Acta Geodyn. Geomater.Vol.1, No.3 (135), 75-81, 2004

RESULTS OF FOUR YEARS MONITORING OF DISPLACEMENTS OF ROCK BLOCKS IN THE KRKONOŠE MTS.

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(*Received* March 2004*, accepted* May 2004)

ABSTRACT
The epoch measurements of diplacements of the rock blocks started in 2000 in western part of Krkonoše Mts. The local area of investigations in vicinity of Labská meadow and Violík was covered by three single geodetic networks named „A, B, C". The measuring activities were initiated by KRNAP (the Krkonoše Mts. National Park Administration) in connection with the research project concerning the complex analysis of long-term changes of the Krkonoše mountain tundra with special aim to investigate the relevantly important hydro-geological structural elements.
The paper presents detailed description of the single networks and the employed measuring technologies. Besides GPS also other classical geodetic measuring techniques (precise levelling, angle and distance measurements) were used for monitoring of the relative horizontal and vertical positional changes. GPS campaigns were repeated after year, epoch interval for height measurements after half a year. In 2003 the network „C' was extended by additional points at rock blocks situated on southern slopes of Violík, where greatest possible changes should be expected. The paper also presents some results of geodetic measurements covering four years of displacements monitoring which indicate possible movements of some measured blocks mostly in vertical direction.

KEYWORDS geodesy, deformation monitoring, geodynamics

1. INTRODUCTION

In upper parts of Krkonoše Mts. a phenomena called „ploughing stones" is often detected (Kociánová, 1999). Main cause for the slow motion of isolated rock blocks is obviously the frost influence. In slope direction a small mound ahead of each block is formed, and behind is a depression (hollow). Such blocks are spread over the Labská - Pančavská Meadows area in great number. Dimension of the blocks differ from 0.5 m to about 2.5 m, and most of them are covered by vegetation – grass, moss, eventually dwarf pine. A typical block is shown in Fig. 1. It is to be expected that the extreme atmospheric conditions prevailing in the mountains have essential influence also on the movements of boulders in rock-block fields. There exists an opinion that the motion velocity is different for free rock-block fields and for those covered by vegetation.

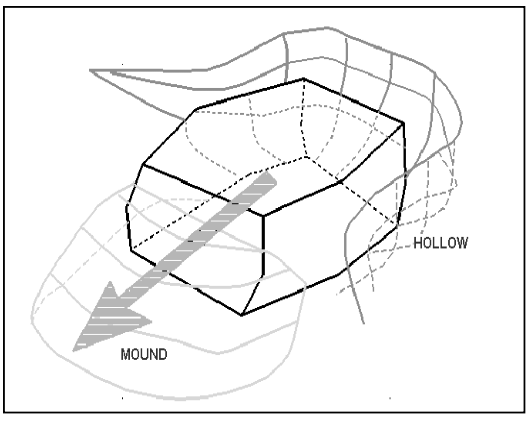

Fig. 1 Ploughing Block – Scheme and Picture

Table 1 Approximate Coordinates of Principal Points

Point	Latitude	Longitude	Height
ZLNA	50° 45′ 24,0′′	15° 32′ 21,2′′	1395,2 m
A1	50° 46′ 10,2′′	15° 32′ 12,1′′	1359,9 m
B1	50° 46′ 26,8′′	15° 32′ 10,7′′	1428,0 m
C1	50° 46′ 39,5′′	15° 32′ 42,8′′	1406,2 m

Specialists from the Krkonoše Mts. National Park Administration are also studying these phenomena in scopes of various grant projects. In cooperation of KRNAP and Brno University of Technology, Department of Geodesy, three areas in western part of Krkonoše Mts., in localities of Labská Meadow and Violík were chosen. In each of the three areas a certain number of stones had been selected for the purpose of long-term monitoring of the eventual displacements. Denominations of the areas are A, B, and C, with elevations from 1350 m to 1430 m above sea level. Average number of blocks in each area is about 10, each stone has special precise small screw marker for precise centring of geodetic instruments. In this way the three individual local geodetic micro-networks were established, and in the period 2000 – 2003 they were subsequently monitored in 7 measuring campaigns. Connection of the three networks to the superior geodetic reference systems was accomplished by GPS method.

2. GEODETIC NETWORKS AND MEASURING METHODS

Three geodetic monitoring networks were established in the territory of interest, in areas named A, B, and C. Area A is located at Labská Meadow range, cca 300 m to the north of crossroad „U čtyř pánů“, on the right side of the tourist path leading to the spring of river Labe. The range is covered by sub-alpine meadow with sparse growth of dwarf pine, on the 6% slope in south-east direction. In 2000 eight selected rock blocks were marked with special geodetic screw markers (A1 - A8). The stones are not standing out very much above surrounding terrain, and most of them are partly or completely overgrown with grass. Exception is the big block (A8) which is about 1.2 m high.

Area B is located southwards to the Labe spring, on both sides of the tourist path. Terrain coverage is the same as in the area A, on the 8% slope in south-east direction. Seven rock-blocks, all of them covered with grass, were marked here with screws (B1 - B7).

Area C is located northwards to both previous areas, in close vicinity of state frontier line between Czech Republic and Poland. It is large rock-block field located 250 m southwards to the rocky top of Violík. The terrain slope is from 10% to 30% here, in south direction. In 2000 first four blocks were marked here, and now (2003) there are ten marked blocks (C1 - C10). Eight of them are spread on a horizontal line which goes through the whole vast rock-block field where greatest possible changes should be expected (Demek 1991). The markers are alternatively on bare and overgrown blocks.

In each network a single main point had been selected, which was then connected to the reference point ZLNA by static GPS method. The point ZLNA is tied to state coordinate system ETRF-89 over the point Žalý, which is included in the national satellite network DOPNUL. Approximate coordinates of these important points are given in Table 1. The heights are given in the state vertical datum Bpv.

The vertical displacements were monitored by very precise levelling method. In each of the networks individual single height differences betwen points were measured so that the loops could be formed and checked by the loop closures. An average loop closure was 0.45 mm, an accuracy of a single height difference was about 0.1 – 0.2 mm.

The horizontal displacements were determined by trigonometric method, with measured angles and distances. Directions were measured by precise optical instruments Zeiss Theo 010A, and distances were measured by parallactic method with 2 m subtense bar. An accuracy level of horizontal positions of points is about 1 – 3 mm.

Six measuring campaigns were carried out here in the past four years. The list of these campaigns together with an overview of measuring techniques employed is given in Table 2. As can be seen, the most frequent technique is precise levelling, which was used in every measuring epoch. In October 2002 the angle and distance measurement could not be carried out because of very unfavourable weather conditions, which was also the case in September 2003.

3. PROCESSING OF THE TERRESTRIAL DATA

Final coordinates and heights of the network points in each measuring epoch were determined by parametric adjustment based on least squares method. Computations were carried out with the help of software G-NET which permits to work with horizontal and/or vertical networks. The software is very flexible when working with input data stemming from various different methods of recording (use of different measuring instruments for data collection). Horizontal and vertical adjustment is accomplished in separate steps, which leads to less demanding computations and to easier testing and checking for

Table 2 History and Structure of Campaigns

Campaign	Network	Method		
		Horizontal	Levelling	GPS
0 9/2000	A	Yes	Yes	Yes
	B	Yes	Yes	Yes
	C	No	No	Yes
1 5/2001	A	No	Yes	No
	B	No	Yes	No
	C	No	No	No
2 10/2001	A	Yes	Yes	Yes
	B	Yes	Yes	Yes
	C	No	No	Yes
3 10/2001	A	No	Yes	No
	B	No	Yes	No
	C	No	No	No
4 10/2002	A	No	Yes	Yes
	B	No	Yes	Yes
	C	No	No	Yes
5 10/2001	A	No	Yes	No
	B	No	Yes	No
	C	No	Yes	No
6 8+9/2003	A	No	Yes	Yes
	B	No	Yes	Yes
	C	Yes	Yes	Yes

outliers. Output contains not only the list of adjusted coordinates and heights, but also the detailed protocole documenting the achieved accuracy and other important attributes of input data and adjustment process. Here belong i.e. mean square errors of coordinates/heights and parameters of the error ellipses for determined points. The software enables to perform a constrained or free adjustment, and it is possible to modify the adjustment procedure with different levels of constraining.

Most frequent measuring method used was the very precise levelling. Because there were no possibilities to establish fixed benchmarks in the areas nor in their vicinity, a special processing method for vertical stability evaluation of the network points had been used. (Štroner 1999), (Tihon 2003).

First step is the selection of identical levelling loops (LL), which were measured in the same configuration, at least in two measuring epochs. The second step is the adjustment of the loops by parametric method with additional conditions. The parameters are the single measured height differences, and the unknowns are the heights of all loop points. To remove the singularity is necessary to introduce here the condition in form of

$$\sum_{i=1}^{n} H_i = const. \tag{1}$$

where H_i is the height of i-th point. In matrix form $\mathbf{B}^T\mathbf{dH} + \mathbf{b} = \mathbf{0}$, where B is the linearized matrix of conditions, and b is the vector of closures in condition equations. Fulfilling the condition (1), the matrixes have form

$$\mathbf{B}^T = \begin{pmatrix} 1 & 1 & \ldots & 1 \end{pmatrix}, \quad \mathbf{b} = \mathbf{0}. \tag{2}$$

Solution of the parametric adjustment with additional conditions is

$$\begin{pmatrix} \mathbf{A}^T\mathbf{PA} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{0} \end{pmatrix}\begin{pmatrix} \mathbf{dH} \\ \mathbf{k} \end{pmatrix} + \begin{pmatrix} \mathbf{A}^T\mathbf{Pl} \\ \mathbf{b} \end{pmatrix} = \mathbf{0}, \tag{3}$$

$$\begin{pmatrix} \mathbf{dH} \\ \mathbf{k} \end{pmatrix} = -\begin{pmatrix} \mathbf{A}^T\mathbf{PA} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{0} \end{pmatrix}^{-1}\begin{pmatrix} \mathbf{A}^T\mathbf{Pl} \\ \mathbf{b} \end{pmatrix}, \tag{4}$$

where k is the vector of arbitrary unknowns. Residuals of the single height differences are then computed after the formula

$$\mathbf{v} = \mathbf{AdH} + \mathbf{l}. \tag{5}$$

Inverted matrix

$$\mathbf{N}^{-1} = \begin{pmatrix} \mathbf{A}^T\mathbf{PA} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{0} \end{pmatrix}^{-1} = \begin{pmatrix} \mathbf{Q}_{HH} & \mathbf{Q}_{kH}^T \\ \mathbf{Q}_{kH} & \mathbf{Q}_{kk} \end{pmatrix} \tag{6}$$

is the same as the resulting matrix of weight coefficients.

Third step is the evaluation of stability of single loop points between two epochs with help of the difference limit. It is possible to calculate the difference value ${}^0d_i$ (left upper index 0 denominates the epoch) for any point height by

$${}^0d_i = \frac{\left({}^0H_1 + {}^0H_2 + \ldots + {}^0H_i + \ldots + {}^0H_n\right)}{n} - {}^0H_i = {}^0H_0 - {}^0H_i, \tag{7}$$

and analogically to calculate ${}^1d_i$. Limit difference of value $\Delta_i = {}^0d_i - {}^1d_i$ for assessment of stability of single points is $\Delta_{\Delta i} = t \cdot \sqrt{\sigma_{odi}^2 + \sigma_{1di}^2}$, where t is confidence factor, and $\sigma_{odi}, \sigma_{1di}$ are the root mean square errors of the differences. If no point is outside the calculated difference limit, then there is no ground to assume any movements in the loop.

In the other case, when some or more of the points are outside the calculated difference limit, the most outlying point is excluded, and then the computation is repeated, with appropriate modification of the formulas. Computations are stopped when all the remaining points are within the given difference limit.

The example of vertical stability evaluation of points from six measuring epochs in area „A“ is given in Table 3.

Table 3 Vertical Stability Evaluation of Points in Area A

Levelling Loop	Between Epochs		Points							
			A1	A2	A3	A4	A5	A6	A7	A8
1,2,8,3	0	3	yes	yes	yes	-	-	-	-	yes
1,3,4,5	0	3	yes	-	yes	yes	yes	-	-	-
1,6,2,8	1	2	yes	yes	-	-	-	yes	-	yes
	1	5	yes	yes	-	-	-	yes	-	no
	2	5	yes	yes	-	-	-	yes	-	yes
1,5,4,3,8	1	4	yes	-	yes	yes	yes	-	-	yes
	1	5	no	-	yes	yes	yes	-	-	yes
	4	5	yes	-	yes	yes	yes	-	-	yes
2,8,3	0	1	-	yes	yes	-	-	-	-	yes
# of Assessments			8x	5x	6x	4x	4x	3x	0x	8x
Positive			7x	5x	4x	4x	4x	3x	0x	7x
Negative			1x	0x	0x	0x	0x	0x	0x	1x
yes - stable point $\Delta_i < \Delta_{\Delta i}$										
yes* - fulfilled $\Delta i < \Delta_{\Delta i}$ after exclusion of most outlying point										
no - non-stable point $\Delta_i > \Delta_{\Delta i}$						possible movement				

Vertical adjustment of the point heights was carried out with the software G–NET. To quantities which are entering the adjustment process (i.e. height differences) the a-priori mean square errors have to be assigned. These were derived in relation to the number of stations *n*.

$$\sigma_h = \sigma_s \cdot \sqrt{n} = 0{,}2\text{mm} \cdot \sqrt{n} ,$$

where σ_h is standard deviation of the total height difference, and σ_s is standard deviation of the single height difference.

Levelling networks at areas A, B were adjusted as free in all the measuring epochs, with respect of the previous stability evaluation of points. As far as the area C had been completely measured only in the last epoch (August-September 2003), there was no possibility to perform any stability evaluation here.

In Fig. 2 the vertical displacements of points A1, and A4 from seven levelling epochs are shown. The point A1 displays possible slow sinking, while the point A4 behaves differently, with indications of some periodical changes.

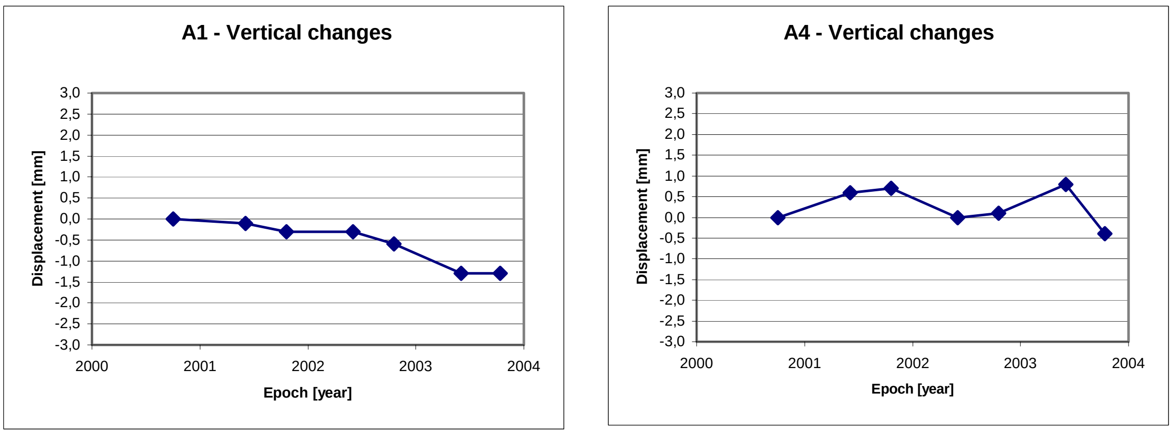

Fig. 2 Vertical Displacements of Points A1, A4 (Levelling)

4. PROCESSING OF THE GPS DATA

GPS measurements were carried out by static method with long observation times up to 24 hours sessions. In Krkonoše campaigns the Leica GPS receivers SR299/399, and SR520 were only used. Data were first checked and then processed according to universal scheme for all campaigns. Processing parameters were 10 degrees elevation mask, computed ionosphere model from reference station data, and standard Saastamoinen troposphere model – no corrections were estimated because of short baselines (under 3 km) and small relative height differences between the reference and the points in monitored areas (under 50 m). Obligatory was the use of precise ephemerides from CODE (University of Berne). The data were preliminarily processed with the help of standard software LEICA SKI-Pro ver. 3.0, and the final solution was obtained with the Bernese GPS Software ver. 4.2 .

In course of preliminary processing analyses there were some indications that possible dicrepancies in antenna phase centers definitions exist. The receiver/antenna SR 299/399 has an internal Ball element, light external AT502 antenna with Aero element is designed for use with receivers LEICA System 500. The appropriate phase center offsets (PCO), and elevation dependent corrections patterns (PCV) are included in standard Leica SKI-Pro processing software. PCO and PCV values are obviously determined by internal Leica testing procedures. Alternative processing with the use of PCO/PCV sets determined by NGS (NOAA) also gave not quite satisfactory results. It was the reason for new own mutual calibration of the antennas used.

GPS antennas test base on the roof of BUT faculty building was completed in 2002. It consists from 5 concrete pillars equipped with forced centring heads, and the station TUBO with fixed choke ring antenna (TRM 29659.00) mounting. Relative positions of the base points were determined by precise angle and distance measurements. Adjusted positions of points were transformed into local horizontal system. The relative horizontal accuracy $\sigma_{x,y}$ is better than 0,3 mm, and vertical accuracy σ_h is better than 0,2 mm. In Table 4 the results of the new calibration of the AT502 in respect to SR299/399 stemming from extensive testing (65 days, over 350 hours of data) are given. Table 5 shows the results of 24 hours testing of relative vertical PCO components for combinations of some of the Leica and Trimble antennas.

Table 4 Leica PCO Values of AT502 in Respect to SR299/399 (in m)

PCO [m]	original values		differences				new values	
	L1	L2	L1	st.dev.	L2	st.dev	L1	L2
dN	0	0	-0.0006	0.0003	-0.0032	0.0004	-0.0006	-0.0032
dE	0	0	-0.0023	0.0004	0.0023	0.0004	-0.0023	0.0023
dU	0.0683	0.0712	0.0026	0.0005	-0.0121	0.0005	0.0709	0.0591

Table 5 Testing of Relative Vertical PCO's of Leica and Trimble Antennas (in m)

Antenna Type	Freq	Height PCO (NGS)	Height PCO Difference	Height PCO (New Values)
Leica SR299/399	L1	0.1284	reference	0.1284
Internal	L2	0.1220	reference	0.1220
Trimble 22020.00+GP	L1	0.0742	0.0198	0.0940
Compact L1/L2	L2	0.0705	0.0064	0.0769
Trimble 22020.00-GP	L1	0.0834	0.0183	0.1017
Compact L1/L2	L2	0.0825	0.0049	0.0874
Trimble 39105.00	L1	0.0712	0.0179	0.0891
Zephyr	L2	0.0674	-0.0028	0.0646

```
LEICA          INTERNAL            SR299/SR399 int. antenna     (  4) 96/06/30
       3.1      -0.2     113.1
   0.0   0.5   1.0   2.0   3.3   4.5   5.7   7.1   8.5   9.0
   8.3   7.0   5.8   4.7   3.4   1.8   0.8   0.0   0.0
       1.3      -3.5     117.2
   0.0   0.2   0.4   0.8   1.5   2.6   3.6   4.2   4.5   5.0
   5.3   5.0   3.8   2.5   1.4  -0.8  -5.1   0.0   0.0
```

Fig. 3 Antenna File Format (IGS_01.pcv)

```
                                                            START OF ANTENNA
TRM29659.00                                                 TYPE / SERIAL NO
FIELD               Geo++ GmbH            12    27-JAN-03 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
IGS_2003                                                    SINEX CODE
AUTOMATED ABSOLUTE FIELD CALIBRATION (ROBOT)                COMMENT
   G01                                                      START OF FREQUENCY
     -0.06     -0.91     91.95                              NORTH / EAST / UP
   NOAZI    0.00   -0.24   -0.94   -2.02   -3.37   -4.83   -6.23   -7.40   -8.21   -
8.58   -8.45   -7.84   -6.73   -5.10   -2.83    0.20    4.11    8.84   14.09
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
     -0.16      0.16    120.49                              NORTH / EAST / UP
   NOAZI    0.00   -0.14   -0.55   -1.17   -1.93   -2.76   -3.61   -4.42   -5.10   -
5.53   -5.59   -5.21   -4.37   -3.15   -1.61    0.24    2.54    5.52    9.37
   G02                                                      END OF FREQUENCY
                                                            END OF ANTENNA
```

Fig. 4 ANTEX Antenna File Format (absolute calibration values)

The antenna PCO/PCV values are introduced into the processing by way of the special phase centre correction files. Fig. 3 illustrates the currently used format of an antenna file. In Fig. 4 is an example of newly proposed ANTEX antenna file format, which should be more convenient for corrections stemming from the modern absolute field antenna calibrations with help of specially designed robots. The values of some absolute correction sets are available at *ftp://igscb.jpl.nasa.gov/igscb/station/general/pcv_proposed/* (Schmid, et. al. 2004).

Besides antenna phase center eccentricities also other factors influence the GPS measurements, like f.e multipath and diffraction of satellite signals. Multipath effects are caused by reflections of signals from nearby surfaces, and can be divided into two parts. One part is invoked by the near field of the antenna (pillar/tripod, tribrach, adapter, marker, ground plane, etc.), second part comes from environment. Dangerous are the first part effects which do not cancel out over long observation times. Residuals analysis may contribute essentially to multipath detection. It is possilble to analyse residuals both in code and phase differences, taking into account different behavior of code and phase residuals. Diffraction is a phenomenon which appears by permeation of signal through light obstructions like f.e. foliage. Both effects cause degradation of signal level which is indicated by lowering of SNR (Signal to Noise Ratio) characteristics. Such signals are likely to scatter more than undisturbed signal. One way of dealing with the problem is downweigting or complete exclusion of such observations in processing procedures (Richter, Euler 2001). The appropriate algorithms are included even in some standard GPS processing tools, f.e. in latest versions of Leica SKI-Pro processing software.

5. CONCLUSIONS

Four years of epoch monitoring of positional displacements of the rock block in Krkonoše Mts. did not prove any significant horizontal changes yet. In vertical direction the measured displacements of some of the points indicate possible changes with better confidence. It is evident that the monitoring period must be extended in time to obtain more decisive information about displacements trends.

GPS measurements are influenced by many factors among which important role-play the uncertainties in phase center positions/variations of the GPS antennas, but also others like multipath and diffraction of satellite signals.

Probably most convenient way to the mitigation of inconsistencies in antenna phase center offsets/variations values is the special individual field testing procedure which can effectively determine the reliable relative correction values for groups of antennae, or even for single combinations of certain types of antennae. Promising are also the results of new absolute field calibrations with robots, which would be available in near future for many current antenna types. Testing of Leica PCO values for SR 299/399 and AT 502 antennas found difference 12 mm in L2 relative height offset, while the horizontal offsets differ only by few milimeters. Testing of NGS (NOAA) vertical PCO values between some of the Leica and Trimble antennas revealed differences in L1 relative offsets up to 20 mm, and in L2 offsets up to 6 mm.

Important is also the detection and elimination/mitigation of multipath effects especially for shorter observation times, which applies also for diffraction diluted signals. These factors have imminent impact on the accuracy and reliability of resulting displacements, therefore it is necessary to cope with them by means of more complete modeling, to minimize their proportion in the final displacement monitoring results. Residuals analysis may contribute essentially to multipath detection. Diffraction effect is dangerous when collecting data in not optimal environment. It can be dealt with by use of SNR information in phase data on both frequencies for the downweighting of affected observations.

Introduction of these advanced contemporary methods for mitigation of the above mentioned disturbing effects into the GPS processing procedures brings the results of diplacement monitoring in Krkonoše Mts. on higher accuracy and reliability level.

ACKNOWLEDGMENT

The contribution was elaborated with support of the research project CEZ: J22/98:261100007.

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