

Modern Height Determination Techniques and Comparison of Accuracies

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Key words: Levelling, GPS, Orthometric height, Accuracy

SUMMARY

In academic studies and engineering works, it is required to determine height differences between points or the height of points itself in those applications such as measurements of national or local networks, vertical applications of bridge, dam and infrastructures, maintenance and control measurements, determination of vertical crustal movements, motorway, railway, sewerage and pipe line measurements.

Height determination can be classified as geometric levelling, trigonometric levelling and GPS/Levelling depending on used instruments or the methods applied. They have advantages and disadvantages.

The purpose of this study is to analyze the trigonometric levelling with using total station, which are capable of high accuracy observing vertical angles and distances, geometric levelling with using digital level and GPS/Levelling with using GPS observations. To fulfill this aim, a levelling line with 11 points was established in Alaeddin Keykubat Campus area of Selçuk University. During the study done on this levelling line, three separate geometric levelling with different three equipments (Wild N3 precise level, invar rods, Sokkia B2 automatic level and wooden rods, Sokkia SDL 30M digital level and bar coded aluminum rods), trigonometric levelling by using different two equipments (Wild T2 theodolite for vertical angle measurements and Topcon GTS 701 electronic total station for distance measurements, only Topcon GTS 701 electronic total station for vertical angle and distance measurements) and GPS/levelling (with Leica 9500 receiver) were used. The height differences of precise levelling were assumed as true values, and these differences were then compared with these from other techniques and mean square errors were computed using these measurement differences. Consequently, it was seen that the results from digital level showed the best approach to those from precise geometric levelling.

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1. INTRODUCTION

Nowadays, not only in academic studies but also in engineering works it is run into problems of determination of height differences between points or the height of points. For these studies, it may be showed some examples, such as:

- Surveying of levelling networks
- Vertical applications, maintenance and control measurements of big structures like bridge, dam, very tall buildings, and tower.
- Determination of vertical crustal movements
- Motorway, railway, sewer and pipeline measurements.

Instruments used in surveying and measurement method are determined in relation to topography of land, target precision, and aim. In this study, accuracies of height determination techniques have been compared with each other according to used instrument, and measurement method.

2. DEFINITION AND ANALYSIS HEIGHT DETERMINATION TECHNIQUES

There are a lot of geodetic methods for determining of heights or height differences. These methods are classified as geometric levelling, trigonometric levelling, and GPS/Levelling according to used surveying instruments and applied measurement method. The historical development of heights determination techniques is given in Figure 1.

2.1. Geometric Levelling

Geometric levelling is the determination of the height differences by using level and hold vertical rods (Figure 2). Geometric levelling may firstly appear a method as a very simple and yielding the best result method. However, the practical applications have shown that carrying out of this method is very difficult on the rough ground and sensitive to regular or irregular model errors. The preventative measures must be taken to eliminate or reduce model errors stemmed from instrumental and outer surroundings. If it is not, these situations decrease the survey velocity, thus the cost of surveying rises (Banger, 1981; Niemeier, 1986; Ceylan, 1988; Baykal, 1989).

The effects of such errors can be reduced by using Schwartz or Red pants methods or, applying appropriate measurement methods, taking equal backward and forward observation range, the round trip surveying, following BFFB (**backward forward forward backward**) or FBBF (**forward backward backward forward**) observation order or surveying calibration in lab and surveying additional parameters such as pressure, temperature and time at the survey moment (Baykal, 1989).

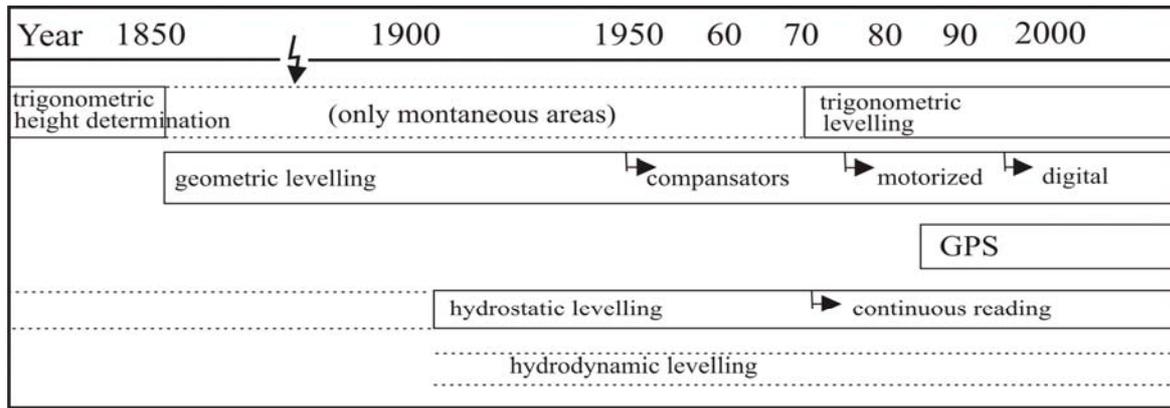


Figure 1. The historical development of heights determination techniques

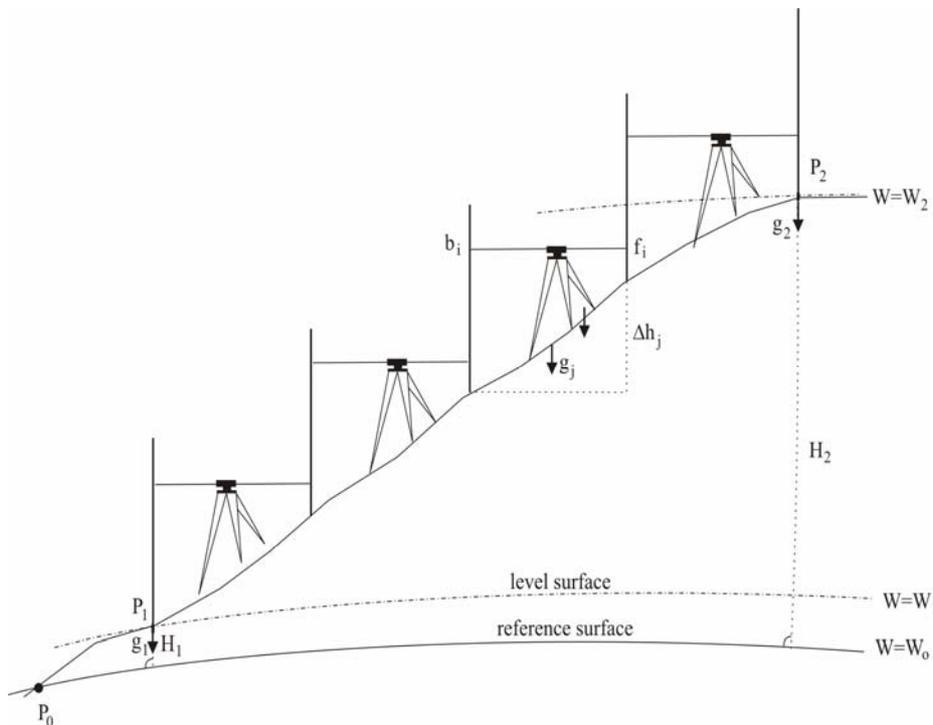


Figure 2. The fundamental principal of geometric levelling (Pelzer, 1983)

Nowadays, also motorized geometric levelling applications have been done by establishing survey hardware on the land vehicle, thus successful results have been obtained. According to geometric levelling, the advantages of the motorized levelling may be summarized as below;

- Improve 40-60% in production velocity
- Decrease errors connected to time
- More observation ray, thus decreasing asymmetric refraction error
- More accuracy

Only disadvantage of this technique is that the cost of instrument and vehicles is very high and level points must be on the edge of the road (Niemeier, 1986; Becker, 1986).

2.2. Trigonometric Levelling

Height differences are computed by using vertical angle and distance in trigonometric levelling. According to the land, time and observing vertical angle, trigonometric levelling can be classified as follows:

- Unidirectional trigonometric levelling
- Leap-Frog (jumped) trigonometric levelling
- Reciprocal trigonometric levelling

With development of the electronic total stations which are able to observe vertical angle and distance by high accuracy the trigonometric levelling has just updated again together, then various studies have been made about this subject (Rueger and Brunner, 1982; Kuntz and Schmitt, 1986; Aksoy, 1993; Erkaya, 1993; Ceylan, 1993; Ceylan, 1997; Kasser, 2002).

Applications of the motorized trigonometric levelling have been made by placing survey hardware of the trigonometric levelling on the land vehicle. The motorized trigonometric levelling is equal accuracy ($\leq \pm 2\text{mm/km}$) and equal cost with the motorized geometric levelling when the motorized trigonometric levelling is done according to following rules;

- The reciprocal and simultaneously vertical angle observations
- The reciprocal distance measurements
- The short observation ranges (~250-300 m)
- Using calibrated instruments
- Carried out by the experienced person

More than 27% speed of production has been reached with motorized trigonometric levelling. Therefore, the studies have shown that the motorized levelling may be alternative method to geometric levelling (Whalen, 1985; Chrzanowski v.d., 1985; Chrzanowski, 1989; Becker, 1986; Uzel, 1991).

2.2.1. Survey and Computation Model in the Unidirectional Trigonometric Levelling

The observations of the unidirectional trigonometric levelling have been made by using total station that is set up in a station point to vertically established target tablet as unidirectional (Figure 3). Z_{ij} vertical angle and S_{ij} slope distance are measured. It is assumed that level surfaces are same centered sphere surfaces in the survey model.

In figure 3,

Z'_{ij} : vertical angle that must be measured

Z_{ij} : vertical angle that is observed

dZ_r : model error that is caused by refraction

ϵ_{ij} : model error that is caused by plumb line deviation

S_{ij} : slope distance

R_m : radius of the Earth spheroid

Height difference between P_i and P_j points (Δh_{ij}),

$$\Delta h_{ij} = (S_{ij} \cdot \cos Z_{ij}) + \left(\frac{S_{ij}^2}{2R_m} \cdot \sin^2 Z_{ij} \right) - S_{ij} \cdot (\epsilon_{ij} + dZ_r) (\sin Z_{ij}) \quad (1)$$

is computed by equation (1). In this equation, first term is nominal height difference and second term shows that radius of the Earth spheroid affects the height difference, third term shows that vertical refraction and plumb line deviation affect the height difference. Because ϵ_{ij} and dZ_r are not known in the application, third term has been neglected, thus the height difference is computed by first two terms (Coşkun, 1996).

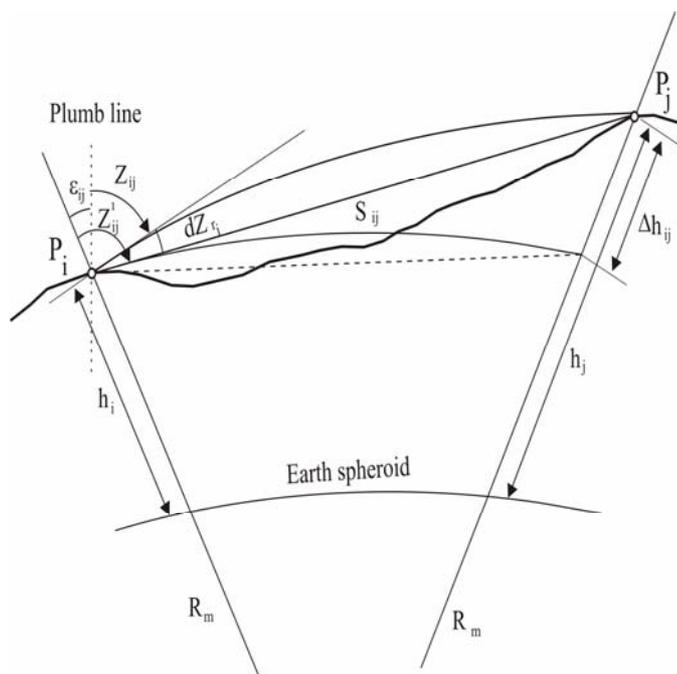


Figure 3. Survey model of the unidirectional trigonometric levelling

2.2.2. Survey and Computation Model in the Reciprocal Trigonometric Levelling

The observations have been made reciprocally for each other in this trigonometric levelling by using total station that is set up in the two stations point (Figure 4). Z_{ij} and Z_{ji} vertical angles and S_{ij} slope distance are measured.

If equation (1) is used in observations that are made in every two points and if arithmetic mean of height difference is computed,

$$\Delta h_{ij} = \frac{1}{2} \left(S_{ij} \cdot (\cos Z_{ij} - \cos Z_{ji}) + \frac{S_{ij}^2}{2R_m} (\sin^2 Z_{ij} - \sin^2 Z_{ji}) - \left(S_{ij} \cdot (\epsilon_{ij} + dZ_{r_i}) \cdot \sin Z_{ij} + S_{ij} \cdot (\epsilon_{ji} + dZ_{r_j}) \cdot \sin Z_{ji} \right) \right) \quad (2)$$

equation (2) is obtained.

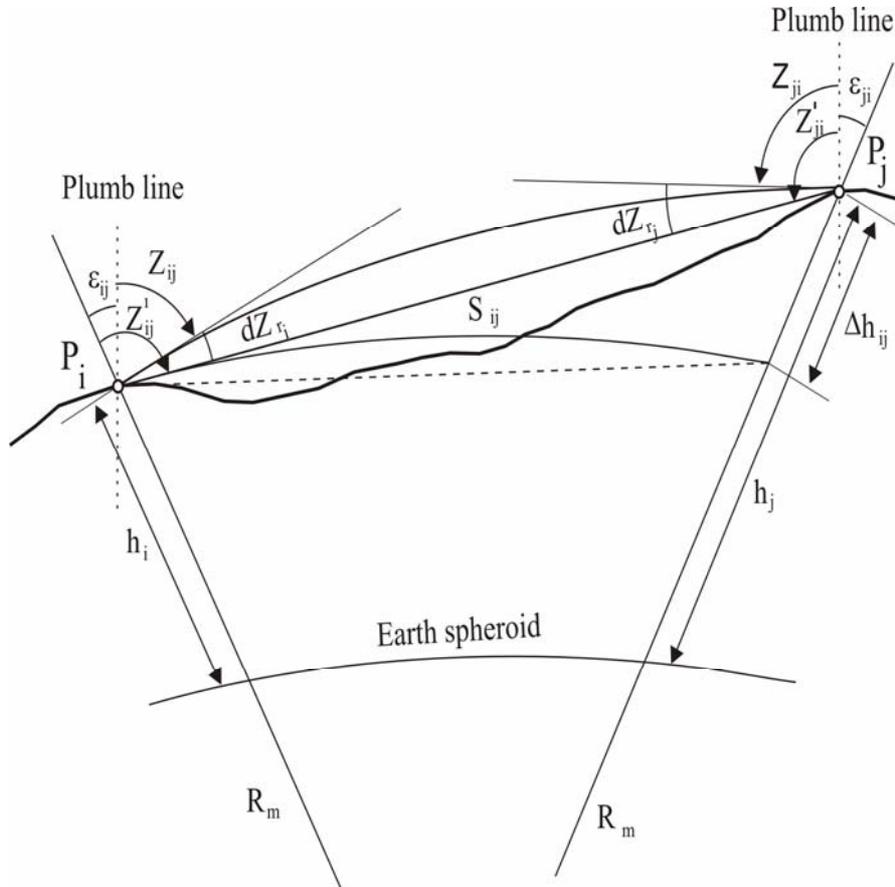


Figure 4. Survey model of the reciprocal trigonometric levelling

In equation (2), first term is nominal height difference and second term shows that radius of the Earth spheroid affects the height difference, third term and fourth term show that vertical refraction and plumb line deviation affect the height difference respectively. Because ϵ_{ij} and dZ_r are not known in the application, third term and fourth term have been neglected, thus the height difference is computed by equation (3) (Coşkun, 2002).

$$\Delta h_{ij} = \frac{1}{2} \left(S_{ij} \cdot (\cos Z_{ij} - \cos Z_{ji}) + \frac{S_{ij}^2}{2R_m} (\sin^2 Z_{ij} - \sin^2 Z_{ji}) \right) \quad (3)$$

2.2.3. Survey and Compute Model in the Leap-Frog (Jumped) Trigonometric Levelling

The observations have been made to target tablets of station points in this trigonometric levelling by using total station that is set up in a point among the station points (Figure 5). Z_{ki} and Z_{kj} vertical angles, S_{ki} and S_{kj} slope distances are measured.

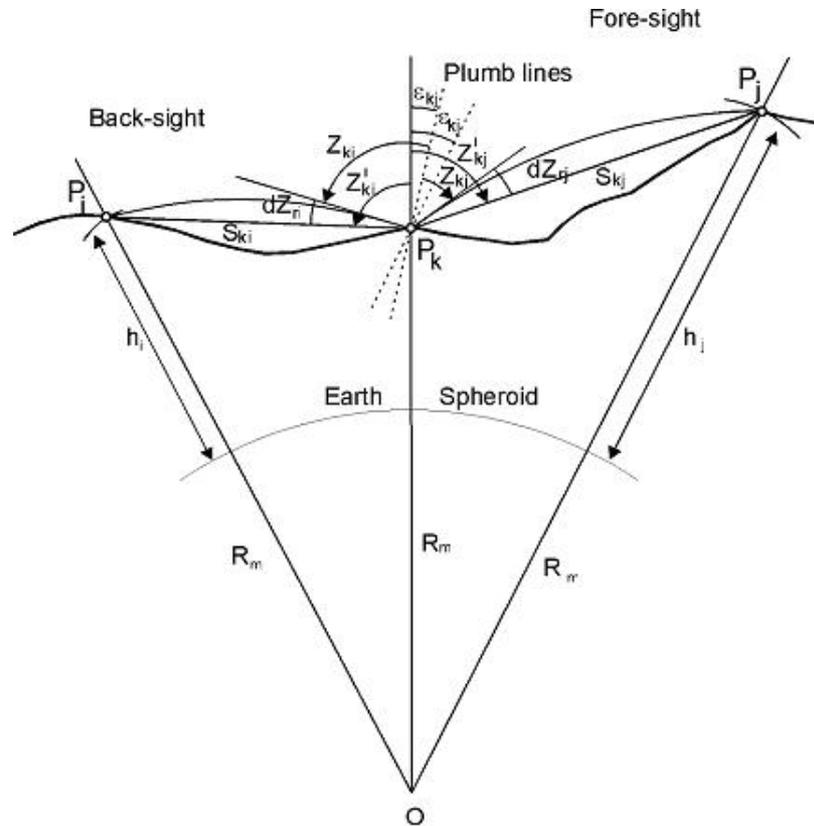


Figure 5. Survey model of the Leap-Frog (jumped) trigonometric levelling

If equation (1) is used in observations in back-sight and fore-sight,

$$\Delta h_{ij} = (S_{kj} \cdot \cos Z_{kj} - S_{ki} \cdot \cos Z_{ki}) + \frac{1}{2R_m} (S_{kj}^2 \cdot \sin^2 Z_{kj} - S_{ki}^2 \cdot \sin^2 Z_{ki}) - S_{kj} (\epsilon_{kj} + dZ_{rj}) (\sin Z_{kj}) + S_{ki} (\epsilon_{ki} + dZ_{ri}) (\sin Z_{ki}) \quad (4)$$

equation (4) is obtained.

In equation (4), first term is nominal height difference and second term shows that radius of the Earth spheroid affects the height difference, third term and fourth term show that vertical refraction and plumb line deviation affect the height difference respectively. Because ϵ_{kj} ,

ε_{ki} and dZ_{r_i} , dZ_{r_j} are not known in the application, third term and fourth term have been neglected, thus the height difference is computed by equation (5) (Coşkun, 1996).

$$\Delta h_{ij} = (S_{kj} \cdot \cos Z_{kj} - S_{ki} \cdot \cos Z_{ki}) + \frac{1}{2R_m} (S_{kj}^2 \cdot \sin^2 Z_{kj} - S_{ki}^2 \cdot \sin^2 Z_{ki}) \quad (5)$$

2.3. GPS/ Levelling

GPS/Levelling is the most recent and advanced method that is used in the determination of heights. Three-dimensional coordinates or coordinate differences can be obtained by GPS in the geocentric Cartesian coordinate system. The Cartesian coordinates are transformed to geodetic latitude, geodetic longitude, and ellipsoidal heights according to selected reference ellipsoid, i.e. WGS84. The ellipsoidal heights obtained by GPS are not directly used for practical surveying. The ellipsoidal height has to be transformed to orthometric height, which is distance measured along the plumb line between the geoid and a point on the Earth's surface and taken positive upward from the geoid (National Geodetic Survey, 1986). Relationship between ellipsoidal height and orthometric height is shown in figure 6.

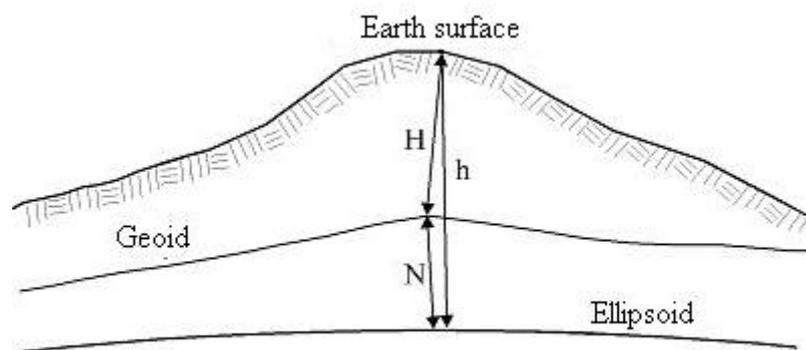


Figure 6. Relationship between ellipsoidal height and orthometric height

Difference between ellipsoidal height and orthometric height is defined as geoid height or geoid undulation. The fundamental equation among these concepts is written as follows

$$h = H + N \quad (6)$$

Here;

h: ellipsoidal height

H: orthometric height

N: geoid height (İnal, 1996)

Geoid heights of all points have to be computed before computing orthometric heights. The geometric approach is carried out more common for computing geoid heights in the regional studies. The mathematical surface is fitted by using the geoid heights of points whose ellipsoidal heights and orthometric heights are known enough density in the geometric approach. Then geoid heights of points whose ellipsoidal heights are known can be computed by the assistance of this surface.

3. NUMERICAL APPLICATION

3.1. Definition of the Study Area and Area Surveys

A levelling line with 11 points that are 50m spaced on the same line, was established throughout east-west direction in Alaeddin Keykubat Campus area of Selcuk University with the aim of searching accuracies which are obtained by geometric levelling, trigonometric levelling, GPS/levelling using the most recent and advanced technological equipments (Figure 7). The measurements were performed independently from each other as combinations with different equipments all the way through line. The fifty-five height differences among points were computed (Table 1).

The different three equipments were used in geometric levelling. First equipment has one Wild N3 precision level and two invar rods that are divided to two-party and three meter in length. Second equipment has one Sokkia B2 automatic level and two wooden rods that are three meters in length. Third equipment has one Sokkia SDL30 digital level and two bar coded aluminum rod that is five meter in length. All rules that must be taken into consideration were carried out carefully in the geometric levelling surveys.

The two different equipments were used in the trigonometric levelling. First equipment has one Topcon GTS 701 electronic total station, Wild T2 theodolite, five prisms, and target table. Second equipment has one Topcon GTS701 total station, five prisms, and target table. In the trigonometric levelling with first equipment, the distances among the points were measured by using Topcon GTS701 total station and the vertical angles were reciprocally measured by using Wild T2 theodolite as four series. The heights of instrument, prisms, and target tables were measured in mm level. Both distances and vertical angles were measured by using Topcon GTS701 total station in the trigonometric levelling with the second equipment.

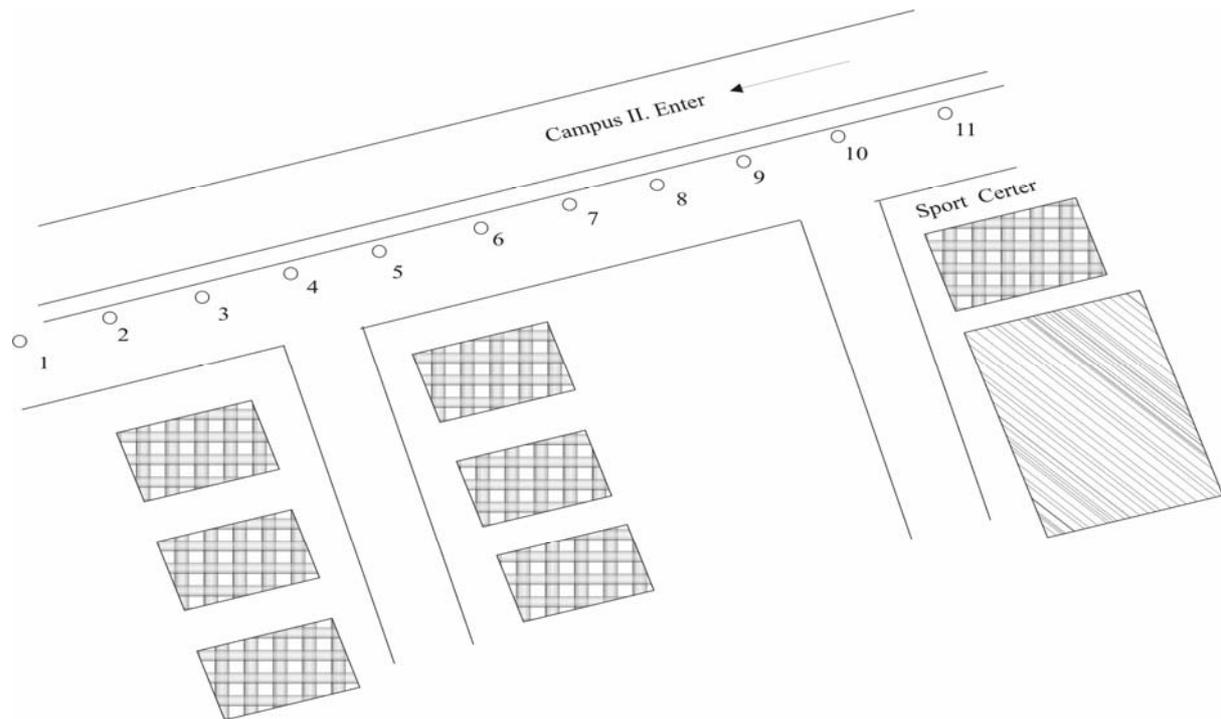


Figure 7. Levelling line

Five Leica GPS receiver and set were used in GPS surveys. The GPS surveys were realized by using static method with 30 minutes sessions. GPS data were processed by SKI 2.3 GPS software after downloading to computer. The ellipsoidal heights were obtained in conclusion of the processing. Geoid heights were taken from study made beforehand at the same area (Çorumluoğlu et al, 2002)

Table 1.The height differences (m)

Line No	Geometric Levelling			Trigonometric Levelling		GPS/ Levelling
	I.Equipment	II.Equipment	III.Equipment	I.Equipment	II.Equipment	
1-2	-2.2776	-2.2779	-2.2740	-2.2814	-2.2826	-2.2636
1-3	-3.9875	-3.9874	-3.9890	-3.9938	-4.0031	-3.9922
1-4	-5.6586	-5.6565	-5.6600	-5.6677	-5.6684	-5.6519
1-5	-7.3062	-7.3062	-7.3060	-7.3155	-7.3240	-7.3168
1-6	-9.0392	-9.0364	-9.0370	-9.0496	-9.0635	-9.0482
1-7	-10.7386	-10.7358	-10.7300	-10.7380	-10.7585	-10.7349
1-8	-12.5076	-12.5059	-12.5050	-12.5021	-12.5326	-12.5286
1-9	-14.1844	-14.1814	-14.1870	-14.1938	-14.1830	-14.2011
1-10	-15.7315	-15.7337	-15.7300	-15.7608	-15.7655	-15.7572
1-11	-17.0885	-17.0854	-17.0880	-17.1283	-17.0973	-17.1136
2-3	-1.7099	-1.7093	-1.7140	-1.7106	-1.7223	-1.7286
2-4	-3.3810	-3.3815	-3.3820	-3.3829	-3.3899	-3.3880
2-5	-5.0285	-5.0277	-5.0330	-5.0419	-5.0430	-5.0532
2-6	-6.7616	-6.7598	-6.7580	-6.7653	-6.7680	-6.7846

Line No	Geometric Levelling			Trigonometric Levelling		GPS/ Levelling
	I.Equipment	II.Equipment	III.Equipment	I.Equipment	II.Equipment	
2-7	-8.4610	-8.4567	-8.4600	-8.4670	-8.4735	-8.4713
2-8	-10.2299	-10.2270	-10.2320	-10.2251	-10.2510	-10.2650
2-9	-11.9068	-11.9044	-11.8990	-11.9102	-11.9305	-11.9375
2-10	-13.4539	-13.4515	-13.4520	-13.4790	-13.4960	-13.4936
2-11	-14.8109	-14.8089	-14.8100	-14.8450	-14.8185	-14.8500
3-4	-1.6712	-1.6689	-1.6690	-1.6757	-1.6704	-1.6597
3-5	-3.3187	-3.3188	-3.3210	-3.3217	-3.3127	-3.3246
3-6	-5.0517	-5.0501	-5.0450	-5.0535	-5.0579	-5.0560
3-7	-6.7511	-6.7463	-6.7510	-6.7547	-6.7568	-6.7427
3-8	-8.5201	-8.5159	-8.5210	-8.5182	-8.5405	-8.5364
3-9	-10.1969	-10.1955	-10.2000	-10.2008	-10.2010	-10.2089
3-10	-11.7440	-11.7416	-11.7400	-11.7696	-11.7740	-11.7650
3-11	-13.1010	-13.1019	-13.1050	-13.1364	-13.1109	-13.1214
4-5	-1.6475	-1.6474	-1.6480	-1.6527	-1.6553	-1.6649
4-6	-3.3806	-3.3782	-3.3790	-3.3798	-3.3854	-3.3960
4-7	-5.0800	-5.0792	-5.0780	-5.0748	-5.0819	-5.0830
4-8	-6.8489	-6.8475	-6.8520	-6.8478	-6.8660	-6.8767
4-9	-8.5258	-8.5265	-8.5300	-8.5277	-8.5340	-8.5492
4-10	-10.0728	-10.0722	-10.0720	-10.0856	-10.0957	-10.1053
4-11	-11.4299	-11.4311	-11.4200	-11.4565	-11.4285	-11.4617
5-6	-1.7330	-1.7322	-1.7330	-1.7235	-1.7395	-1.7314
5-7	-3.4324	-3.4304	-3.4280	-3.4184	-3.4360	-3.4181
5-8	-5.2014	-5.1999	-5.2020	-5.1971	-5.2133	-5.2118
5-9	-6.8783	-6.8764	-6.8800	-6.8701	-6.8852	-6.8843
5-10	-8.4253	-8.4216	-8.4200	-8.4405	-8.4378	-8.4404
5-11	-9.7823	-9.7776	-9.7730	-9.8055	-9.7909	-9.7968
6-7	-1.6994	-1.6979	-1.7000	-1.6951	-1.7042	-1.6867
6-8	-3.4683	-3.4688	-3.4680	-3.4712	-3.4855	-3.4804
6-9	-5.1452	-5.1434	-5.1430	-5.1485	-5.1584	-5.1529
6-10	-6.6923	-6.6921	-6.7020	-6.7213	-6.7085	-6.7090
6-11	-8.0493	-8.0489	-8.0500	-8.0753	-8.0548	-8.0654
7-8	-1.7690	-1.7690	-1.7680	-1.7738	-1.7791	-1.7937
7-9	-3.4458	-3.4456	-3.4440	-3.4502	-3.4513	-3.4662
7-10	-4.9929	-4.9936	-4.9940	-5.0177	-5.0079	-5.0223
7-11	-6.3499	-6.3512	-6.3470	-6.3789	-6.3468	-6.3787
8-9	-1.6766	-1.6766	-1.6770	-1.6820	-1.6865	-1.6725
8-10	-3.2239	-3.2231	-3.2190	-3.2473	-3.2335	-3.2286
8-11	-4.5809	-4.5799	-4.5790	-4.6120	-4.5710	-4.5850
9-10	-1.5470	-1.5471	-1.5450	-1.5674	-1.5535	-1.5561
9-11	-2.9041	-2.9045	-2.9030	-2.9305	-2.8958	-2.9125
10-11	-1.3570	-1.3576	-1.3580	-1.3606	-1.3375	-1.3564

3.2. Processing of Surveys

The height differences of precise levelling were assumed as true values in computation of the accuracies of measurements that were made by every one of the equipment. By means of ϵ true errors, root mean square errors (RMSE) of height differences were computed as follows (Table 2);

$$m = \mp \sqrt{\frac{[\epsilon\epsilon]}{n}} \quad (8)$$

Here, n is the number of measurements.

Table 2. The root mean square errors computed according to different measurement methods, different equipments, and their measurement times.

Levelling method	Equipment	RMSE (mm)	Total Time (Hour)
Geometric Levelling	SOKKIA B2 Automatic Level and Wooden Rods	±3.7	31
	SOKKIA SDL 30M Digital Level and Bar coded Rods	±2.0	18
Trigonometric Levelling	WILD T2 Theodolite TOPCON GTS 701 Total Station	±16.4	25
	TOPCON GTS 701 Total Station	±14.7	17
GPS/ Levelling	LEICA 9500 GPS receiver and set	±18.8	5

4. CONCLUSIONS

Not only horizontal positioning has to be determined but also heights of points have to be determined in geodetic studies. The situation of the present instrument or equipment, cost, production velocity, topographical structure of study area must be considered before initialising survey procedures.

When table 3 and the results of the present written sources are investigated, questions of which levelling method must be carried out and in which occupation may be answered as follows:

- If there is a geoid information at levelling in rural area in which density of point is so low and in which shadow area is not formed because of tree, etc., the GPS/levelling method must be chosen. In the opposite situations, the geometric levelling method with digital level or the trigonometric levelling method with total station may be chosen.
- It is appropriate to choose the geometric levelling with digital level or the trigonometric levelling with total station at levelling in urban area or semi-urban area in which density of point is so high
- If the deformation surveys are carried out in big structures as bridge, dam, GPS receivers may be used for observations on condition that they are not far from the reference points. In addition, the precision levelling method should be chosen by using digital level with invar rods or optic-mechanic level in type of these deformation surveys.

- In construction projects as highway, railway, smoothing area, the GPS/levelling, the trigonometric levelling with total station, the geometric levelling with digital level, and laser level may be chosen respectively.

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