The Fourth Precise Levelling Campaign of Poland in 1999–2003

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Key words: levelling networks, Lallemand's and Vignal's formulas, analysis of variance.

SUMMARY

The re-levelling of the 1st order vertical control network in Poland with total length of 382 lines of 17 516 km had started in May 1999 and was completed in June 2002. First, the paper describes, equipment used in the field measurements, method of levelling, corrections introduced to raw observations.

Then in order to estimate the levelling accuracy, the observed height differences were both statistically and classically (Lallemand's and Vignal's formulas) analyzed to see distribution of systematic and random errors in the network. Accuracy of the levelling network computed from Lallemand's formulas is $\pm 0.27\, mm/\sqrt{km}$ for random mean error and ±0.08 mm/km for systematic mean error. According to Vignal's formulas, random mean error is $\pm 0.27\, mm/\sqrt{km}$ and systematic mean error is and 0.44 mm/km.

To better understand the character of systematic errors, the levelling observations were studied by the variance and covariance methods, which showed that the lines are affected by systematic errors.

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1. INTRODUCTION

Spirit levelling seemed to be one of the most accurate techniques in height difference determination. However, errors originating from instruments, ambient circumstances and observer, have such character that it is very difficult to remove them from observations, also assessment of leveling accuracy is not an easy task.

During the last decades, several methods for accuracy estimation have been developed. A detailed discussion of these methods is presented in (Jordan at al.,1956, pp.223-255).

According to (ibid.) in 1912 at the Hamburg meeting of International Association of Geodesy Lallemand proposed hypothesis that levelling was affected by the two kind of errors i.e. random mean errors which followed the Gauss law and could be estimated by a random mean error per one kilometer η and systematic mean error *s*, called as a probable systematic mean error per kilometer, acting along the full extension of a line *L*. So the random error of height difference of two benchmark distant *L* kilometers apart is $\eta\sqrt{L}$ while the systematic error is $s \times L$. Lallemand regarded the variation of the systematic mean error per one kilometer from one section to the other as purely random, even if the sections were consecutive, and for that reason admitted that the total value of systematic mean error per kilometer would add up as random errors did.

$$\hat{\sigma}_L^2 = \eta^2 L + s^2 L^2 \tag{1}$$

where $\hat{\sigma}_L$ is the mean error to be expected in a line of *L* kilometers long.

The most critical objections to this formula arise due to decay of the value of systematic mean error with the increase of the length of leveling line (Fig. 3). To evade this difficulty Vignal, in 1936, proposed a different classification of the levelling errors. The class of random mean errors was retained because they acted everywhere. They could be presented by the random mean error per kilometer η so the random error of height difference of two benchmark distant *L* kilometers apart was $\eta\sqrt{L}$. The systematic errors were replaced by the random error per kilometer but its propagation depended on whether the distance *L* was greater or smaller than a certain minimum length *Z*. If *L* was greater than Z the systematic error of height differences was given by $\zeta\sqrt{L}$. If *L* was smaller than Z, the influence of the systematic errors was still proportional to $\sqrt{L}$ but the coefficient ζ decreased from ζ to zero. The minimum length *Z* was the distance at which the value of calculated from the cumulative discrepancies ceased to depend on *L*.

Since 1955 (Wassef, 1955), (Wassef and Messh, 1960) and (Wassef, 1962), have proposed the application of mathematical statistics specifically to study levelling error in levelling networks. Since that time numerous statistical studies of levelling networks were done e.g. the study of discrepancies in precise Italian levelling network made by (Chiarini and Pieri, 1971) or detection of systematic errors by variance components estimation was studied by (Nafisi, 2003) etc.

In the present paper the accuracy of the fourth precise levelling campaign is investigated by classical Lallemand's and Vignal's formulas and by the statistical analysis of section, line and loop discrepancies. First, the fourth campaign is described, then the Lallemand's and Vignal's formulas are given and practical computations are described. At last the analysis of variance for discrepancies grouped according due to lines, observers and instruments is carried out.

2. THE FOURTH PRECISE LEVELLING CAMPAIGN

In Poland the fourth precise levelling campaign started in 1999 and was finished in 2003 The measurements have been done using Zeiss Ni 002 (66% of the network), Zeiss DiNi 11 (31% of the network) and Topcon NJ (3% of the network) levels (Paczus,2001).

The network consists of 16 132 sections with average length 1.1 km, 382 line with average length about 46 km, 135 loops, and 245 nodal points. Total length of levelling lines is 17 516 km (see Fig. 1).

Generally, the levelling sections have been measured forward and backward. The length of sight up to 40 m, sequence of reading "backward – forward - forward - backward" and then "forward-backward-backward-forward" or "backward – backward - forward - forward". Each station observations were corrected for scale, temperature and earth tide. Before and after every field season the rods were calibrated.

The measurement results used in this study were corrected due to rod scale, temperature and earth tides (ibid.).

Fig. 1 Precise levelling network in Poland (1999-2003).

3. ACCURACY ESTIMATION BY LALLEMAND'S AND VIGNAL'S FORMULAS

3.1 Lallemand's formulas

According to the Lallemand's formulas, the random mean error is computed from

$$\eta^2 = \frac{1}{4}\left[\frac{\sum\Delta^2}{\sum L} - \frac{\sum r^2}{\left(\sum L\right)^2}\sum\frac{S^2}{L}\right] \tag{2}$$

and the systematic mean error is computed from

$$s^2 = \frac{1}{4\sum L}\sum\frac{S^2}{L} \tag{3}$$

or using the loop misclosures φ by the formula

$$s^2 = \frac{1}{\sum L^2}\left[\frac{1}{2}\sum\varphi^2 - \eta^2\sum L\right] \tag{4}$$

where Δ is section discrepancy, r is a length of a section, S is a line discrepancy, φ is a loop misclosure and L is a length of a line or levelling loop.

Using 16 132 section discrepancies, 382 line discrepancies and 135 loop misclosures, according to the formulas (2) - (4), the random mean error η is ±0.27 $mm/\sqrt{km}$ and the systematic mean error s from the line discrepancies is ±0.08 *mm/km*, while the same error computed from loop misclosures is ±0.10 *mm/km*. Therefore the total mean error, which is a combination of both errors, is $\pm 0.28 \ mm/\sqrt{km}$ (Łyszkowicz and Leończyk, 2005).

Comparison of computed values with the results obtained in the previous campaigns (Wyrzykowski, 1988) shows decreasing tendency of the random error, while the systematic error remains almost the same (see Fig. 2). The going down tendency of the random error can be explained by the higher technology of manufactured levelling instruments while the more or less the same systematic error could be explained by the physical phenomena such as climate or topography, which remains changeless.

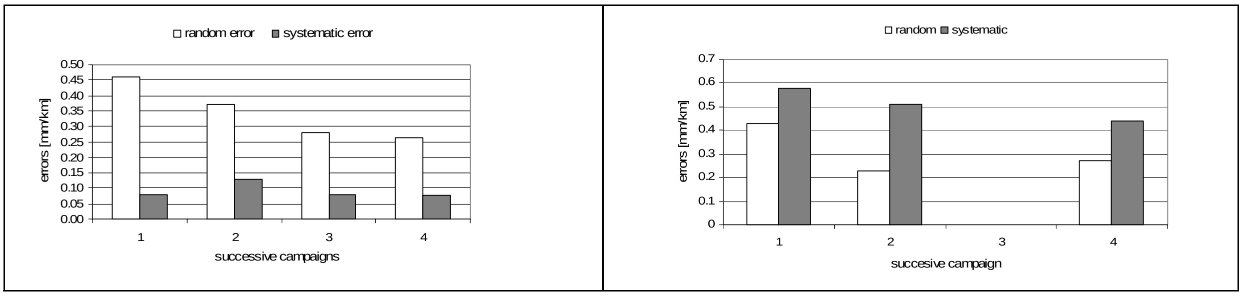

Fig. 2 Random and systematic errors in successive levelling campaigns from Lallemand's formulas (left), and from Vignal's formulas (right).

3.2 Vignal's formulas

According to these formulas the total error in the fourth levelling was computed in the following way. First the mean accidental limiting value of the total error (Kääriäinen,1966) can be computed from

$$u_L^2 = \frac{1}{4n_L}\sum\frac{S^2}{L} \tag{5}$$

where *S* is line misclosures, *L* is length of a line and n_L is number of line in the network.

The limit distance *Z* is a distance at which the value of u_L calculated from the cumulative discrepancies *S*, ceased to depend on *L* and can be evaluated from (Fig. 3).

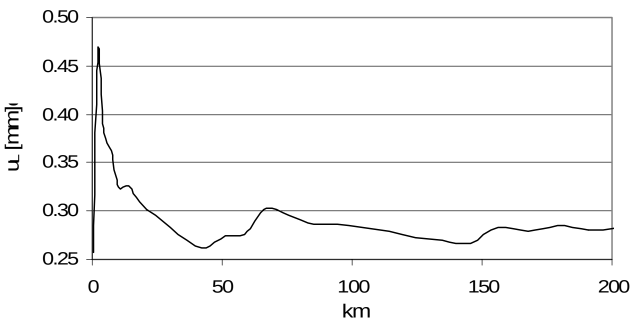

Fig. 3 Decrease of value of mean accidental error with the increase of the length of leveling line in Polish precise levelling network.

Then the random mean error is computed from

$$\eta^2 = u_r^2 - \xi^2 \times j^2$$

(6)

where u_r and j are computed from the formulas

$$u_r = \frac{1}{4n_r}\sum\frac{\Delta^2}{r} \quad \text{and} \quad j^2 = \frac{K}{Z}\times r_m \tag{7}$$

where r is the length of the section and r_m is mean length of the sections. For Z the value of 50 km was assume (Fig. 3) and for K we assumed K=2 (Kääriäinen, 1966). After that the systematic error is consequently equal

$$\zeta^2 = u_L^2 - \eta^2 \tag{8}$$

Using discrepancies computed for each section and for each line and then applying formulas (6) - (7) by iteration, the value $\pm 0.27 \ \ mm/\sqrt{km}$ for the random and *0.44 mm/km* for systematic error was obtained. We see very good agreement with value of random mean error computed by the Lallemand's formula and significant difference in evaluation systematic error. First estimation gives value about $\pm$*0.1 mm/km* while Viginal's formula gives value four time bigger ($\pm$*0.44 mm/km*). Vignal also suggested that the combined influence of all errors could be assessed by the mean error per kilometer i.e. $\pm\sqrt{0.27^2 + 0.44^2}$ = ±0.52 mm.

These values can be compared with values obtained in the second Polish campaign (1952-1955), for which computed random error is *0.23 mm/km* and systematic error is 0.51 mm/km (Wyrzykowski,1969, p.30). For the first precise levelling campaign, random error was estimated as ±0.43 mm/km and systematic error was estimated as ±0.58 mm/km (Łyszkowicz and Leonczyk,2005) see Fig. 2.

An independent assessment of levelling network precision can be drawn from the network adjustment by the least squares method. In the free adjustment of the fourth levelling campaign root square of empirical variance factor (standard deviation) equal 0.90 mm/km was obtained (Łyszkowicz and Jackiewicz, 2005).

Summarizing, one can say that the accuracy of the fourth levelling campaign estimated by Lallemand's formula is ±0.28 mm/km, by Vignal's formula is ±0.52 mm/km and from the network adjustment we have ±0.90 mm/km

4. STATISTICAL DISTRIBUTION OF DISCREPANCIES

Since 1955 A.M. Wassef and others have demonstrated the application of mathematical statistics specifically to study levelling error and levelling networks.

First, we remind that, several statistical tests assume that the observations and their residuals are normally distributed. Therefore, before the tests can be applied it is necessary to check if the observations are normally distributed. If they are not normally distributed then the results of measurements are probably biased by systematic or gross errors.

To test observations for normal distribution, the skewness

$$\hat{\gamma}_1 = \frac{\hat{\mu}_3}{\hat{\sigma}^3} \tag{9}$$

and kurtosis

$$\hat{\gamma}_1 = \frac{\hat{\mu}_4}{\hat{\sigma}^2} - 3 \tag{10}$$

is calculated, where $\hat{\mu}_3$, $\hat{\mu}_4$ are the third and fourth empirical central moment of observed variables and $\hat{\sigma}$ is its empirical standard deviation.

For a symmetrical distribution skewness $\hat{\gamma}_1$ should be zero. If kurtosis $\hat{\gamma}_2$ is greater than zero then the distribution is more sharply peaked than normal distribution. If $\hat{\gamma}_2$ is less than zero then the distribution is less sharply peaked than a normal distribution. Usually empirical distribution of observation is presented in the form of histogram (Fig. 6). To determine how close a histogram is to a normal distribution *chi-squares* goodness of fit test is used.

Secondly, two variables should be stochastically independent. If two o more observations are affected by a common external influence (in the field) they are said to be physically correlated. The degree of correlation between two variable *x* and *y* can be calculated from

$$\hat{\rho}_{xy} = \frac{\hat{c}_{xy}}{\hat{\sigma}_x \hat{\sigma}_y} \tag{11}$$

where $\hat{\rho}_{xy}$ is empirical correlation coefficient, $\hat{c}_{xy}$ is empirical covariance and $\hat{\sigma}_x$, $\hat{\sigma}_x$ are empirical standard deviation of *x* and *y*.

When correlation equals 1 or -1 there is a perfect linear correlation between the two variables. If correlation is positive it means that increases in one variable are associated with increases in the other variable.

4.1 Statistical distribution of section discrepancies

Initially the discrepancies Δ_i from forward and return sections levelling computed in chapter 3 were analyzed. The absolute values of discrepancies show significant correlation with a length of a section (see Fig. 4, right). Therefore in the paper (Wassef, 1955) author proposed analyzing the quantity Δ/r, where *r* is the length of a given section. Instead of Δ/r A. Chiarini (Chiarini and Pieri, 1971) suggested to investigate the quantity $\Delta/\sqrt{r}$, which recommended itself, but in the presence of systematic errors, as demonstrated in (Wassef, 1962), differences $\Delta/\sqrt{r}$ give incorrect results.

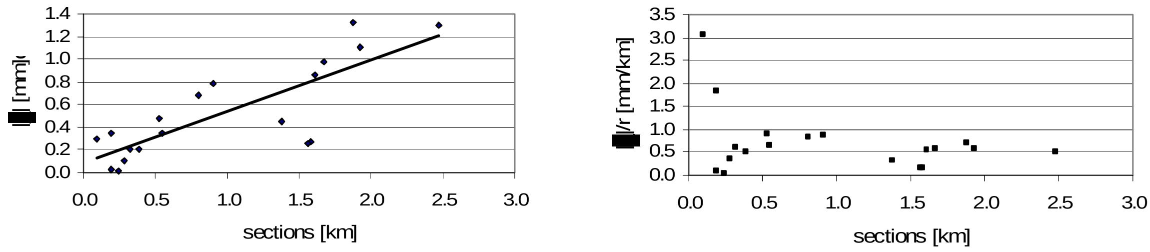

Fig. 4 Correlation (0.80) between section length *r* and its discrepancy *Δ* (left), and not correlated discrepancies *Δ/r* (right) for one levelling line.

Table 1 Statistics of all discrepancies $\Delta\!/_{r}$ of the levelling network (in mm/km)

Number of discrepancies	Mean	Standard deviation	Min value	Max value	Skewness	Kurtosis
16 132	+0.071	±0.783	-23.83	+17.72	0.782	78.850

In the present paper, discrepancies Δ_i were divided by the length of a section and discrepancies per 1 kilometer were computed. These discrepancies do not show significant correlation with the length of the section (Fig. 4, left) .The total number of such discrepancies is 16 132, its mean value is 0.071 mm/km, empirical standard deviation is ±0.783 mm/km, minimum value -23.83 mm/km, maximum value +17.72 mm/km, skewness = -0.782, kurtosis = 79.850. Summary of these statistics are given in Table 1.

Calculated values of skewness and kurtosis (Table 1) as well as histogram of discrepancies $\Delta\!/_{r}$ of the whole levelling network (Fig. 6) show not a quite good agreement with normal distribution.

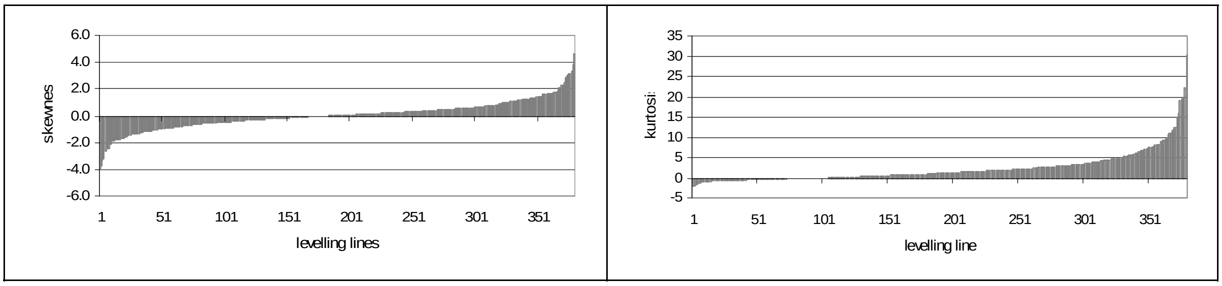

Fig. 5 Skewness of the levelling lines, from minimum to maximum value, computed from Δ/r discrepancies (left), Kurtosis of the levelling lines, from minimum to maximum value, computed from Δ/r discrepancies (right)

In order to determine how close the histogram of $\Delta\!/_{r}$ is to a normal distribution chi-squares was applied, and for the statistic χ^2 the value of 2504.1 was calculated, while the theoretical value, at the significant level 0.05, is 33.9. It confirms that the empirical distribution (Fig. 6) does not agree with normal distribution. The main reason of that is due to the presence of gross errors in considered set of data.

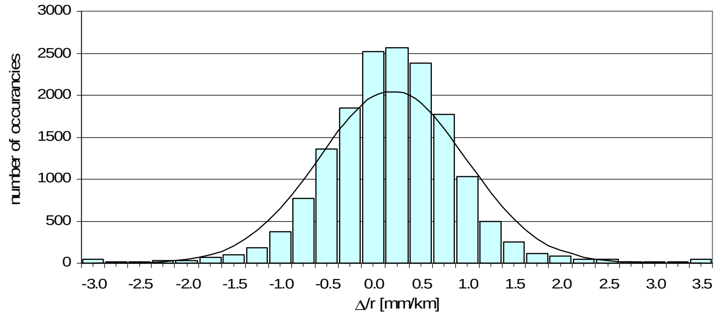

Fig. 6 Histogram of section discrepancies Δ/r for the entire levelling network (in mm/km)

Table 2 Statistics of the discrepancies Δ/r of the levelling network (in mm/km), after removing 74 outstanding data

Number of discrepancies	Mean	Standard deviation	Min value	Max value	Skewness	Kurtosis
16 058	+0.069	±0.685	-8.50	4.33	-0.071	3.807

After removing from the data set 75 discrepancies which apparently are outliers (0.5% of all discrepancies) the data seems to have normal distribution (see Table 2), and such reduced data set has been used for further investigation.

4.2 Statistical distribution of line discrepancies

As was mentioned in chapter 2, levelling network comprises 382 lines which from forward and backward leveling give discrepancies *S*. These discrepancies divided by the length of a line are subject of study. Three discrepancies visible on Fig. 7 have outstanding values and were removed from the data set. Finally 379 values were analyzed.

For such reduced data mean value is equal +0.07 mm/km, empirical standard deviation is ±0.16 mm/km, minimal value is-0.61 mm/km, maximum value is 0.97 mm/km, skewness is -0.11 and kurtosis is 2.85. Correlation, in the case of lines is smaller then for sections, and decreased to 0.51.

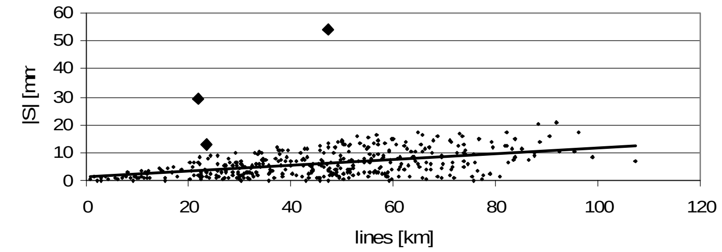

Fig. 7 Correlation (0.41) between line lengths L and its discrepancies $|S|$. Three discrepancies are clearly visible as blunders

4.3 Statistical distribution of loop discrepancies

Levelling network have 133 loops, for which from forward and backward levelling the appropriate discrepancies φ were calculated, which after division by the length of the loop gave values for statistical analysis. No blunders were observed. The statistic of these "normalized" discrepancies are the following: mean value is +0.001 mm/km, empirical standard deviation is ±0.057 mm/km, minimum value is -0.158 mm/km, maximum value is +0.140 mm/km, skewness 0.124 and kurtosis is 0.138. Correlation between discrepancies $\frac{\varphi}{L}$ and the length of a loop is equal 0.12.

The "normalized" loop misclosures show the best agreement with normal distribution, have no blunders, and their correlation with the length of the loop is very low.

5. VARIANCE ANALYSIS

In the paper (Wassef, 1974) author has proposed the application of the analysis of variance to study levelling discrepancies. This method was used in Poland for testing third levelling campaign (Tyra, 1983). Obtained results (ibid.) indicate that the levelling lines are affected by the systematic errors.

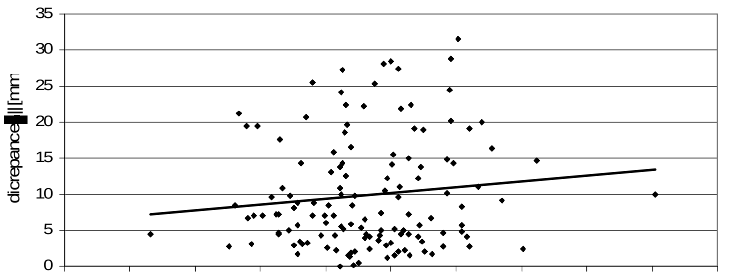

Fig. 8 Correlation (0.12) between loop lengths and its discrepancies $|\varphi|$.

Let us assume, that variables x_1, $x_2 \dots x_n$ (section discrepancies) are independent variables which have normal distribution and the same, but unknown standard deviation. These n variables can be classified into r group (lines) such that variables belong to the i group ($i=1, 2 \dots r$) have the same expected value m.

Analysis of variance is a statistical method to examine if there are no significant differences between mean values computed for each group, that is, if $\hat{x}_1 = \hat{x}_2 = \dots \hat{x}_r$ where r is a number of groups (lines), and mean value is computed from

$$\hat{x}_i = \frac{1}{n_j} \sum \Delta_j \tag{12}$$

where n_j is the number of section in a given line i.

The analysis of variance yields an F-statistic, which signifies the probability that the means of the dependent variable statistically differ from the each other. When the F-statistic is significant and the independent variable has more than two group, then a post-hoc test, such as the Scheffe test is necessary to determine which of the groups differ from each other.

Table 3 Analysis of variance of levelling lines

Source of variation	SS (sum of squares)	DF (degree of freedom)	MS (mean squares)	F	p	F_{theo}
Between lines	423.43	381	1.111	2.45	0.00	1.12
Within lines	7121.41	15676	0.454			
Total	7544.84	16057				

The assumptions of analysis of variance are that variables are normally distributed, the variables are independent, and the variances are equal in each group. Conducting goodness of fit statistics, such as the Kolmogorov-Smirnov, can be used to assess normality. To assess the equality of variance assumption, Levene's test of homogeneity of variance can be used.

To start with, we checked if mean values of line discrepancies computed according to equation (12), do not differ significantly. F test (see Table 3) showed that the practical value of statistic F is much bigger than its theoretical value, which means that assumption of equals means is not true, and that the lines must be contaminated by different systematical errors.

The levelling height differences were observed by 23 different surveyors. Some of them observed one, two or three lines only. Such observers were removed from our analysis. Finally we checked if systematical errors of 16 observers have important influence on the levelling observations. For this purpose all section discrepancies were sorted according to the relevant observer and variance analysis was carried out. The result of analysis is given in Table 4. Since the practical statistic is 6.33 while its theoretical value is 1.70, then the assumption of equal mean values in groups is not true and its mean that each observer has his own different systematic error.

Table 4 Analysis of variance of the observers of levelling lines

Source of variation	SS (sum of squares)	DF (degree of freedom)	MS (mean squares)	F	p	F_{theo}
Between observers	2.66	15	0.177	6.33	0.00	1.70
Within observers	9.79	350	0.028			
Total	12.45	365				

As we mentioned in chapter 2 in the fourth campaign Zeiss Ni 002, Zeiss DiNi 11 and Topcon NJ were used. 250 lines were measured using Zeiss Ni 002 level, 117 lines were measured by the Zeiss DiNi 11 and 11 lines were measured by Topcon NJ level.

All section discrepancies were sorted according to the instrument type and then variance analysis was done to check if the type of levels produced the systematic errors, which have influence on levelling observations. From Table 5 is seen that practical value of statistic F is smaller then its theoretical value. It means that there is no influence of systematic errors coming from the different kind of levels.

Table 5 Analysis of variance of the type of level instruments

Source of variation	SS (sum of squares)	DF (degree of freedom)	MS (mean squares)	F	p	F_{theo}
Between instruments	0.0556	2	0.028	0.83	0.44	3.02
Within instruments	12.602	375	0.034			
Total	12.657	377				

6. SUMMARY AND CONCLUSION

The random mean and systematic mean error computed from the Lallemand's formula is $\pm 0.27\ mm/\sqrt{km}$ and ± 0.08 mm/km respectively. Comparison of these values with the results obtained in the previous campaigns shows going down tendency of random error, while systematic error remains nearly the same.

Random mean error estimated by the Lallemand's and Vignal's formulas give more or less the same numerical value, whereas the systematic error computed from Vignal's formula is significantly higher then value computed by Lallemand's.

The set of discrepancies Δ do not show any outliers, while numerous discrepancies Δ/r apparently have outstanding values. Discrepancies Δ are significantly correlated with the length of section r, line discrepancies S are less correlated with the line length L, while loop misclosures are almost independent from the loop length.

Variance analysis shows that assumption of equal means in the case of lines and observers is not true, and it means that observations are contaminated by systematic errors. In the case of different type of levels the assumption of equal means is correct.

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