Local stability monitoring of the Koper tide gauge station

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1 Introduction

The Koper tide gauge station (hereinafter referred to as TGS) was set up in 1958 for monitoring the sea level, which enables us to establish the position of the height reference surface. Following the guidelines of the Intergovernmental Oceanographic Commission (IOC), in 2002 the Environmental Agency of the Republic of Slovenia started the refurbishment of the TGS. The old TGS was torn down. In place of the old gauge station, a state-of-the-art TGS was built, which is compatible with international standards for registering and monitoring sea level [9]. The permanent GPS station at TGS is a part of the Slovene network of GPS stations – SIGNAL [1]. Fig. 1 shows the old tide gauge station of 1958 and the new tide gauge station with the permanent GPS station.
Since the GPS Antenna Reference Point (GARP) is considered as a control point of TGS, it has to be locally stable or, alternatively, we must know its displacements in space and time. To determine the statement of stability or identification a potential displacement, a geodetic micro network was set up around the new TGS. The points for monitoring of horizontal stability were stabilised in a way to enable reliable long-term ground stability. The observations were performed from eccentric points, thus enabling measurements and reduction of observations without the knowledge of the height of the instrument. The benchmarks for determination of vertical stability were also stabilised. Based on three comparable measuring epochs we are able to control the horizontal and vertical stability of the GARP or its displacements in space.

2 Geometry of the terrestrial micro network

The local geodetic terrestrial micro network is composed of three reference points, that is, points SMKP, KP02, KP03, which are assumingly stable in terms of their horizontal position and height. Three further auxiliary points were stabilized, S01, S02, S03, representing the eccentric points for the performance of terrestrial observations. In the tide gauge station there is the GARP located on top of a mast, called the KOPE control point, whose stability is the subject of the monitoring. Based on simulations of observations in the network it is possible to say that the network geometry enables the accuracy of determining the control point position, which is better than 1 mm. The horizontal geodetic network is a terrestrial triangulation/trilateration micro network, and the heights of points in the network are determined with trigonometric leveling. Fig. 2 shows the horizontal geometry of the terrestrial micro network.
Eccentric points S01, S02 and S03 are positioned near the reference points. The shortest distance in the terrestrial micro network between points S03 and KP03 is 7 m, and the longest 73 m between points S03 and SMKP. Tab. 1 illustrates the status of points in the terrestrial micro network.
The coordinate system of the horizontal terrestrial micro network is defined with three assumingly stable points, that is, reference points SMKP, KP02, KP03. The coordinates of eccentric points S01, S02, S03 and control point KOPE are determined in the adjustment procedure. The zero epoch height of the reference points is determined with the geometric leveling from the benchmark of tide gauge station 9001 [9].

Fig. 1: The old tide gauge station of 1958 (left) and the new tide gauge station with the permanent GPS station (right)

3 Stabilisation and signalisation of points in the terrestrial micro network

Three types of point stabilisation were used in the terrestrial micro network: the control point, reference points and eccentric points (Fig. 2, Tab. 1). In the terrestrial micro network very small displacements are expected, therefore the stabilisation of points is very important. We choose ground stabilisation, where the points are determined with two physically stabilized points – the reference point and the eccentric point [4]. Forced centring of the reflector is performed at the reference points, whose displacements we are trying to determine. The measurements are performed from the eccentric points. In this way the centring error at the reference point is eliminated.
The control point KOPE is the point whose vertical stability is of primary interest. Fig. 3 shows the stabilisation of control point KOPE.
Since control point KOPE is stabilised at the top of the mast, the change in the length of the mast is expected. Therewith is expected the change of the height of the point, due to the expected seasonal temperature changes in the range from − 5 °C in winter to 35 °C in summer. Therefore we decided to fit the GPS antenna to the supporting carbon fibre pipe of a diameter of approx. 80 mm. The carbon pipe is inserted into a stainless steel pipe of a diameter of approx. 100 mm. Between the pipes, there is an empty space. The lower part of the GPS antenna supporting pipe is rigidly fitted into the plate carrying the tide gauge instrument. Before the setting up of the tide gauge station the influence of temperature changes to the carbon fibre pipe was tested.

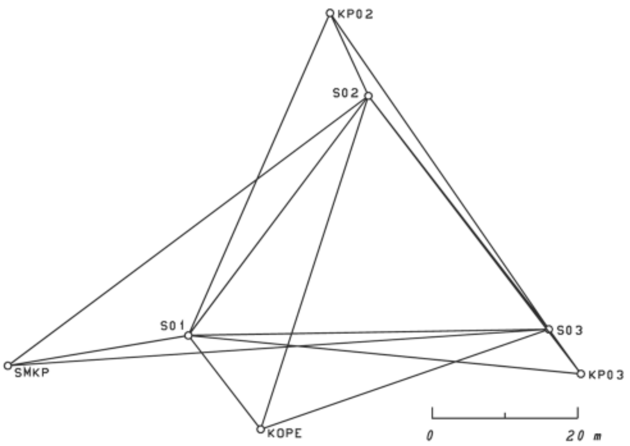

Fig. 2: The horizontal geometry of the terrestrial micro network

Tab. 1: Status of points in the terrestrial micro network

Points	Name	Number
Reference points	SMKP, KP02, KP03	3
Eccentric points	S01, S02, S03	3
Control point	GARP (KOPE)	1
Total number of points in the terrestrial micro network		7

Fig. 3: Control point KOPE – GPS antenna or reflector

It was established that the supporting pipe of the GPS antenna had a thermal expansion coefficient of $\alpha = \frac{l}{\Delta l \cdot \Delta T} = -0.0012\,\frac{\mathrm{mm}}{\mathrm{m}} \cdot {}^{\circ}\mathrm{C}^{-1} = -1.2 \cdot 10^{-6} \cdot {}^{\circ}\mathrm{C}^{-1}$.
Since the length of the pipe is approx. 3 m, one can expect, taking into account extreme seasonal temperature oscillations, up to 0.15 mm change in the length of the carbon fibre pipe, and also in GPS antenna height. This is comparable to the accuracy of determination of the point height using trigonometric levelling and is well above the IOC recommendations.
Reference point SMKP was stabilised prior to the refurbishment of TGS and has been included into many GPS campaigns. The physical stabilisation was performed with a brass rod. At the top of the rod is a hole with pipe thread, which is fitted with the mount for the GPS antenna, mount for the *Leica* prism for terrestrial observations or mount for geometric levelling. Reference points KP02 and KP03 are stabilised in the same way as point SMKP, only they are made of stainless steel.
Eccentric points S01, S02 and S03 are stabilised with a common plug with a hole, fitted into the concrete. During the measurements they are signalized with a tripod, which is mounted by a measuring instrument or an adequate socket with the precision prism. Fig. 4 shows the stabilisation and signalisation of reference points (left) and eccentric points (right) during the measurements.

4 Measuring equipment and measuring method

For the terrestrial measurement we used precision measuring equipment. For measuring horizontal angles, zenith angles and slope distances we used the precision electronic total station *Leica Geosystems TC2003*. As declared, the standard deviation (DIN 18723) of angle measurement is $\sigma_\alpha = 0.15$ mgon, and the standard deviation of distance measurement is $\sigma_s = 1$ mm; 1 ppm. Prior to the measurements the instrument was tested in an authorised company.

Fig. 4: Stabilisation and signalisation of reference points (left) and eccentric points (right) during the measurements

Additional fittings were used for centring, signalization of the observed points, measuring of meteorological parameters for determination of the first correction of velocity in distance measurements and determination of differences in height between points. We used original *Leica* prisms, sockets with prism mounts (Fig. 3 and 4), precision aspiration psychrometer and digital Paroscientific barometer. Each point in all measuring campaigns was signalized with the same prism mount and the same prism, in order to minimize the signalization error.

In order to determine the horizontal and vertical stability of control point KOPE three independent measuring campaigns were performed. For determination of horizontal coordinates we used the *triangulation/trilateration* method. The horizontal angles were observed following the sets of angles method and at the same time slope distances were measured. For the reduction of slope distances we measured the zenith angles. For determination of elevation of reference points and the control point we used the method of trigonometric levelling.

5 Processing of observed data

The horizontal coordinates of the reference points and the control point are obtained with the observations adjustment in the network. We tested the observations for possible presence of gross error, following the Danish method [2]. It was also established that the accuracy of angle and distance measurements among the different measuring campaigns are comparable.

The horizontal coordinates are computed within the local coordinate system at the level of the lowest point in the network, that is, reference point SMKP ($H = 1.3427$ m), so the measured distances had to be reduced to the level of this point. For the calculation of the refractive index for normal atmosphere we used Edlen's (1966) equation, while the actual refractive index was calculated by use of the Barrel&Sears equation [5]. We took into account the first velocity correction. The second velocity correction and reduction due to curvature of the light beam were not taken into account due to the short-range of the distances measured [5]. The corrected slope distances were reduced to a common level based on the measured zenith distances and computed height differences. Due to the eccentric location of stands, the reduction of observations is possible without the information on the height of the instrument. Height differences between the points were calculated according to the equations of trigonometric leveling by means of the observed zenith angles and slope distances.

6 Estimates of point coordinates in the terrestrial micro network

We assumed that the angle measurements in each measuring campaign were performed with the same precision. The distances are short-ranged, so we supposed that the precision relied upon the initial error, which does not depend on the distance.

The unbiased assessment of observations and points position accuracy in the network is obtained with the free network adjustment. The precision of groups of angle and distance measurements was determined with the *a posteriori* weight assessment method according to Ebner [3]. The achieved precision is expected, considering the chosen instrument and observations method. Tab. 2 gives the precision of the measurements in measuring campaigns M1, M2 and M3.

The observations in the terrestrial micro network were adjusted in a free network adjustment, which was then transformed with S-transformation to reference points SMKP, KP02 and KP03. Since all three reference points in the horizontal sense had the same status, the geodetic datum of the horizontal network was obtained from coordinates of all three reference points.

Approximate values of the heights of the reference points were determined on the basis of the adjustment of height differences in the first measurement campaign. The height differences in the vertical terrestrial micro network were adjusted as free network and then transformed with S-

Tab. 2: Standard deviations of angle and distance measurements in each campaign

Measuring campaigns	σ_s [mm]	σ_α [$''$]
M1 (27.12.2005)	0.20	2.29
M2 (7.2.2006)	0.30	2.46
M3 (9.3.2006)	0.44	2.91

Tab. 3: Elements of standard error ellipses of the horizontal coordinates and standard deviations of heights

	Point	A [mm]	B [mm]	Θ [°]	σ_H [mm]
M1	SMKP	0.1	0.1	54	0.1
	KP02	0.1	0.1	20	0.1
	KP03	0.1	0.1	114	0.1
	KOPE	0.2	0.1	139	0.1
M 2	SMKP	0.1	0.1	66	0.2
	KP02	0.2	0.1	4	0.2
	KP03	0.1	0.1	118	0.2
	KOPE	0.3	0.2	141	0.2
M 3	SMKP	0.2	0.1	68	0.1
	KP02	0.2	0.2	175	0.1
	KP03	0.2	0.1	122	0.1
	KOPE	0.4	0.2	140	0.1

transformation to the heights of reference points SMKP, KP02 and KP03. Tab. 3 gives the elements of the standard error ellipses and standard deviations of heights.

The coordinates in the horizontal and vertical network obtained in measuring campaigns were compared. We are interested in the possible changes of spatial coordinates of the reference and control points between the three measuring epochs.

7 Testing the significance of horizontal and vertical displacements

We had three series of comparable measuring results that enable us to investigate the stability or possible displacements of the reference points and the control point in the network. In testing the significance of displacements the stable geodetic datum, i.e. reference point stability and identical network geometry are of great importance. When the displacements are statistically significantly bigger than the standard deviation of the displacements the point displacements can be detected with a high enough probability.

The horizontal point displacement d between two campaigns is computed as

$$d = \sqrt{\Delta y^2 + \Delta x^2} = \sqrt{(y_{t+\Delta t} - y_t)^2 + (x_{t+\Delta t} - x_t)^2} \qquad (1)$$

and displacement variance σ_d is calculated as

$$\sigma_d^2 = \left(\frac{\Delta y}{d}\right)^2 (\sigma_{y_t}^2 + \sigma_{y_{t+\Delta t}}^2) + 2\frac{\Delta y}{d}\frac{\Delta x}{d}(\sigma_{y_t x_t} + \sigma_{y_{t+\Delta t} x_{t+\Delta t}}) + \left(\frac{\Delta x}{d}\right)^2 (\sigma_{x_t}^2 + \sigma_{x_{t+\Delta t}}^2). \qquad (2)$$

When estimating horizontal displacements the test statistic is obtained

$$T = \frac{d}{\sigma_d}. \qquad (3)$$

Point displacement d is a nonlinear function of Δy and Δx, consequently the test statistic (3) is not normally distributed although the Δy and Δx are. It is difficult to analytically determine the form and type of the probability distribution function for the discussed test statistic, therefore we decided to determine it by simulations. The basic idea for generating a sample of dependent normally distributed random variables is to generate a sample of independent normally distributed random variables and then use the linear transformation to obtain a sample of dependent random variables. Consequently in n simulations, this procedure allows us to determine the empirical cumulative probability distribution function of the test statistic (3) for individual points in the network [6].

Critical value T_{crit} and actual risk α_T are determined from the obtained empirical cumulative distribution function. In practice, for estimation of significant displacements it is possible to calculate the actual risk α_T to reject the null hypothesis, which is written as $H_0: \ d = 0$. Test statistic (3) is compared to the critical value of T_{crit} at a chosen significance level α [7, 8]. For the estimation of statistically significant displacements we choose the significance level $\alpha = 5\%$, estimating that such risk is still acceptable. Points meeting the condition of $\alpha_T < \alpha = 5\%$ cannot be considered as stable. Tab. 4 gives the calculated horizontal displacements with corresponding standard deviations between the measuring epochs and quantities needed for the assessment of statistically significant point displacements in the terrestrial micro network.

In estimating the significance of horizontal displacements of reference points and the control point in the terrestrial network it has been established that in some cases the calculated value of test statistics exceeded the critical value of T_{crit}. This means that all points complying with the condition $\alpha_T < \alpha = 5\%$ cannot be automatically considered as stable. The calculated size of displacements of reference points is between 0.1 and 0.6 mm, and the standard deviations of point displacements σ_d are between 0.1 and 0.2 mm. Due to the high accuracy of displacement determination it is difficult to say that reference points KP02 and KP03, which complied with the condition $\alpha_T < \alpha = 5\%$ during the first two measuring campaigns, yielded a statistically significant horizontal displacement, therefore they cannot be considered as unstable. In assessing the significant displacement of control point KOPE it has been found that the horizontal displacement is statistically significant, being 1.0 mm between the first and the third measuring campaigns. The risk of rejecting the null hypothesis is too small, meaning that the point can be regarded as unstable.

The vertical point displacement dH between two campaigns is calculated as

$$dH = H_{t+\Delta t} - H_t \qquad (4)$$

Tab. 4: Testing significant horizontal displacements in the terrestrial micro network

Point		Changes of point coordinates		Horizontal displacement of points between two campaigns		Testing significance of displacements Actual risk		
		dy [mm]	dx [mm]	d [mm]	σ_d [mm]	T	T_{crit}	α_T [%]
SMKP	Between	0.1	− 0.2	0.2	0.1	1.7936	2.3884	19
KP02	M1 and M2	0.4	− 0.2	0.4	0.2	2.8346	2.4016	2
KP03		− 0.5	0.3	0.6	0.2	3.1766	2.3651	0
KOPE		1.0	0.6	**1.2**	**0.2**	4.8358	2.3777	0
SMKP	Between	− 0.3	− 0.2	0.4	0.2	1.6819	2.629	22
KP02	M1 and M3	0.2	0.2	0.3	0.2	1.2748	2.4041	43
KP03		0.1	0.0	0.1	0.2	0.4563	2.3577	90
KOPE		1.0	− 0.2	**1.0**	**0.4**	2.7849	2.3691	2

Tab. 5: Testing significant vertical displacements in the terrestrial micro network

Point		Vertical displacement of points between two campaigns		Testing significance of displacements Actual risk		
		dH [mm]	σ_{dH} [mm]	T	T_{crit}	α_T [%]
SMKP	Between	− 0.09	0.22	− 0.4053	1.9600	69
KP02	M1 and M2	− 0.26	0.20	− 1.3213	1.9600	19
KP03		0.33	0.19	1.7467	1.9600	8
KOPE		− 0.36	0.28	− 1.2959	1.9600	20
SMKP	Between	0.02	0.12	0.1721	1.9600	86
KP02	M1 and M3	− 0.02	0.10	− 0.1942	1.9600	85
KP03		− 0.01	0.10	− 0.1011	1.9600	92
KOPE		− 0.14	0.15	− 0.9627	1.9600	34

and displacement variance σ_{dH} is calculated as

$$\sigma_{dH}^2 = \sigma_{H_t}^2 + \sigma_{H_{t+\Delta t}}^2. \tag{5}$$

When estimating vertical displacements the test statistic is obtained

$$T = \frac{dH}{\sigma_{dH}}. \tag{6}$$

The test statistic (6) is normally distributed. Test statistic (6) is compared to the critical value of T_{crit} at a chosen significance level α. Points meeting the condition of $\alpha_T \geq \alpha = 5\%$ can be considered as stable. Tab. 5 gives the calculated vertical displacements with corresponding standard deviations between the measuring campaigns and quantities needed for the assessment of statistically significant point displacements in the network.

In estimating the significance of vertical displacements of reference points and the control point in the network it has been established that the calculated test statistics T never exceeded the critical value of T_{crit}. This means that all points complying with the condition $\alpha_T \geq \alpha = 5\%$ can be considered as stable. The calculated size of vertical displacements of reference points is between − 0.26 and + 0.33 mm, and the standard deviation of point displacements σ_{dH} are between 0.10 and 0.22 mm. Considering the control point KOPE it has been found that the vertical displacement is not statistically significant, being − 0.14 mm between the first and the third measuring campaigns. The risk of rejecting the null hypothesis is too big, meaning that the point can be regarded as stable.

8 Conclusions

Close to the TGS Koper a terrestrial micro network was set up, with a purpose of geodetic monitoring of the local horizontal and vertical stability of control point KOPE (GPS Antenna Reference Point). Precise ground stabilisation of geodetic points was applied, thus enabling forced centring. Three independent measuring campaigns were performed, ensuring the high repeatability of measurements.

Based on three comparable measuring campaigns it has been established that the precise ground stabilisation ensured the stable geodetic datum. From assessing the statistically significant horizontal displacements, control point KOPE gives a statistically significant displacement, which is 1.0 mm in a period of three months. In the vertical sense, control point KOPE cannot be considered as unstable. Between the first and the last measuring campaign there is a tendency of subsidence, which is – 0.14 mm, being within the limits of accuracy in determining the height of the control point. The measurements were performed during winter time to ensure optimum conditions, which, however, does not ensure a reliable estimate of the control point stability. Admitting to the fact that only two months passed between the measurements, we think that for a reliable stability estimate of the control point KOPE the monitoring of stability over longer time periods is necessary.

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Abstract

In 2002 the Environmental Agency of the Republic of Slovenia started with the modernization of the tide gauge station in Koper, which was first set up in 1958. Besides the recording of mean sea level, the modern tide gauge station will also provide precise meteorological data and permanent GPS observations. This makes it possible to permanently monitor the position of the GPS antenna to determine the position of the reference point of the tide gauge station, and it allows us to connect the monitoring of the sea level with the terrestrial reference system. The paper presents geodetic activities at the tide gauge station Koper during the test period, carried out in order to monitor the local stability of the GPS antenna within the terrestrial micro network.

Im Jahre 2002 begann die Umweltagentur der Republik Slowenien mit der Modernisierung vom im Jahre 1958 aufgebauten Mareograph in Koper-Capodistria. Der moderne Mareograph wird neben der Registrierung vom Tidemittelwasser auch präzise meteorologische Daten übertragen sowie eine ständige Kontrolle am permanenten GPS- Empfänger ausführen. Das ermöglicht eine ständige Überwachung der Position vom Antennenreferenzpunkt, um die Position vom Pegelreferenzpunkt zu bestimmen, was uns erlaubt, die Überwachung vom Tidemittelwasser an das terrestrische Referenzsystem anzuschließen. Der Artikel präsentiert die geodätischen Aktivitäten am Mareograph in Koper-Capodistria während der Testperiode, die ausgeführt wurde, um die lokalen horizontalen und vertikalen stabilen Parameter des GPS-Antennenreferenzpunktes am permanenten GPS-Empfänger des terrestrischen Mikronetzes zu überwachen.