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Pregledni znanstveni članak

The Statistical Approach for Estimation of Horizontal Uncertainty of the Points of Digital Large-scale Maps

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ABSTRACT. The paper presents results of estimation of the horizontal uncertainty of digital map data produced by means of various methods: new total station survey (method A), re-calculation of previous direct measurements realised by orthogonal and polar system surveys (B), manual vectorisation of a raster orthophotomap image (C) and graphical-and-digital processing of analogue maps (D). The research was made on large-scale maps (i.e. on investigated objects A, B, C and D, which were produced by means of various methods) with use of statistical approach. Statistical analysis has been performed for large statistical samples of vectors sets of control points shift ε_L *and their components, i.e. true errors of increments of the plane coordinates* ε_X, ε_Y. *In result of research was stated that large-scale digital maps based on data acquired from various methods do not always meet the requirements of accuracy level specified in technical standards.*

Keywords: large-scale digital maps, horizontal uncertainty, statistical approach.

1. Introduction

Nowadays, when the Geospatial Web services are typically use by individual Web users, the broader context of the accuracy issue is huge valid for personal and public (European or Global) users of Spatial Data Infrastructure (Goodchild 2009). The feature of positional uncertainty of digital large-scale maps is very important for state geodetic administration and surveying documentation centres, and for good relation between producers and users of digital map data (Dřbrowski and Doskocz 2008).

The discussed issue is not a local problem, that occurs in Poland only. Accuracy of digital data has already been investigated by numerous researchers (Husár 1996,

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López and Gordo 2008). Those investigations are also performed with the use of statistical analysis (Bolstad et al. 1990), as well as other, modern research methods (Podobnikar 1999, Croitoru and Doytsher 2003, De Bruin 2008). They concern, however, maps produced at medium and small scales available in particular countries. In Poland the large-scale maps exist for the entire country in the form of the base map therefore the investigations will be thus focused on that base technical map.

The aspect of direct relations between results of analysis and certainty (accuracy) of data (the GIGO principle, i.e. "Garbage In, Garbage Out") has been often discussed in literature (Urbaìski 1997). Correlations between data quality and costs of data acquisition are also stressed. Costs of measurement depend, in general, on the accuracy of measurement (GaŸdzicki 1995).

Today the uncertainty of the digital databases is the key aspect to integration of geographic data and their interoperability in the base of spatial data infrastructure (Rönsdorf 2004).

The paper presents the estimation of the horizontal uncertainty of digital large-scale maps with use of statistical approach. Large-scale maps are the most accurate cartographic resources, which precisely presented of topographical objects without generalization of its geometry. Large-scale maps in vector form or databases of Land Information Systems show geometry of objects in the scale 1:1 (there are real lengths and areas which was calculated from coordinates).

2. Methodology of research and characteristics of investigated objects

Statistical analysis for estimation of accuracy of digital maps was executed basing on true errors ε_X, ε_Y of increments of plain coordinates of geometric details of the 1st accuracy group (of selected details of the 1st group, being the so-called, well defined control points). In the case of a map produced on the basis of measurements with the use of an electronic tachymeter (object A), the differences of coordinates of control points, surveyed twice (following the theory of measurements in pairs) were used as true errors. With respect to other analysed methods of acquisition of location details used for creation of large-scale digital maps (objects B, C and D), true errors of control points were calculated basing on differences of coordinates obtained from the investigated map and coordinates determined from a new field measurement.

Four digital maps (objects of the cities of Olsztyn and Zielona Góra) were the subject of research. The object A is the digital map in the scale 1:500, produced on the basis of direct survey performed at the university campus in Olsztyn in 1995–96 by student teams with use of an electronic tachymeter. The survey was based on the 3rd order geodetic control network. 481 control points covering the area of approximately 200 ha were used for estimation of accuracy.

The object B is the digital base map of the City of Zielona Góra. The digital map has been produced basing on existing results of surveys, performed in the period of 1974–1999 (basing on technical traversing of the 2nd order from 1973–74, developed in accordance with the B-III Instruction), by means of the method of orthogonal measurements, and, in the recent period, by means of the polar method, using an electronic tachymeter (in relation to the restorable 3rd order network). The map accuracy was evaluated for the area of approximately 330 ha (out of 5800 ha of the total area of the city), using 1619 control points.

The object C is the digital orthophotomap of the City of Olsztyn. The digital orthophotomap was produced basing on 1:5000 aerial photographs taken within the Phare Programme in 1995. Aerial photographs were processed to the digital form using a matrix scanner with the resolution of 1000 dpi; then the orthophotomap was developed at the scale of 1:2000. The orthophotomap accuracy was evaluated basing on 311 control points from the area of approximately 115 ha.

The object D is the digital base map of the City of Olsztyn. The digital map was produced using the method of graphical-and-digital processing of the analogue base map at the scale of 1:500 with the layers of utilities, at the scales of 1:500 and 1:1000. The base map was produced basing on technical traversing of the 2nd order from 1974. Survey of details was performed by means of a photogrammetric method, for initial conditions of October 1977. The map was updated by means of direct surveys, connected to the control network of 1974, and, after 1986 – to the newly established restorable control network of the 3rd order. Accuracy of the digital map was estimated for the area of approximately 355 ha (out of 8800 ha, being the total area of the city), using 2282 control points.

Coordinates of analysed details of locations of the objects A, B and D were acquired in the form of text listings or database reports; in the case of the object C coordinates were acquired by means of manual vectorisation of the raster image of the orthophotomap (Doskocz 2002).

3. Results of research

Idea of estimation of the horizontal uncertainty of digital map data based on true errors. With accordance the Polish standardisation document PN-N-02206:1978, the true error is the difference between the observed value and the true (certain) value of the measured element (so-called measurand). The certain (true) value of measurand is the ideal value and the true value of the measurand is a fundamental concept. In studies of assessing the horizontal uncertainty of the large-scale digital maps for certain (ideal) values was adopted the coordinates of the control points determined from direct measurements by total station. Its accuracy is about ten times higher than the accuracy of the coordinates obtained from investigated of digital maps (objects B, C, D).

3.1. Statistical analysis for estimation of the horizontal uncertainty of digital map data

In the course of statistical analysis for estimation of the horizontal uncertainty of digital map data based on sets of true errors, estimation of parameters of distribution of the random variable and verification of compliance of its distribution with theoretical models of errors were performed (Doskocz 2005). It highly influenced the statistical estimation of accuracy of control objects, since – in the case when compliance between the distribution of both sets of true errors ε_X, ε_Y of the given control objects with the normal distribution is stated – the random variable ε_L^2 ($\varepsilon_L^2 = \varepsilon_X^2 + \varepsilon_Y^2$) – the square of the length of the shift vector of the control point) would have the χ^2 distribution with two degrees of freedom (Ney 1976).

For the needs of measuring and plotting of topographic data, the ε_L type variable is often used. That variable of two degrees of freedom, expresses the length of the vector, the components of which represent two independent random variables of normal distribution and of equal standard deviations. Some transformations of the χ^2 distribution of practical value are known from literature (Cramér 1958). An example of such a variable is the linear error of the point location (Ney 1976).

The strategy of estimation of the horizontal uncertainty of digital map data was realized with following order on three stages (Doskocz 2005):

I stage: determination of parameters of the random variable:

– calculation of empirical parameters of the random variable "true error";

II stage: analysis of distribution of the sets of true errors:

– determination of the type of the random variable "true error" (continuous or discrete type);
– formulation of initial assumptions on the distribution of true errors (basing on empirical parameters and determined type of the random variable);
– verification of non-parametric hypotheses with respect to compliance of distribution of the sets of true errors ε_X, ε_Y with the normal distribution;

III stage: estimation of accuracy of control objects (independence of ε_X, ε_Y errors assumed):

(III-a) – In the case when compliance of distribution of the sets of true errors ε_X, ε_Y of the given control object with the normal distribution is stated – estimation of accuracy of the control object using the χ^2 distribution (with two degrees of freedom) for the random variable ε_L^2 ("the square of length of the shift vector of the control point").

(III-b) – In the case when no compliance of distribution of at least one of the sets of true errors ε_X or ε_Y of the given control object with the normal distribution is stated – estimation of accuracy of the control object with the use of statistical definition of probability, where the probability of occurrence is expressed as the relative frequency of occurrence – occurrence of a specified length of the shift vector (ε_L) in the set of control points of the given object (for the sufficient number of sample population).

3.2. Determination of parameters of a random variable

Two groups of parameters, i.e. measures of location and measures of scattering are most frequently applied. The basic numerical characteristics of the distribution of the random variable are particular cases of moments of the random variable (Baran 1983). Some values of the basic numerical characteristics are helpful to specify (hypothetical) reasons of anomalies of distributions of empirical sets (Szacherska and Kurpiewska 1976, Wiśniewski 1986):

- Existing skewness ($S \neq 0$) in an empirical set proves that the set was created from combination of subsets of various size and of various expected values. This also proves that a deterministic factor occurs (a factor of non-random characteristics) which is systematic with respect to the sign but variable with respect to the value.
- Theoretical justification of $e > 0$ coefficient (slender an empirical curve) is the occurrence of elements of various accuracy in a set.
- Flattens an empirical curve ($e < 0$) proves that systematic errors occur.
- Non-zero expected value of the error ($\bar{x} \neq 0$) indicates the occurrence of permanent errors.

In the initial statistical analysis of true errors the following values have been empirically determined: the average values $\bar{x} = \sum_{i=1}^{N} \varepsilon_{X_i} \Big/ N$ (expressed by its estimator – the arithmetic mean) and standard deviation of the random variable $m = \sqrt{\sum_{i=1}^{N} \varepsilon_{X_i}^2 \Big/ N}$ (estimated by the mean square error). Asymmetry of the distribution has been specified by asymmetry factor (skewness) $S = \mu_3/m^3$ and the level of flattening of curves of empirical distribution with respect to theoretical models has also been determined. The factor of flattening (excess) has been calculated as $e = (\mu_4/m^4) - 3$. The following quantities have also been calculated: the mean square error of the average value of the random variable $m_{\bar{x}} = m \big/ \sqrt{N}$, the average error of the random variable $d = \sum_{i=1}^{N} |\varepsilon_{X_i}| \Big/ N$, and the d/m ratio, where N is the size of the set. Parameters of random variables of control sets investigated were presented in the paper (Doskocz 2005).

3.3. Analysis of distribution of true errors

The second stage of analysis was focused on the determination of the distribution of empirical sets. At the beginning the type of the random variables "true error of increment of coordinates" ε_X and ε_Y was specified. Initially the type of the random variable was visually recognised, since in empirical sets of discrete random variables the number of elements of various values would be small (less then twenty). However, in the case of a theoretically continuous variable each element of a set has different value but the same value of variable may occur several times (Ney 1976). Finally, the type of the random variable was specified with use of the hypothesis of wave structure of errors (Adamczewski 1961). In the case of sets of true errors ε_X, ε_Y of all control objects, the continuous function of attenuation has been stated (Doskocz 2002).

Basing on empirical parameters, initial specification of distribution of true errors was performed. It was noted that the majority of sets are asymmetric ($S \neq 0$) and are affected by a systematic factor ($\bar{x} \neq 0$). It was also found that, for the considerable part of sets, that obtained d/m ratio vary from its theoretical value in the normal distribution (for Gaussian distribution that ratio equals to $d/m = \sqrt{2/\pi} \approx 0{,}80$, Ney

1976). The excess values in empirical sets are almost all positive, what indicates more distinctive slenderness of empirical curves of probability density of errors than a normal curve of the variance determined in the given empirical set. Therefore, the use of modified normal distribution, in particular the Modulated Normal Distribution (MND) was considered (Romanowski 1974, Romanowski 1979). The analysis of relative frequency of true errors ε_X, ε_Y in the investigated sets indicates the similarity of their distribution with the MND distribution of the 1st-type.

The empirical sets of observation errors frequently substantially differ from the Gaussian model; it concerns asymmetry and excess (Szacherska 1974, Łyszkowicz 1975b, Wiśniewski 1984, Wiśniewski 1986). Such differences were also exhibited by the empirical sets investigated. In order to determine the empirical distribution density curves, Pearson method was applied, that requires calculating numerical coefficients β_1, β_2, k (basing on values of central moments of empirical sets, calculated earlier): $\beta_1 = \mu_3^2/\mu_2^3$, $\beta_2 = \mu_4/\mu_2^2$, $k = \beta_1 \times (\beta_2 + 3)^2 / 4 \times (2 \times \beta_2 - 3 \times \beta_1 - 6) \times (4 \times \beta_2 - 3 \times \beta_1)$. Those coefficients become the basis for determination the curve, out of 12 Pearson curves, that might be used for approximation of the given empirical set. Pearson distributions of I, II, IV and VII types were identified as suitable for typical surveying data (Łyszkowicz 1975a, Łyszkowicz 1975b).

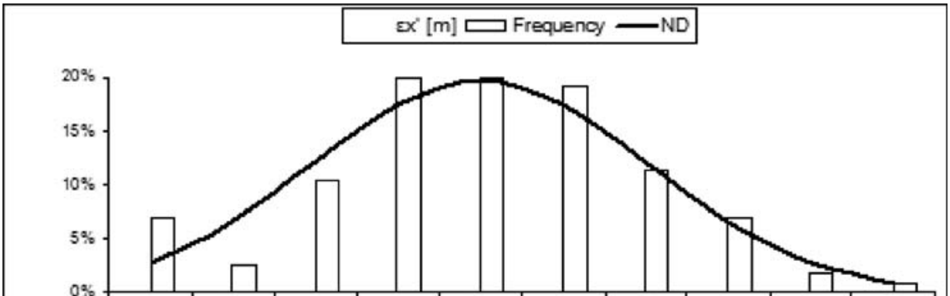
The search for Pearson distributions that might be used for approximation of empirical sets was undertaken. Besides, two statistical tests, i.e. Pearson χ^2 test and Kołmogorow λ test were used for verification of non-parametric hypotheses concerning the compliance of distributions of empirical sets with theoretical distributions (Gaussian and MND 1st-type distribution characterized by the leptokurtosis index ω_t). Investigations of compliance of distribution of true errors of ε_X, ε_Y with theoretical models was performed for the standardized random variable (e.g. $\varepsilon'_X = (\varepsilon_X - \bar{x})/m$).

The χ^2 test is of higher sensitivity than λ test, but, at the same time, it requires larger set (at least above one hundred elements) (Ney 1970). The χ^2 test better characterizes the difference between the empirical distribution and the theoretical model, since it uses all class intervals of a distributive series. In the λ test the level of compliance between the empirical and theoretical distributions is expressed by the point value D_i. The argument that supports the use of the Kołmogorow λ method is that the λ test is not sensitive on discrepancies which occur for final small class intervals of the distributive series (which often prevail in empirical sets) (Hellwig 1998). The Kołmogorow λ method was applied when it was necessary as an auxiliary test.

Analysed the sets ε_X, ε_Y are slender (leptokurtic) in majority of cases, with respect to Gaussian distribution (except of ε_X and ε_Y sets of the object A, the ε_Y set of the object D-5 and the ε_Y set of the object B-7); prevailing discrepancies of their distribution occur in central class intervals of the distributive series. Detailed results of investigations of compliance between distributions of sets of true errors with theoretical distributions were presented in the paper (Doskocz 2005).

3.4. Results of analysis of distribution of true errors

In the first two stages of statistical analysis it was found that the distributions of ε_X, ε_Y sets "they are governed by their own law" which makes it difficult to



	1	2	3	4	5	6	7	8	9	10
εx' [m]	-0,580	-0,435	-0,290	-0,145	0	0,145	0,290	0,435	0,580	0,725
Frequency	0,070	0,026	0,104	0,200	0,200	0,191	0,113	0,070	0,017	0,009
ND	0,0278	0,0656	0,1210	0,1747	0,1974	0,1747	0,1210	0,0656	0,0278	0,0092

Fig. 1. *Compliance between the distribution of the empirical set ε_X of D-6 control object with the normal distribution.*

present them by means of known, theoretical models of errors. Only in a few cases the compliance between empirical distribution with the theoretical distribution was stated. The only set which proved the compliance between the distribution of the empirical set and the normal distribution (ND) was the empirical set ε_X of D-6 control object (Fig. 1).

Distributions of investigated sets of true errors are, in general, not compliant with MND Romanowski distributions (Doskocz 2005), what results from their skewness as it is known from literature “utilisation of modulated normal distributions is not fully consistent in conditions of existing asymmetry” (Wiśniewski 1986). Also Pearson curves, which accept the presence of asymmetry and excess in an empirical empirical set, could, to a very limited extend (ε_Y set of A, ε_Y set of B-7, ε_X and ε_Y sets of D-3, ε_Y set of D-5) approximate investigated sets of true errors (Doskocz 2005).

3.5. Results of estimation of the horizontal uncertainty of digital map data

Because of lack of compliance between the random variable “the square of the length of the shift vector” and the theoretical distribution χ^2, the probability of occurrence of specified values of the point location error m_p (expressed by the length of the vector of shift of the control point ε_L) has been estimated on the basis of the relative frequency W_N of occurrence of particular values ε_L within the control objects. The required probability was determined by means of the method presented in (Smirnow and Dunin-Barkowski 1969). Probabilities have been estimated for the confidence level $\gamma = 0.997$ for $t_\gamma = 3$.

The confidence interval for the unknown probability may be determined by that method when the condition $N{\cdot}P{\cdot}Q > 9$ is met (N is the size of the set; P is the event probability to be determined; Q is the probability of the complementary event). This condition define sufficient size of the samples who is needed for estimating probability of an analysed event.

The limits of confidence interval for the estimated probability P are expressed as $P_1(W, N) < P < P_2(W, N)$ (Smirnow and Dunin-Barkowski 1969), where:

$$P_1(W,N) = \frac{2 \times N \times W_N + t_y^2 - t_y \times \sqrt{D}}{2 \times (N + t_y^2)}$$

$$P_2(W,N) = \frac{2 \times N \times W_N + t_y^2 + t_y \times \sqrt{D}}{2 \times (N + t_y^2)}$$

$$\sqrt{D} = \sqrt{4 \times N \times W_N \times (1 - W_N) + t_y^2}.$$

Statistical estimation of positional uncertainty of digital map data in particular control objects is given in Table 1. Columns 6 and 8, present probabilities that the digital map data error does not exceed stated point location error (m_P) multiplied by factor 3 and 2, respectively, at the given control object. Column 10 presents the probability that the theoretical error will be exceeded (m_t – determined in accordance to the accuracy standard for mapping). The symbol (*) by the confidence interval means that the probability is determined in situation when the relative frequency of the considered event in the empirical set had not ensured that the condition of the sufficient sample size was fulfilled.

4. Discussion and conclusions

Results of statistical analysis proved the lack of compliance of considered sets of true errors with the normal distribution (except ε_X set of the control object D-6, presented in Fig. 1). That is why estimation of the horizontal uncertainty of investigated of sets of digital map data was based on statistical definition of the probability, where the probability of an event is identified with the relative frequency of this event. Obtained results of certainty (accuracy) of data estimation using statistical analysis (Table 1) are coherent with conclusions developed on the basis of classical estimation of accuracy (Dřbrowski and Doskocz 2008).

Statistical analysis confirmed high accuracy of the digital map data produced on the basis of survey with an electronic tachymeter (object A). Probability that the theoretical error (0.3 mm at the map scale) will be exceeded in the object A does not exceed 5%.

The probability of occurrence of the point location error which does not meet the accuracy standards in the case of a digital map data produced on the bases of the past field surveys is relatively low (object B); in general it does not exceed 10% (except control objects B-3 and B-7).

Statistical analysis confirmed the high accuracy (in relation to well identified details of the 1st group, i.e. characteristic points of technical utilities) of a digital orthophotomap (object C). In the case of that object the probability of occurrence errors larger than the theoretical error does not exceed 3%.

Table 1. *Estimation of positional uncertainty of digital map data with use of statistical approach.*

Control object	Analysed value	Size of the set	m_P [m]	Estimated probabilities of occurrence of the (Δ) error in general population					
				W_N	$\Delta \le 3m_p$	W_N	$\Delta \le 2m_p$	W_N	$\Delta > m_t$
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
A	ε_L	478	0.04	0.95	$0.91<P<0.97$	-	-	0.02	$0.01<P<0.05$*
B-1	ε_L	257	0.15	-	-	0.97	$0.92<P<0.99$*	0.004	$0<P<0.04$*
B-2	ε_L	217	0.21	0.99	$0.94<P<1$*	0.96	$0.90<P<0.98$*	0.03	$0.01<P<0.09$*
B-3	ε_L	209	0.33	0.98	$0.93<P<1$*	0.92	$0.85<P<0.96$	0.13	$0.08<P<0.22$
B-4	ε_L	241	0.22	-	-	0.94	$0.87<P<0.97$	0.05	$0.02<P<0.12$
B-5	ε_L	318	0.20	0.98	$0.94<P<0.99$*	0.97	$0.93<P<0.99$*	0.03	$0.01<P<0.07$*
B-6	ε_L	264	0.14	0.98	$0.94<P<0.99$*	0.96	$0.90<P<0.98$	0.02	$0<P<0.06$
B-7 *total*	ε_L	96	0.41	0.98	$0.88<P<1$*	0.91	$0.78<P<0.96$*	0.15	$0.07<P<0.28$
B-7 *sheet 2(2)*	ε_L	72	0.21	-	-	0.97	$0.84<P<1$*	0.03	$0<P<0.16$*
C	ε_L	311	0.21	-	-	0.97	$0.92<P<0.99$	0	$0<P<0.03$*
D-1	ε_L	1001	0.38	0.99	$0.98<P<1$*	0.95	$0.93<P<0.97$	0.19	$0.16<P<0.24$
D-2	ε_L	549	0.45	0.99	$0.97<P<1$*	0.95	$0.92<P<0.97$	0.27	$0.22<P<0.33$
D-3	ε_L	240	0.46	1	$0.96<P<1$*	0.95	$0.90<P<0.98$	0.32	$0.24<P<0.42$
D-4	ε_L	236	0.33	0.98	$0.93<P<0.99$*	0.96	$0.90<P<0.98$*	0.15	$0.09<P<0.23$
D-5	ε_L	134	0.30	-	-	0.96	$0.88<P<0.99$*	0.14	$0.07<P<0.26$
D-6	ε_L	115	0.39	-	-	0.97	$0.88<P<0.99$*	0.29	$0.18<P<0.42$

The lowest accuracy was confirmed for a digital map data produced by means of graphical-and-digital processing of analogue maps (object D). The estimated probability of occurrence of the point location error that exceeds the theoretical error value (0.3 mm at the map scale) within the object D equals to 20 ÷ 30%.

Results of performed investigations allow to formulated the general conclusions:

1) Large-scale digital maps based on data acquired from various methods do not always meet the requirements of accuracy level specified in technical standards.

2) There is a need for estimating the accuracy of large-scale digital maps in order to ensure an appropriate quality of the state surveying resources.

3) The future investigations should be focused on automation process of estimation of the certainty of digital map data bases with application mathematical and statistical methods.

Besides in accordance with opinions too other researchers, quality control for spatial data refers to developing methods to ensure the final spatial data are produced to meet the user requirements (Shi 2008).

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Statistički pristup procjeni horizontalne nesigurnosti točaka na digitalnim kartama krupnog mjerila

SAŽETAK. Rad prikazuje rezultate procjene horizontalne nesigurnosti podataka digitalnih karata izrađenih uz pomoć različitih metoda: nova izmjera mjernom stanicom (metoda A), preračunavanje prethodnih direktnih mjerenja ostvarenih izmjerama uz pomoć ortogonalnih i polarnih sustava (B), ručna vektorizacija prikaza rasterske ortofoto karte (C) i grafičko-digitalna obrada analognih karata (D). Istraživanje je provedeno na kartama krupnog mjerila (tj. na predmetima istraživanja A, B, C i D, koji su izrađeni različitim metodama) koristeći statistički pristup. Statistička analiza provedena je na velikim statističkim uzorcima vektorskih nizova pomaka kontrolnih točaka ε_L *i njihovih komponenata, tj. pravih pogrešaka povećanja ravninskih koordinata* ε_X, ε_Y. *Rezultati istraživanja pokazali su da digitalne karte krupnog mjerila bazirane na podacima dobivenim različitim metodama ne ispunjavaju uvijek zahtjeve točnosti koji su specificirani u tehničkim standardima.*

Ključne riječi: *digitalne karte krupnog mjerila, horizontalna nesigurnost, statistički pristup.*

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