassemblies. Cuypers *et al* (2009) related optical measurement techniques of mobile metrology in large volumes, explaining briefly its operating principle. Also, Depenthal e Schwendemann (2009) carried out iGPS accuracy measures in terms of the equipment distribution on a particular work area.

In order to establish a metrological reliability of the iGPS sensors, this paper addresses to the measurements comparison between two iGPS sensor-configurations: the iProbe and the mini-vector bar. Each one of these two configurations is used to measure the same distance on a test sample.

2. IGPS SENSORS

2.1. iGPS Physical principle

The iGPS uses the physical principle of triangulation that is also used in the current global positioning system. Thus, the iGPS transmitters act like satellites and the iGPS sensors represent the desired location points on the earth surface (ARCSECOND, 2005). Fig.1 shows the iGPS elements.

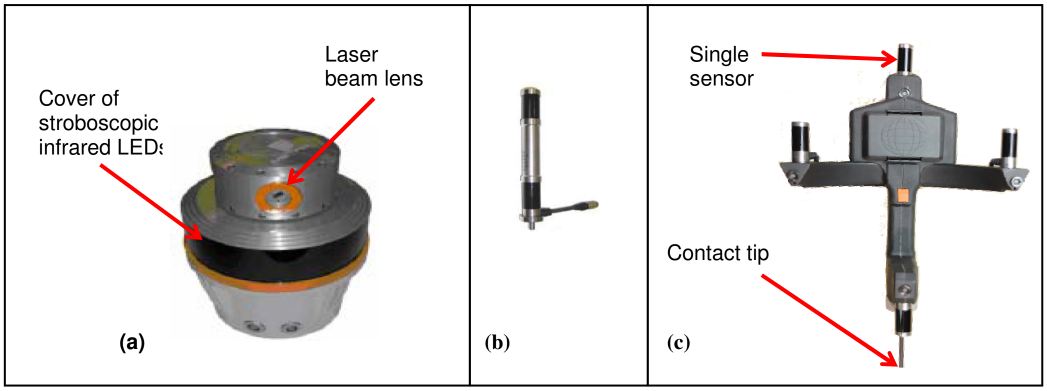


Figure 1. iGPS main elements: (a) Transmitter, (b) Mini-Vector Bar, (c) iProbe. Source: METRIS (2009.)

A 3D information is necessary to set a location point in the space; this is attained using spherical coordinates through sensors elevation and azimuth angles in relation to a spinning transmitter head. Each transmitter head rotates at a specific frequency and emits two laser beams, as well as, a stroboscopic infrared signal that is captured by sensors located in the mini-vector bars or in the iProbe.

The sensors, shown in Fig. 1b and 1c are composed of a photodiode detector connected to a signal processing (or amplifier) that detects and converts the received signal and then sends the receiver.

Figure 2 explains the azimuth and elevation angles interaction. Because the inclination angle of the two laser beams is known, the angular value is converted to azimuth and elevation angles. So, the time difference between the passage of laser beams 1 and 2 (see Fig. 2) defines the elevation angle (θ) due to beams inclination. The azimuth angle (ø) is defined as the difference between the periodic reference pulse and the mid-point in the passage of two laser beams. Thus, the two angles of elevation and azimuth define the radius of the transmitter to the sensor.

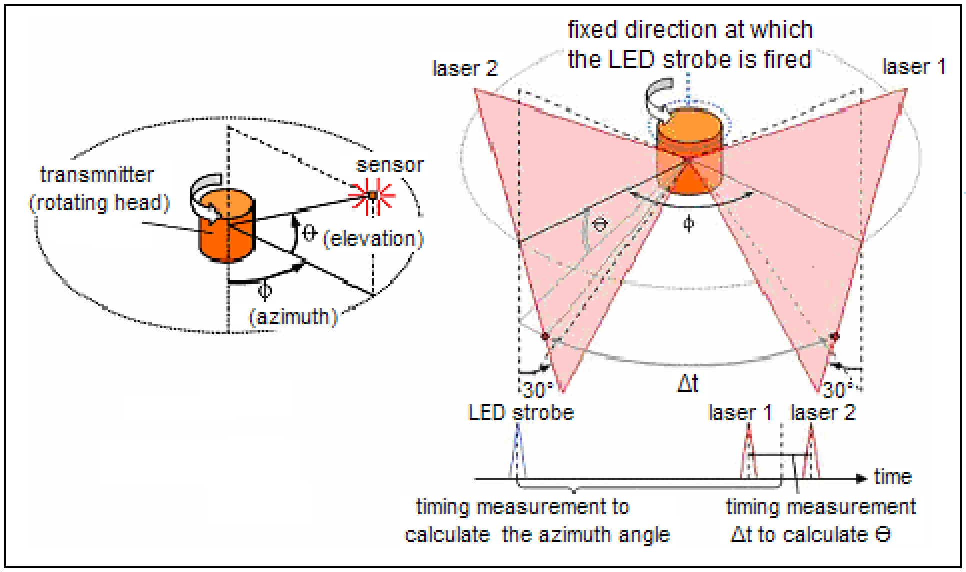


Figure 2. Azimuth and elevation angles. Source: Maisano (2008).

Because a sensor position cannot be known with only one transmitter, at least, another transmitter is necessary to use the triangulation principle. Whenever more transmitters are used, the system accuracy increases (METRIS, 2009).

3. EXPERIMENT DEVELOPMENT

This experiment is a complement of a previous one carried out by Landeta and Sutério (2010) related to the analysis of the influence of distance and transmitters quantity in coordinate measuring using the iGPS. Thereby, this experiment followed all the manufacturer guidelines (METRIS, 2009) as well, as stated below.

- Even though the iGPS could run on an outdoor space work, it is better to minimize the light amount as long as possible because its signal detection capacity decreases in a lighter work space.
- Temperature range should be between 10 °C and 30 °C. This experiment was performed at 22 °C with a maximum variation of ± 2 ºC.
- Vibration sources such as wind currents jeopardize measurements, and they could affect both transmitters and sensors. Thus, wind currents were avoided altogether for this experiment.

3.1. Experiment configuration

Using the same experiment configuration of that Landeta and Sutério (2010) shown in Fig. 3, the distance *D* was measured twice, firstly, with mini-vector bars and the second one with the iProbe.

The sample test is a tubular structure that has two machined surfaces. There is one hole with size tolerances H7 type by each surface. So, *D* is the sample test diagonal formed from the center of each surface hole to the origin of the iGPS coordinate system, which in turn, is theoretically located in the center of the hole 0. It is indicated in the Fig. 3a. Due to hole size tolerance, a mini-vector bar fits perpendicularly to the machined surface.

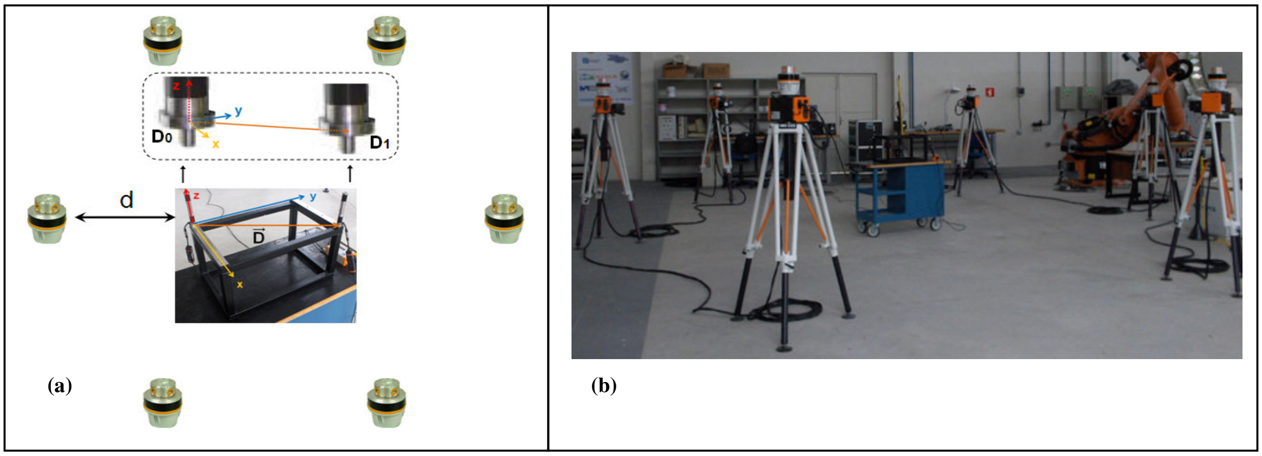


Figure 3. Experimental configuration: (a) Transmitter and sensors layout position around the sample test. (b) Transmitters position around sensors located on the sample test. Source: Landeta and Sutério (2010)

Table 1 shows the nominal values of D_0 and D_1 distances measured with a coordinate measuring machine (brand: Zeiss, model: MD-049/09, measure uncertainty: ± 14 µm with 95% confidence level.)

Table 1. D_0 and D_1 measures using a coordinate measuring machine. Source: Landeta and Sutério (2010.)

		D_0 [mm]	D_1 [mm]
Nominal value	x	0	312
	y	0	510
	z	0	0
Nominal *D*	597,9 mm		
Measured value	x	0,000	312,369
	y	0,000	510,287
	z	0,000	-0,019
Measured *D*	598,304 mm		

Using the same distance **d** and changing only the number of active transmitters, a previous experiment showed that the adequate number of samples is three (LANDETA, 2010). Thus, D_0 and D_1 distances were measured three times each with both mini-vector bar and the iProbe. Due it is a factorial experiment, the number of transmitter used and the distance **d** (between transmitter and sample test) changed for each case. So, 300 measures were performed in total (150 for D_0 and 150 for D_1, 75 using a mini-vector bar and 75 with iProbe for each *D*).

During the hole measurement process, the sample test remained still. By varying the number of transmitters to perform the measurement, a uniform distribution of active transmitters was kept around the sample test.

The difference between nominal *D* values and sensor´s measures is obtained with Eq (1).

$$\Delta D = \sqrt{(x_{iGPS} - x_{CMM})^2 + (y_{iGPS} - y_{CMM})^2 + (z_{iGPS} - z_{CMM})^2} \tag{1}$$

where:

ΔD = iGPS Position error (ΔD_0 and ΔD_1) in relation to reference value.
x_{iGPS} = iGPS measure of axis x (mini-vector bar or iProbe).
y_{iGPS} = iGPS measure of axis y (mini-vector bar or iProbe).
z_{iGPS} = iGPS measure of axis z (mini-vector bar or iProbe).
x_{CMM} = axis x measure of a coordinate measuring machine.
y_{CMM} = axis y measure of a coordinate measuring machine.
z_{CMM} = axisz measure of a coordinate measuring machine.

Equation 2 indicates a statistical model that uses the statistical technique of variance analysis known as *ANOVA,* fully detailed in Montgomery (2001).

$$w_{ijk} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijk} \tag{2}$$

where:

w_{ijk} = ΔD_0 or ΔD_1.
μ = Overall mean of ΔD_0 or ΔD_1.
τ = Effect of the *i*-th level of distance *d* (between transmitter and sensor) (Factor A).
β = Effect of the *j*-th level of transmitters number (Factor B).
γ = Effect of the *k*-th level of iGPS sensor type used (mini-vector bar or iProbe) (Factor C).
ε = Random experimental error.

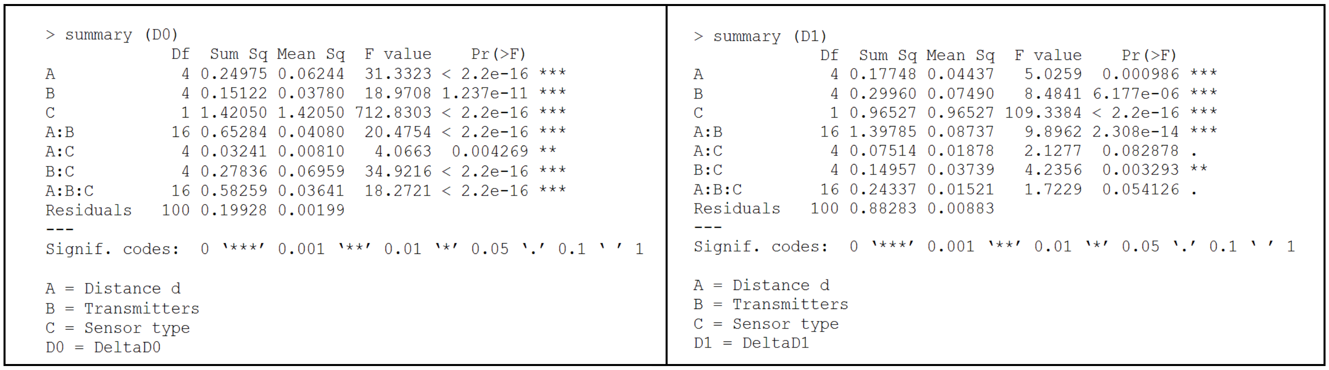
The hypothesis tests verified in the Eq. (2) model are shown in Tab. 6 which assess the influence of various factors upon the measurements. It is emphasized that these assumptions are valid for the interactions among the factors that are not represented in Tab. 2.

Table 2. Hypothesis tests

Null Hypothesis:	Alternative Hipothesis:
$H_0:\ \tau_1 = \tau_2 = \ldots \tau_i = 0$	$H_1:\ \tau_i \neq 0$
$\beta_1 = \beta_2 = \ldots \beta_j = 0$	$\beta_j \neq 0$
$\gamma_1 = \gamma_2 = \ldots\ \gamma_k = 0$	$\gamma_k \neq 0$

3.2. Measurements results

Using the application of R. (2009) (a free statistical computing software), the variance analysis of Eq. (2) incidence factors was carried out, and the values of ΔD_0 and ΔD_1 are shown in Fig. 4.



```
> summary (D0)
             Df  Sum Sq Mean Sq  F value    Pr(>F)
A             4 0.24975 0.06244  31.3323 < 2.2e-16 ***
B             4 0.15122 0.03780  18.9708 1.237e-11 ***
C             1 1.42050 1.42050 712.8303 < 2.2e-16 ***
A:B          16 0.65284 0.04080  20.4754 < 2.2e-16 ***
A:C           4 0.03241 0.00810   4.0663  0.004269 **
B:C           4 0.27836 0.06959  34.9216 < 2.2e-16 ***
A:B:C        16 0.58259 0.03641  18.2721 < 2.2e-16 ***
Residuals   100 0.19928 0.00199
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

A = Distance d
B = Transmitters
C = Sensor type
D0 = DeltaD0
```

```
> summary (D1)
             Df  Sum Sq Mean Sq  F value    Pr(>F)
A             4 0.17748 0.04437   5.0259  0.000986 ***
B             4 0.29960 0.07490   8.4841 6.177e-06 ***
C             1 0.96527 0.96527 109.3384 < 2.2e-16 ***
A:B          16 1.39785 0.08737   9.8962 2.308e-14 ***
A:C           4 0.07514 0.01878   2.1277  0.082878 .
B:C           4 0.14957 0.03739   4.2356  0.003293 **
A:B:C        16 0.24337 0.01521   1.7229  0.054126 .
Residuals   100 0.88283 0.00883
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

A = Distance d
B = Transmitters
C = Sensor type
D1 = DeltaD1
```

Figure 4. Variance analysis related to ΔD_0 and ΔD_1.

In Fig. 4, the hypothesis H_0 of Tab. 2 is rejected in all factors and in almost all combinations (except in BC and ABC for ΔD_1) due the *Pr* value of Fig. 4 is less than the significance coefficient (α = 0, 05). Therefore, in all factors (distance *d*, transmitter numbers and sensor type) and their interactions, in which this condition is fulfilled, affect ΔD_0 and ΔD_1 values. Figs 5 and 6 indicate these factor variances and their interactions.

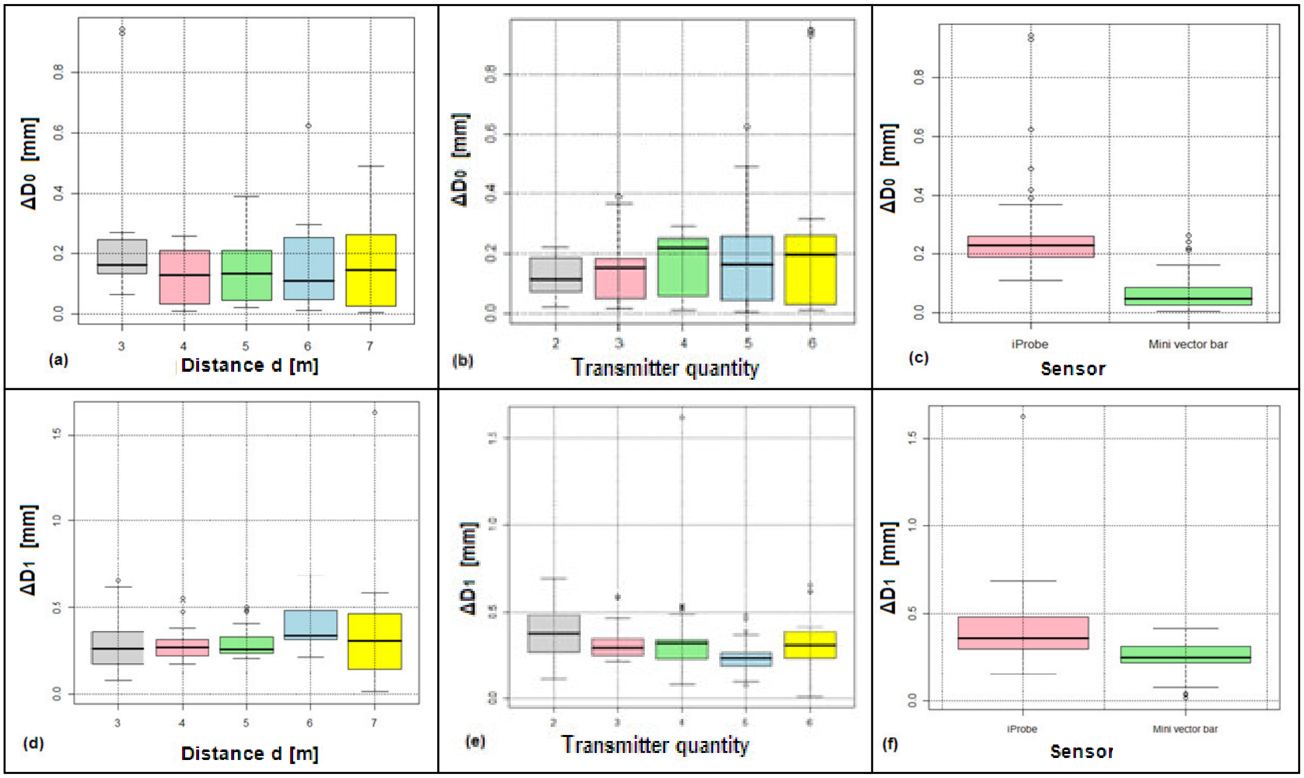


Figure 5. ΔD_0 and ΔD_1 in terms of distance d, transmitter quantity and sensor type.

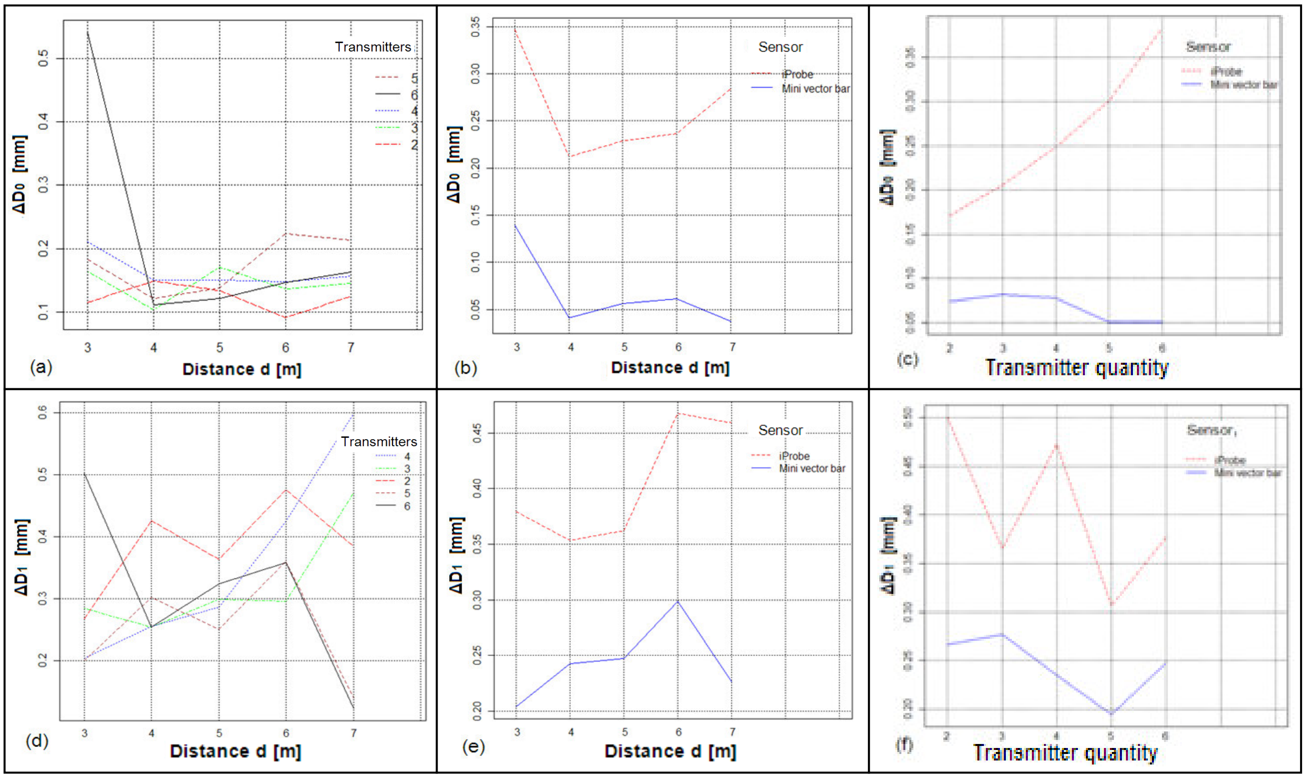


Figure 6. Interactions of distance *d*, transmitter quantity and sensor type for ΔD_0 and ΔD_1.

In Fig. 5 and 6 both distance **d,** and transmitters quantity affect on ΔD_0 and ΔD_1. However, the most significant is the mini-vector bar error range lower than iProbe´s, shown in Figures 5c, 5f and in factors interaction in Figures 6b, 6c, 6e e 6f.

In order to verify the proper adjustment of the statistical model used in Eq. (2), normality and residuals tests were executed. Fig. 7 indicates no significant structure or tendency graph as normality is met in most measurements.

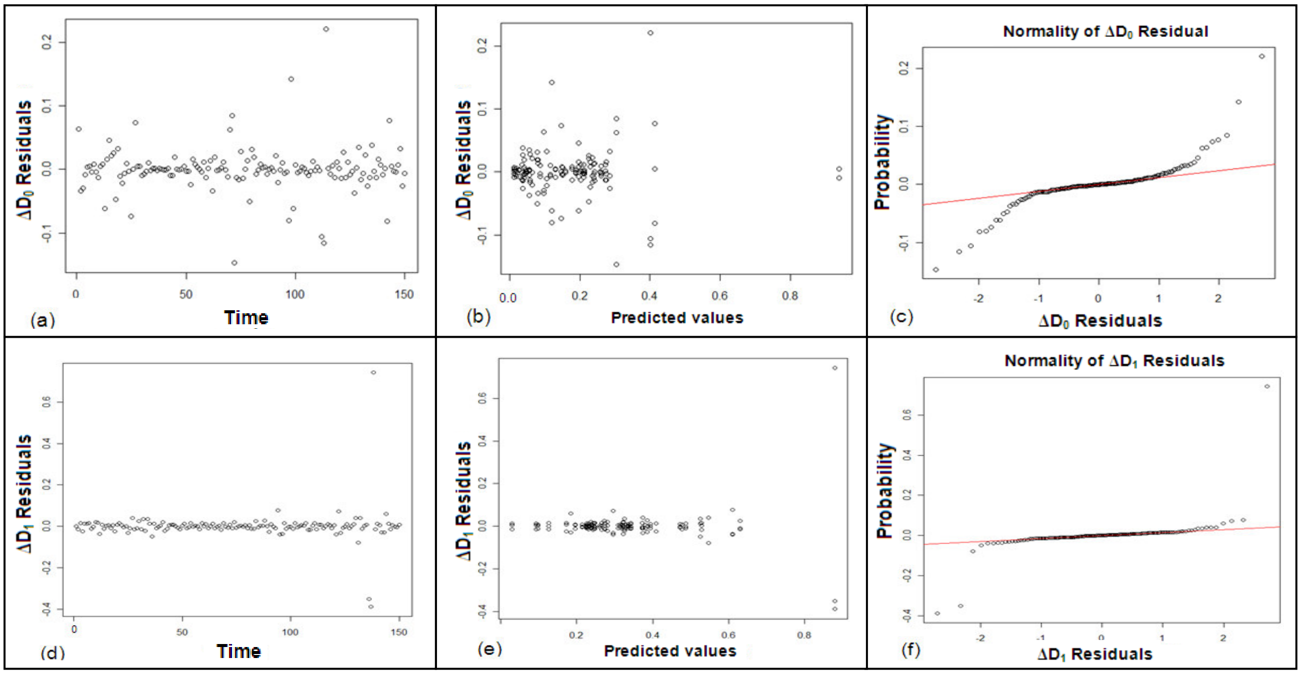


Figure 7. Residuals and residual normality for ΔD_0 and ΔD_1.

3.3. Reproducibility, repeatability and accuracy of iGPS sensors.

Repeatability is related to the rate at which it is expected the random error in repeated measurements and performed under similar conditions. Reproducibility has the same definition, but performed in different conditions. The reproducibility in this case was determined by varying the transmitter quantity and transmitter - sensor distance to measure ΔD.

In this paper, both reproducibility and repeatability (shown in Tables 2 and 3, respectively) were calculated according with the Equations (3) and (4). The iGPS system accuracy was represented by the sum of the mean of the modulus measurements (ΔD_0 and ΔD_1) and repeatability.

$$reproducibility = \sigma_1 * st_1 \qquad (3)$$

where:

σ_1 = Standard deviation for 75 measures with iProbe or 75 measures with mini-vector bar
st_1 = *t-student* coefficient for 74 degrees of freedom and a significance level of 0,05

$$repeatability = \sigma_2 * st_2 \qquad (4)$$

where:

σ_2 = Standard deviation for 3 measures with iProbe or 3 measures with mini-vector bar for each factors case
st_2 = *t-student* coefficient for 2 degrees of freedom and a significance level of 0,05

Table 2. iGPS system reproducibility.

		ΔD_0 [mm]		ΔD_1 [mm]	
Sensor type	n	Error mean	Reproducibility	Error mean	Reproducibility
iProbe	75	0,26	0,32	0,40	0,38
Mini-vector bar	75	0,07	0,11	0,24	0,18

Table 3. iGPS system repeatability.

			ΔD_0 [mm]			ΔD_1 [mm]		
Distance *d* [m]	Transmitter quantity	n	Mean error	Repeatability	Accuracy	Mean error	Repeatability	Accuracy
iProbe								
3	2	3	0,13	0,03	0,16	0,41	0,09	0,50
	3	3	0,18	0,05	0,23	0,32	0,14	0,46
	4	3	0,23	0,18	0,40	0,31	0,04	0,35
	5	3	0,26	0,03	0,29	0,23	0,02	0,25
	6	3	0,94	0,04	0,98	0,63	0,09	0,72
4	2	3	0,21	0,01	0,22	0,53	0,19	0,71
	3	3	0,16	0,01	0,17	0,28	0,09	0,37
	4	3	0,26	0,00	0,26	0,31	0,03	0,34
	5	3	0,23	0,09	0,32	0,37	0,06	0,43
	6	3	0,20	0,05	0,26	0,27	0,07	0,34
5	2	3	0,19	0,01	0,20	0,49	0,05	0,54
	3	3	0,30	0,55	0,86	0,33	0,03	0,37
	4	3	0,24	0,06	0,30	0,33	0,01	0,34
	5	3	0,20	0,03	0,23	0,27	0,09	0,36
	6	3	0,21	0,01	0,22	0,39	0,11	0,50

6	2	3	0,12	0,04	0,15	0,61	0,29	0,90
	3	3	0,15	0,03	0,18	0,34	0,06	0,40
	4	3	0,24	0,05	0,29	0,53	0,07	0,60
	5	3	0,40	0,83	1,23	0,48	0,05	0,53
	6	3	0,27	0,05	0,33	0,38	0,03	0,41
7	2	3	0,21	0,04	0,26	0,47	0,04	0,51
	3	3	0,24	0,09	0,32	0,55	0,30	0,84
	4	3	0,28	0,06	0,34	0,88	2,77	3,64
	5	3	0,41	0,34	0,75	0,18	0,22	0,41
	6	3	0,29	0,13	0,41	0,21	0,03	0,25
Mini-vector bar								
3	2	3	0,10	0,24	0,33	0,13	0,06	0,19
	3	3	0,15	0,03	0,18	0,25	0,06	0,30
	4	3	0,20	0,24	0,44	0,10	0,04	0,14
	5	3	0,11	0,12	0,23	0,17	0,09	0,26
	6	3	0,15	0,32	0,46	0,37	0,16	0,53
4	2	3	0,09	0,04	0,13	0,33	0,13	0,46
	3	3	0,05	0,01	0,05	0,23	0,05	0,27
	4	3	0,04	0,07	0,11	0,20	0,05	0,25
	5	3	0,01	0,02	0,03	0,23	0,06	0,29
	6	3	0,02	0,02	0,03	0,23	0,01	0,25
5	2	3	0,08	0,13	0,21	0,24	0,05	0,29
	3	3	0,04	0,05	0,09	0,27	0,07	0,34
	4	3	0,06	0,11	0,16	0,24	0,07	0,31
	5	3	0,08	0,19	0,27	0,23	0,04	0,26
	6	3	0,03	0,03	0,05	0,26	0,02	0,28
6	2	3	0,06	0,09	0,15	0,34	0,04	0,39
	3	3	0,12	0,53	0,65	0,25	0,06	0,31
	4	3	0,06	0,02	0,08	0,32	0,02	0,34
	5	3	0,05	0,01	0,06	0,24	0,07	0,31
	6	3	0,02	0,03	0,05	0,34	0,04	0,38
7	2	3	0,04	0,10	0,14	0,30	0,26	0,56
	3	3	0,06	0,16	0,21	0,39	0,04	0,44
	4	3	0,04	0,15	0,18	0,32	0,04	0,36
	5	3	0,01	0,03	0,05	0,09	0,06	0,15
	6	3	0,04	0,03	0,07	0,03	0,06	0,09

Of all the distance D_1 values measured with the iProbe (n = 75), only one is out of the range, i.e., less than 1 mm in the value of differences in measurement (ΔD_1 = 1.620 mm, one of the three measurements with 4 transmitters and d = 7m.) This measurement was casted out and the average difference and the reproducibility for iProbe in ΔD_1 were 0.39 and 0.25 mm, respectively.

Regarding the overall average ΔD_1 of Tab. 3, the iProbe has a repeatability of ± 0.10 mm and an accuracy of ± 0.49 mm, whereas with the mini-vector bar, repeatability is ± 0.07 mm and accuracy of ± 0.31 mm. Finally, for the same ΔD_1, the most accurate measure for iProbe and mini-vector bar is carried out with six transmitters at a distance of 7 m from the center of the experiment area ($d = 7m$).

4. CONCLUSIONS

Both the transmitter quantity and the sensor- transmitter sensor affect on the iGPS measurements. Between the iProbe and the mini-vevtor bar, more accurate measures are reached with the second sensor type. Thereby, the lower iProbe accuracy indicated in the interactions of Fig. 6 is related to its calibration process, which, after many attempts, it was not possible to obtain error values less than 0.314 mm. Furthermore, it must be assumed that the iProbe indicates the center position from its contact sphere (Ø = 8 mm). Therefore, it is necessary a z axis offset to reach the centers position of the sample test holes (Ø = 6.357 mm and 6.355 mm for D_0 and D_1 respectively).

Considering the hole tolerance (H7), equivalent to tolerance of 20 µm, even though it is negligible compared to the magnitude of the measurements results, gaps created between sample test holes and connnection base of mini-vector bars cause concentricity variation of the longitudinal axes (z) of mini-vector bar and hole. Thereby, it represents an error source of iGPS sensor measures.

In order to evaluate the metrological reliability of the iGPS sensors, especially the iProbe, and also to minimize the error sources of iGPS sensor measures, new experiments are planned to carried out using another metrological system with a higher accuracy, such as the laser radar.

5. ACKNOWLEDGEMENTS

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7. RESPONSABILITY NOTICE

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