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Heighting and Distance Accuracy with Electronic Digital Levels

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Abstract. A Leica NA3000 electronic digital level, one of the newly-introduced heighting equipment, was evaluated for vertical and horizontal distance measurement. A well protected 170 m long 17-section test line was first established for this purpose using geodetic surveying techniques. The test instrument was then used to remeasure the line. Two approaches were followed. In the first, closed loops were run from one end of the line to each of the pegs on the line and back to the starting point in an out-and-back manner. Misclosure errors of loops were then computed and compared to known levelling standards. In the second approach, heights of some pegs on the line were re-established several times with the instrument erected on the one end of the line. Standard deviations of height measurement of each peg were then computed and compared with known standards. The results showed that in the first approach, the test instrument was able to achieve accuracy values commensurate with first order class I levelling standards as set out by the U.S.A.-based Federal Geodetic Control Committee (FGCC), i.e. better than $\pm 3.0 \sqrt{k}$ mm. In the second approach, for distances up to 64 m, standard deviations better than ± 60 microns could easily be obtained. Again, this is within the requirements of first order class I levelling standards. Overall, therefore, it can be said that digital electronic levels, as exemplified by the Leica NA3000 model, could be used to support high accuracy levelling operations being them of the geodetic or ordinary type.

The distance measuring stage of the test showed that, for up to 64 m from instrument station, the test instrument is capable of measuring distances to accuracy values better than 1/2000. This is sufficient accuracy for some localized survey works, e. g. site preparation in construction industry, pavement maintenance surveys, sewer pipe placement and monitoring etc. where distance errors of a few centimeters in several tens of meters are tolerable.

Introduction

In the last five to ten years, a remarkable stage of development in electronic surveying has taken place. This development ranges from surveying with high tech global positioning systems (GPS), through yet more improved electronic digital theodolites and total stations to electronic heighting instruments. Some of these new techniques (and instruments) are more appropriate for surveying large areas, others were designed to support rather localized survey operations such as site preparations in construction industry, channel dredging, sewer placement and monitoring etc. Among the latter type are the laser and the electronic digital levels. These two instruments have recently been introduced to the market to make the levelling process easier, rapid and economical. A concise account on the design, construction and operation together with the accuracy with which elevations could be determined using the laser level have been reported by Ali and Al-Garni [1].

The Electronic Digital Level

Over the years, the same interest to measure distances and angles automatically, (thus resulting in the invention of electro-optical and electronic distance measurement devices and electronic digital theodolites) continued for the search of some means of measuring heights electronically. Recent advances in digital electronic technology have facilitated the design and production of the electronic digital level. In this instrument, as with the automatic optical level, a pendulum compensator is used to level the instrument, after an operator accomplishes rough levelling with a bull's eye bubble. With its telescope and cross-hairs, the electronic digital level could be used to obtain readings manually, just like any of the automatic optical levels using a standard levelling rod. However, the instrument is designed to operate by employing electronic digital image processing and is used in conjunction with a special bar-coded staff. Furthermore, recording of data can be accomplished automatically without operator interference and then processed later using computer. The instrument has a beam splitter in the optical path which arranges for infrared radiation to reach a photodiode array whilst visible light passes through a reticule and eyepiece. When being used in scanning mode, the photodiodes effectively replace the eye of the observer when the bar-coded staff is used. The photodiode array, consisting of 256 diodes within a length of only 6.5 mm, converts the bar-code image into a video signal which is then amplified, digitized electronically and passed to a built-in microprocessor. At the same time the position of the internal focussing lens is established by the encoder whilst the compensator action is monitored by an electronic position detector. A two-stage correlation procedure is carried out in the evaluation of the signal, the measured data being compared to an internal reference. When a correlation (or match) is realized, which takes about four seconds in the present generation of digital levels , the staff reading is digitally displayed. The result can be recorded manually on a levelling fieldbook or else automatically stored in the data collector of the level.

A main feature of the electronic digital level is that the length of the staff appearing in the field of view is a function of the distance from the staff. So, as part of the image processing operation, the level is also able to compute the horizontal distance to the staff automatically. This is advantageous for (i) balancing backsights and foresights while carrying out the levelling operation, and (ii) for measuring other desirable distances. Usually the bar-coded staff has meter (or foot) graduations on the other side thus allowing digitally displayed staff readings to be checked by turning the rod. Examples of electronic digital levels are Leica NA2000, NA2002 and NA3000, and Zeiss Oberkochen DiNi 10,11,12 and 21.

So with the digital level, the operator can work faster and with less stress. Other advantages of the system are its ease of use, the absence of reading and booking errors, the automatic height calculation during measurement and data recording. The applications therefore extend from conventional staff reading measurement, through line and area levelling to on-line operations with a computer connected.

Sources of Error in Electronic Digital Levels

Most of the instrumental sources of error affecting automatic optical levels also affect the electronic digital level e.g. centering of bull's eye bubble, instability of pendulum system and collimation error. This is in addition to natural errors (e.g. curvature, refraction, ground settlement and instability and effects of heat on instrument) and personal errors (e.g. parallax, rod out of plumb, etc.). However, as the human reading error is no longer a problem with digital levels, double measurement could be necessary just because of the problem of sinking. Because the time it takes to perform a measurement using a digital level is so much shorter than with optical or laser levels, the problem of sinking does not carry so much weight so that when measuring on fairly firm terrain it can be considered negligible and double measurement may even be unnecessary. Further, with electronic digital levels, the software residing in the microcomputer of the instrument would automatically correct for earth curvature. The instrument is usually capable of taking several measurements on a rod held at a point, averaging the readings and computing standard deviation of rod height readings. For more refined work, enhanced "extended " system accuracy can be chosen [2]. However, the question to be asked is how accurate is this new instrument in height measurement compared to other optical levels? Also, if the instrument is to be used for measuring distances, what ranges of error could be obtained and how are these compared with standard specifications.

The purpose of this paper is, therefore, to evaluate the accuracy with which heights and distances can be measured using electronic digital levels. However, it should be pointed out from the outset that it is not the intention of the authors to recommend or endorse the instrument used in the test for a certain kind of survey work. Rather, the goal of the experiment is to evaluate, in a limited manner, the test instrument by contrasting the results obtained with it with those determined by optical levelling. The results will give some insight into the measuring capabilities of this new instrument for everyday surveying work.

Procedure of Test

A procedure similar to that followed by Ali and Al-Garni [1] in testing the accuracy of heighting with a Sokkia LP3A laser level was adopted. Namely, the test consists of first establishing precise elevation values of selected points using geodetic means. The test instrument was then used to remeasure the heights of these points. For this purpose a line of levels 170 m long was first established on reasonably flat ground of an adequately protected site. Steel pegs were then firmly driven flush with the ground at 10 m intervals along the test line. The heights of the steel pegs were then derived using a recently-adjusted Wild N3 geodetic level in conjunction with a Wild GPLE3 invar levelling rod. During the levelling operation the instrument was placed midway (to within approximately ±0.1 m) between the steel pegs when observing backsights and foresights in an attempt to minimize collimation error as well as errors contributed by residual curvature and refraction. Also, to minimize the effects of heat shimmer, every effort was made to make the line of sight at least 1 m above the surface of the ground. Further, all measurements were carried out either in early mornings or late afternoons in order to make use of the stable nature of the atmosphere at these times.

The computed misclosure error of this part of the test satisfied the requirements for first order classs I levelling standards as set out by the Federal Geodetic Control Committee (FGCC) of the U.S.A. Geological Survey ; that is better than $\pm 3 \sqrt{K}$ mm where K is the length of the levelling circuit in kilometers [3].

Instrument Used in the Test

The instrument used in this experiment is a Leica NA3000 electronic digital level. This level is the third in succession from Leica (the NA2000 and NA2002 preceded). The level was used in the electronic mode of operation using the ALL decimal (5 decimal places) display in order to match staff readings obtained from geodetic levelling observations. The instrument was operated on the rigid Wild GST40 tripod to increase instrument stability. The staff used was a GPCL2 invar bar-coded staff with sensitive bond level to ensure good verticality when taking readings. Due to some particulars pertaining to the circumstances of this test, no attempt was made to record staff reading displays in the Rec-module provided with the instrument, hence all staff readings were recorded manually. To avoid problems created by possible differences of staff zero-point error, only one staff was used with the test level. Also to compensate for possible residual errors in the automatic compensation, the bull's eye bubble was centered alternatively in one direction then in the other (i.e. in fore-and back sights). Table 1 shows some of the characteristics of the test instrument as set out by the manufacturer. These are believed to be of some relevance to the circumstances of the present experiment.

Table 1. Characteristics of the test instrument (electronic measurement mode)

Measuring range	1.8 m to 60 m
Accuracy (standard deviation)	±0.4mm/1km
Measuring time	4 seconds
Display	LCD
Bull's eye sensitivity	8'/2mm
Accuracy of compensator	±0.4"
Display resolution decimal place	0.1mm/0.01mm (selectively)
Distance measurement accuracy	2-5 mm/10m
Telescope magnification	24x

Before being used for levelling, the test instrument was made to undergo some adjustment tests. These were the bull's eye bubble and the two-peg tests. Adjustments were made when found necessary.

Two approaches were followed in this test. In the first, the test instrument was used to run several closed loops on the test line running from the one end of the line (station 0 on Fig. 1) through each of pegs 1, 2, 3 ... 17 and back to station 0. Each loop was run independently. Loop misclosures were then computed and compared with known levelling standards.

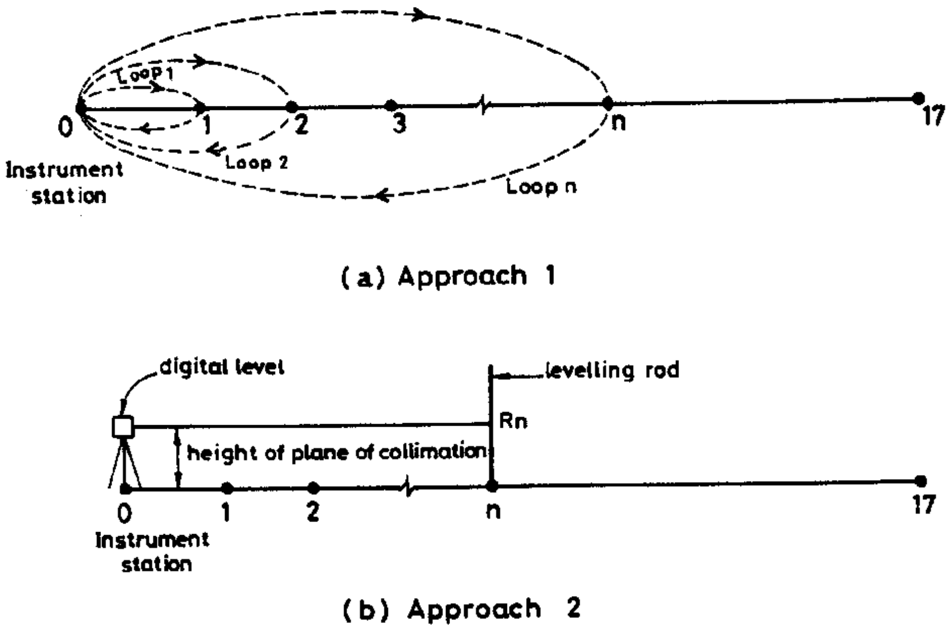

Fig. 1. Configuration of test.

In the second method, the test level was erected over station 0, levelled and switched on. The levelling rod was then placed on a bench mark 5 m from the instrument station, thus allowing the height of collimation at that benchmark to be determined. This served as reference plane for the rest of the pegs on the test line. The bar-coded invar rod of the electronic digital level was then made to occupy positions on pegs 1, 2, 3,... thus allowing independent measurement of the elevations of these pegs using the height of plane of collimation method. Measurements were carried out on three different days. Six sets of data were acquired on each day, three in the morning and three in the afternoon. Thus, elevation of each peg was derived eighteen times. This made a reasonable range of values. Comparison of the measured height of a peg with the corresponding assumed-true value derived from precise levelling allowed computation of root-mean square error of elevation measurement of each peg as standard deviation. The derived accuracy values were then compared with known levelling standards.

Computations, Results and Analysis

In this test, as mentioned before, the electronic mode was selected, i.e. the bar-coded face of the rod was used. Staff readings were recorded manually to five decimals and computations were carried out to determine peg heights.

Every effort was made to use the instrument and bar-coded staff very carefully in the field. Some observational difficulties were experienced, however. These include, holding the rod exactly vertical and on exactly the same point of the peg, slight movement of bull's eye bubble off center while taking readings, occasional use of a parasol to protect instrument; and instability of the NA3000 to display rod readings at distances longer than 65 m. Other difficulties faced include some windy times of observation, fatigue on the part of the observer due to lengthy measurements and occasional difficulties of communication between the rod and instrument persons at longer distances. Utmost care was made to reduce the effects of all these difficulties on the results of the experiment.

For the second approach, the root mean square error σ was computed using the standard formula:

$$\sigma_j = \pm\sqrt{\frac{\sum_{i=1}^{n} v_i^1}{n}} \quad (1)$$

where v_i = discrepancy between measured height h_i (i=1,...,18) of peg j (j=1,...8 (eight distances 10, 20, 30, 40, 50, 60, 63, 64 m were possible)) and its counterpart as measured from precise levelling;

n = acceptable number of measurements of heights of peg j.

A rejection criteria was adopted when implementing Eq. 1 in which observations showing discrepancies more than 3σ were rejected and therefore not used for the computation of σ. Tables 2 and 3 show the results of the experiment.

Table 2. Height accuracy of test instrument (approach 1)

Loop (m)	Misclosure (mm)	Accuracy standard
20	+0.15	$\pm1.06\sqrt{K}$
40	-0.10	$\pm0.5\sqrt{K}$
60	+0.39	$\pm1.59\sqrt{K}$
80	-0.13	$\pm0.46\sqrt{K}$
100	+0.27	$\pm0.85\sqrt{K}$
120	+0.20	$\pm0.58\sqrt{K}$
140	+0.36	$\pm0.96\sqrt{K}$
160	+0.44	$\pm1.1\sqrt{K}$
180	+0.19	$\pm0.45\sqrt{K}$
200	+0.33	$\pm0.74\sqrt{K}$
220	+0.28	$\pm0.60\sqrt{K}$
240	+0.12	$\pm0.25\sqrt{K}$
260	-0.15	$\pm0.29\sqrt{K}$
280	-0.11	$\pm0.21\sqrt{K}$
300	+0.20	$\pm0.37\sqrt{K}$
320	+0.18	$\pm0.32\sqrt{K}$
340	-0.13	$\pm0.22\sqrt{K}$

Table 3. Distance and height accuracy of test instrument (approach 2)

Distance (m)	Height r.m.s.e. (mm)	Distance error (mm)	Distance accuracy standard
10	±0.03	3	1/3333
20	±0.048	8	1/2860
30	±0.041	9	1/3333
40	±0.051	12	1/3333
50	±0.053	16	1/3125
60	±0.055	20	1/3000
63	±0.059	25	1/2520
64	±0.058	29	1/2207

The tables look fairly self-explanatory. It seems appropriate, however, to supplement them with extra comments. A quick glance at the contents of Table 2, which were obtained using approach 1, shows that with few exceptions, the test instrument was able to achieve height accuracy values better than $\pm$ 1.0 $\sqrt{K}$ mm. Also accuracy standards better than $\pm$ 2.0 $\sqrt{K}$ mm were achieved for all loops. In both cases, therefore, the results obtained are better than first order class I levelling standards set out by the FGCC of the U.S. Geodetic Survey (i.e. ±3.0 ÖK mm). It is noted that the misclosure values obtained with the various loops (and hence the derived accuracy standards) tend to be rather inconsistent with the lengths of the loops (see Fig.2). This may be explained by the fact that, with digital levels, in addition to the absence of reading errors(due to the elimination of the human factor), the software of the instrument effectively corrects for some known systematic errors believed to affect levelling accuracy, e. g. earth curvature, atmospheric refraction and residual collimation. The high accuracy of the display resolution of rod reading (0.01mm) may also be one reason for these findings. Further, taking into account the fact that the test was conducted on hard ground of a well-protected site, errors caused by instrument instability and ground subsidence were believed to be minimum. Also, since the bar-coded levelling rod is supplied with high sensitivity bond level to hold it vertical on the peg, one expects less adverse effects on the results due to nonverticality of the rod. Combined together, these factors seem to have resulted in the high accuracy standards shown on Table 2 which made variation of levelling accuracy with length of circuit less evident.

Table 3 presents the results obtained with the second approach. In column 2, for sighting distances up to 64 m (the maximum distance reached in the present test, i.e.

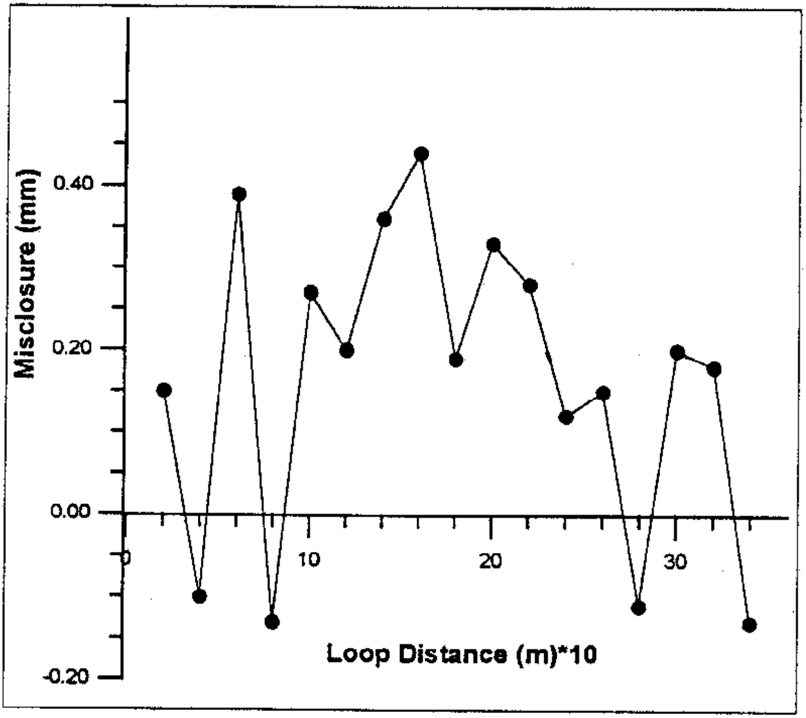

Fig. 2. Loop misclosures as function of circuit length.

distance after which the microcomputer of the instrument was not able to process the image of the bar-coded staff) the standard deviation in height measurement is better than 60 micrometers (0.06 mm). To the best knowledge of the authors these results are far better than those obtained with optical levels of all kinds as tested out by a number of investigators e. g. Ali [4], Berry [5,6], Huether [7], Whalen and Balacz [8], and Kellie [9].

Thus, it is noted that in both techniques, the Leica NA3000 digital level was able to achieve height accuracy values well within the requirements for first order class I levelling standards. This may mean that, if some precautional measures are made (as practiced in this experiment) this new levelling instrument can readily be used for precise geodetic work of all kinds and could well replace traditional optical levelling instruments being them of the automatic (compensator) type or of the spirit design. Also, in the second approach the test instrument was able to obtain rod readings beyond the maximum sighting distance specified by the manufacturer (64 m instead of 60m).

The last two columns of Table 3 present the results obtained with distance measurement using the test instrument (i. e. tacheometric accuracy of the level). It is noted that the best

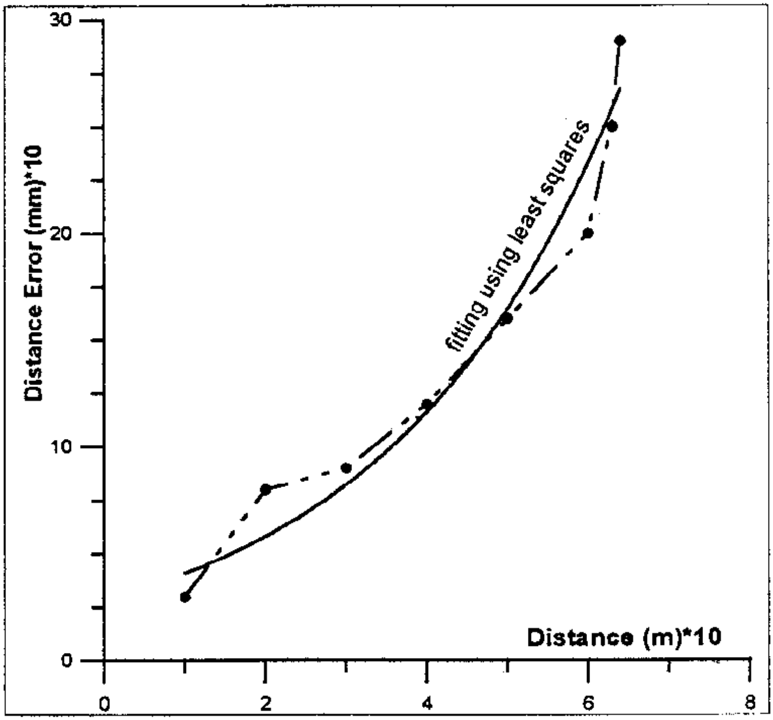

Fig. 3. Accuracy of horizontal distance obtained with the test instrument.

accuracy in distance measurement is obtained at shorter sights. Thus values ranging from ±3mm to ±29mm were obtained at sighting distances of 10m and 64m respectively (the instrument was not able to process staff images at distances greater than 64m). These correspond to linear fractional errors of 1/3333 to 1/2207. Therefore, distance accuracy deteriorates gradually as sighting distance increases. Fig. 3 shows a graphical representation of the results of this part of the test. The figure is in general agreement with results obtained elsewhere in tacheometric surveys (see e. g. Ali [10]). Further, it is noted that the results of distance measurement obtained in this test are well within specifications set out by the manufacturer that is 3mm -5mm /10m (1/3333 - 1/2000 fractional error) (i.e. tape accuracy). The range of distance accuracy values obtained in this experiment may be sufficient for a number of localized engineering surveys such as site preparation for construction works, sewer placement and monitoring, pavement maintenance surveys etc. where errors of a few centimeters in several tens of meters are acceptable.

Before concluding, a worthwhile note needs to be mentioned. In this era of computerization, one of the major credits of any measuring equipment is its liability for automation and direct integration with other equipment for on-line data processing. Digital levels, such as the Leica NA3000, have been designed to meet these requirements. The collected data can be recorded automatically using the Rec-module of the instrument and then, after finishing the job at hand, telemetered to the base of operations, processed and made to serve as topographic layer in a geographic or land information system (GIS or LIS).

Conclusion

The test was conducted for the sake of appraising the measuring capability of digital electronic levels as examplified by the new Leica NA3000 model. For this purpose, the test instrument was used to remeasure an already established 17-section 170 m long test line. Two approaches were followed in this respect. In the first approach, all available loops on the test line were levelled begining from the one end of the line through all intermediate pegs to peg i and then closing back on the initial point of the line. The resulting loop misclosures were then calculated and compared to known levelling specifications.

In the second approach, and within the capability of the instrument, rod readings for some pegs on the line were observed several times from the starting point using the method of height of plane of collimation. The discrepancies between computed peg elevations and their counterparts as obtained from precise levelling were used to compute root-mean-square errors of height measurement of pegs as standard deviation.

The results obtained with the first approach showed that, the Leica NA3000 digital level was able to give misclosure values ranging from $e = \pm 0.10$ mm to $e = \pm 0.44$ mm and levelling specification range of $\pm 0.21 \sqrt{K}$ mm to $\pm 1.59 \sqrt{K}$ mm. This is within height accuracy requirements for first order class I standards (i.e. geodetic levelling specifications). The results obtained with approach two showed that for sighting distances of up to 64 m (the practical limit of the capability of the instrument to process staff images) standard deviation values better than ±0.060 mm could easily be achieved. Again, this is commensurate with first order class I levelling standards.This means that if sighting distances are kept within 60 m from instrument station, the electronic digital level can efficiently and accurately cope with all kinds of first order geodetic levelling operations (e. g. precise control surveys, deformation measurement of structures, crustal movement surveys, checking benchmark stability etc). Taking into account the many excellent features and amenities offered by the instrument and the easy way by which the instrument is operated, electronic digital levels will have much to offer in order to repalce conventional optical levelling instrumentation for all kinds of levelling work being it geodetic or ordinary.

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دقة قياس المسافتين الرأسية والأفقية باستخدام الميزانية الإلكترونية الرقمية

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الرياض ١١٤٢١، المملكة العربية السعودية

(أستلم في ٢٤/٥/١٩٩٧م؛ وقبل للنشر في ٨/١٠/١٩٩٧م)

ملخص البحث. تم في هذه الدراسة تقويم جهاز الميزانية الإلكترونية الرقيمة NA3000 (المصنع بواسطة شركة LWICA) من حيث دقته في قياس المسافتين الرأسية والأفقية ومن ثم محاولة تصنيفه حسب معايير الدقة المتعارف عليها عالمياً. من أجل ذلك، حُدد في الميدان خط اختبار طوله ١٧٠متراً، ووقع عليه سبع عشرة نقطة عُينت ارتفاعاها عن سطح البحر بطرق جيودسية معلومة الدقة. أجريت التجربة الميدانية لقياس هذه الارتفاعات باستخدام جهاز NA3000 بطريقتين مختلفتين: تم في الأولى قياس الارتفاعات بعمل مدارات مغلقة تنطلق تدريجيا من النقطة الأساس في أول الخط، بحيث يزيد كل مدار منها عن سابقه بنقطة واحدة إلى أن تأتي على أقصى نقطة فيه. ثم حسب خطأ الإغلاق في كل حالة. وفي الطريقة الثانية، ثُبت الجهاز على نقطة الأساس، ورصدت ارتفاعات النقاط الأخرى عدة مرات ليتسنى لنا حساب الانحراف المعياري في قياس كل نقطة. وبمقارنة النتائج في كلتا الحالتين بمعايير الدقة في الجيوديسيا المساحية، وجد أن الميزانية الرقمية ذات دقة عالية لا تضاهى وأنها توفي بالغرض الذي صُنعت من أجله، بحيث يمكن إحلالها محل الميزانية البصرية المعروفة. كانت الدقة في الطريقة الأولى أحسن من ± ٢ √ك مم، وفي الثانية أفضل من ٦٠ميكرون، بمعنى تحقيق هذا الجهاز لدقة تقع في الدرجة الأولى (first order) من المستوى الأول (class I) حساب معيار (FGCC) الأمريكية. كما تم تقويم الجهاز من حيث قياس المسافة لغرضين هما معرفة المدى الذي يمكن أن يحققه في البعد الأفقي، ومعرفة الدقة المصاحبة لذلك. فوجد أنه بالإمكان قياس أي مسافة تقل عن ٦٤متراً مباشرة، لكن بدقة متواضعة، تصلح، بالرغم من هذا، لأعمال هندسية كثيرة منها على سبيل المثال، إعداد المواقع للمنشآت الهندسية، وصيانة الطرق، وتوقيع ومراقبة أنابيب الصرف الصحي، وغير ذلك من الأعمال الهندسية المماثلة، حيث الدقة الأفقية المطلوبة لا تتجاوز سنتيمترات قليلة في عدة عشرات من الأمتار.