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# THE PERMANENT MODRA-PIESOK GPS STATION MODRA-PIESOK AND ITS LONG-TERM AND SHORT-TERM STABILITY

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**ABSTRACT:**
The history, technical equipment and data management of the permanent Modra-Piesok (MOPI) GPS station. Analysis of 4-year interval of continuous observations at MOPI – derived site velocities, biases of the station coordinates, and effect of antenna radome.

**KEY WORDS:**
- Global Positioning System
- permanent GPS observations
- continuity and integrity of time series of geocentric coordinates
- maintenance of reference frames

## 1. INTRODUCTION

The permanent observations of satellites of the U.S. Global Positioning System (GPS) are an important step in the intensive and effective exploitation of GPS in geodesy, surveying and geodynamics. Recently, more national and international permanent GPS networks are being established; the most important one is the International GPS Service (IGS). Currently the IGS network is comprised of 200 permanent stations distributed all over the globe. The most important products of IGS are the orbits of GPS satellites and coordinates and velocities that contribute to the definition of the International Terrestrial Reference Frame (ITRF). The denser network of permanent stations situated on the European continent is processed within the EUREF (European Reference Frame) Permanent Network. Its main task is to maintain and extend the terrestrial reference frame in Europe.

Slovakia has been participating in the EUREF permanent network's activities since 1996, when the GPS station at Modra-Piesok (MOPI) started regular continuous observations of GPS satellites. The GPS antenna mounting for permanent observations at MOPI is identical with the mounting used in the past during the EPOCH'92 and Central Europe Geodynamic Project (CERGOP) epoch observation campaigns. In this way the GPS permanent observations at MOPI are related to the same reference pillar as the epoch campaigns which started in 1992.

The MOPI station is operated and maintained by the Department of Theoretical Geodesy (DTG) of the Civil Engineering Faculty of the Slovak University of Technology (SUT) in Bratislava. The main task of the MOPI permanent GPS station is to take part in EUREF activities and serve as the reference for GPS campaigns in Slovakia. Other MOPI activities are also worth mentioning. The GPS station is less than 30 m from the UNIGRACE (Project for Unification of Gravity System in Central and Eastern Europe) point used for absolute gravity measurements. The GPS observations are used for Differential GPS (DGPS) corrections for GIS applications; and the local network around the MOPI permanent station pillar is used for testing the GPS receivers and antennas. As of 2001, the permanent observations of meteorological parameters (temperature, atmospheric pressure and relative humidity) are also performed.

The aim of this paper is to describe the current status of the technical equipment of the MOPI station and its evolution. We will then examine the 4-year interval of coordinate determination at MOPI within the EUREF network and analyse the discontinuities in the coordinate time series observed. The annual velocity of MOPI will be determined and compared with the ITRF velocity estimates and the velocity determinations from the CERGOP epoch campaigns.

## 2. TECHNICAL EQUIPMENT OF THE MODRA-PIESOK GPS STATION

The MOPI permanent GPS station is situated in the Little Carpatians mountain range, 40 km northeast from Bratislava and close to the small town of Modra. The station itself is in the local region of Modra called Piesok. The GPS equipment is placed in the site of the Observatory for Astronomy and Geophysics of the Comenius University in Bratislava. The environment of the observatory is mainly a forest with local rocky formations. The concrete pillar for mounting the antenna is embedded directly into bedrock as is shown in Fig. 1. This kind of monumentation secures the sub-millimetre fixing the adapter holding the antenna to the rocky fundament.

The GPS pillar was installed in May 1991. The first long-term GPS observation took place in 1992 during the EPOCH'92 international observation campaigns. Then MOPI was used for observations during a series of national and international epoch campaigns like SLOVGERENET (Slovak Geodynamic Reference Network, Priam, 1987), CERGOP (Fejes & Sledzinski, 1998), EXTENDED SAGET (Satellite Geodynamic Traverse), etc. The MOPI pillar is the geodetic reference point with the longest GPS observational history in Slovakia. The antenna fixing facility has not changed since it was installed.

The permanent station is equipped with the Trimble 4000SSi receiver and the Trimble 4000ST L1/L2 geodetic antenna No. 3351A4750. The observations started on June 10, 1996. Since that time the observations have been regular without and interruptions, except for short periods when power failures caused breaks, but usually not exceeding 24 hours.

**Fig.1.** The concrete pillar for the GPS antenna with a radome for antenna protection

The block diagram in Fig. 2 shows the main components of the MOPI hardware and software instrumentation. The GPS antenna is covered by a plastic radome manufactured by the Department of Theoretical Geodesy. The radome was placed over the antenna on February 2, 1997. Since that time it has been removed several times and vertically shifted in due to technical arrangements and antenna testing. All the manipulations with the radome are summarised in Tab. 1. Since May 21, 1998, the MOPI radome has been permanently fixed, and no further changes are expected. The effects of the radome's manipulation will be analysed in Part 3 of this paper. The antenna is connected to the GPS receiver by a 30 m cable.

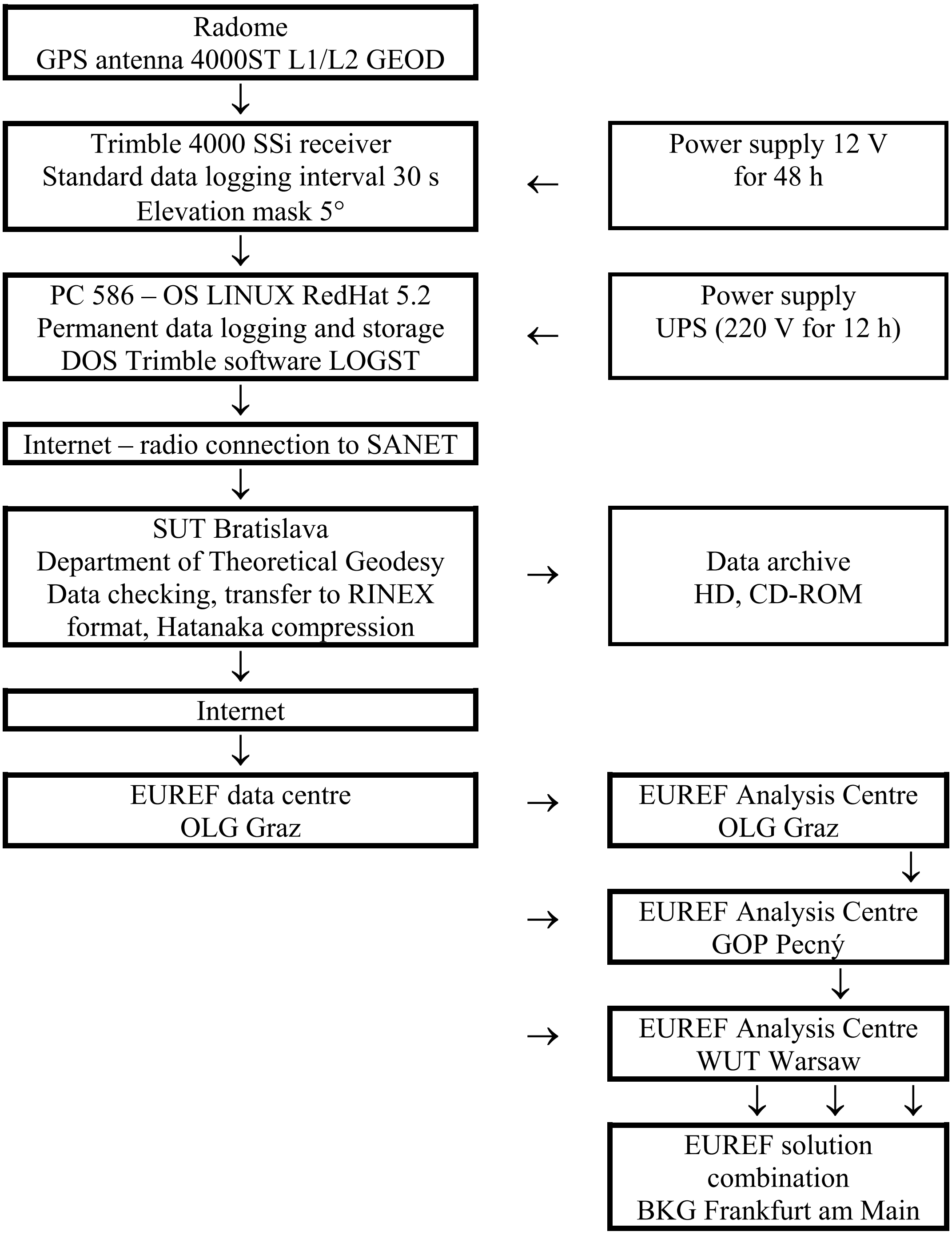


**Fig. 2.** Block diagram of hardware and software of MOPI permanent GPS station

The standard operation of a Trimble GPS receiver is a 30 s data sampling. The alternative 1 s sampling is used only for special demands; in fact, the receiver was switched to 1 s only for one week in 1998. A permanent 1 s sampling is presently not reasonable due to the technical limitation of the Internet connection to the Modra-Piesok observatory. The cut-off angle for the elevation mask as of June 2, 1997, was set to 5°; before this date it was 15°.

The observed GPS data are permanently stored at 5-minute intervals to a PC 586 operating under the LINUX system, RedHat 5.2. Trimble LOGST software is used for transferring GPS data to the PC. As this software is available only for the DOS operating system, the LINUX DOS emulator is used as the environment for the LOGST procedure. The stored raw observational data are transferred from Modra-Piesok via Internet in daily batches to a PC located at SUT in Bratislava. The LINUX-based data management has been operating since November 1999. It replaced the previously applied system, which was based on DESQiew multitasking software, which was frequently malfunctioning due to Internet communication problems. The receiver and PC have a backup with a 12V battery and UPS to overcome 220 V power source failures. The whole system is capable of working up to 12 h during power breaks without interruption of any satellite observations. In case of longer power failures the receiver itself stores the observed data into the receiver memory. In this case operation up to 48 h is possible; however, manual data management is then necessary.

The MOPI observed data are checked at SUT by routine procedures and transferred to the RINEX format and the Hatanaka compressed format. The raw and rinexed data are stored on HD and CD-ROM media. All the MOPI data observed since June 10, 1996, are available on request. The compressed data are sent then to the Graz EUREF regional data centre to be available for regional processing of the EUREF permanent network. The MOPI is processed by three EUREF analysing centres – Observatory Graz-Lustbuehel (OLG), Austria; Geodetic Observatory Pecný (GOP), Czech Republic; and Warsaw University of Technology (WUT), Poland. The combined EUREF permanent network solution, including the MOPI station, is available at the anonymous ftp igs.ifag.de /pub/EUREF/CLUSTERS/wwww, where wwww is the GPS week number.

## 3. COORDINATE EVOLUTION OF THE EUREF POSITION AT MODRA-PIESOK FROM 1996.8 TO 2000.6

The MOPI data have been processed within the EUREF network since November 1996, when MOPI was included in the EUREF permanent network. The evolution of weekly MOPI coordinates is shown in Fig. 3. The three plots represent the north-south ($n$), east-west ($e$) and up ($v$) components in the local Cartesian system. For the sake of simplicity only the relative values are given on the y-axes.

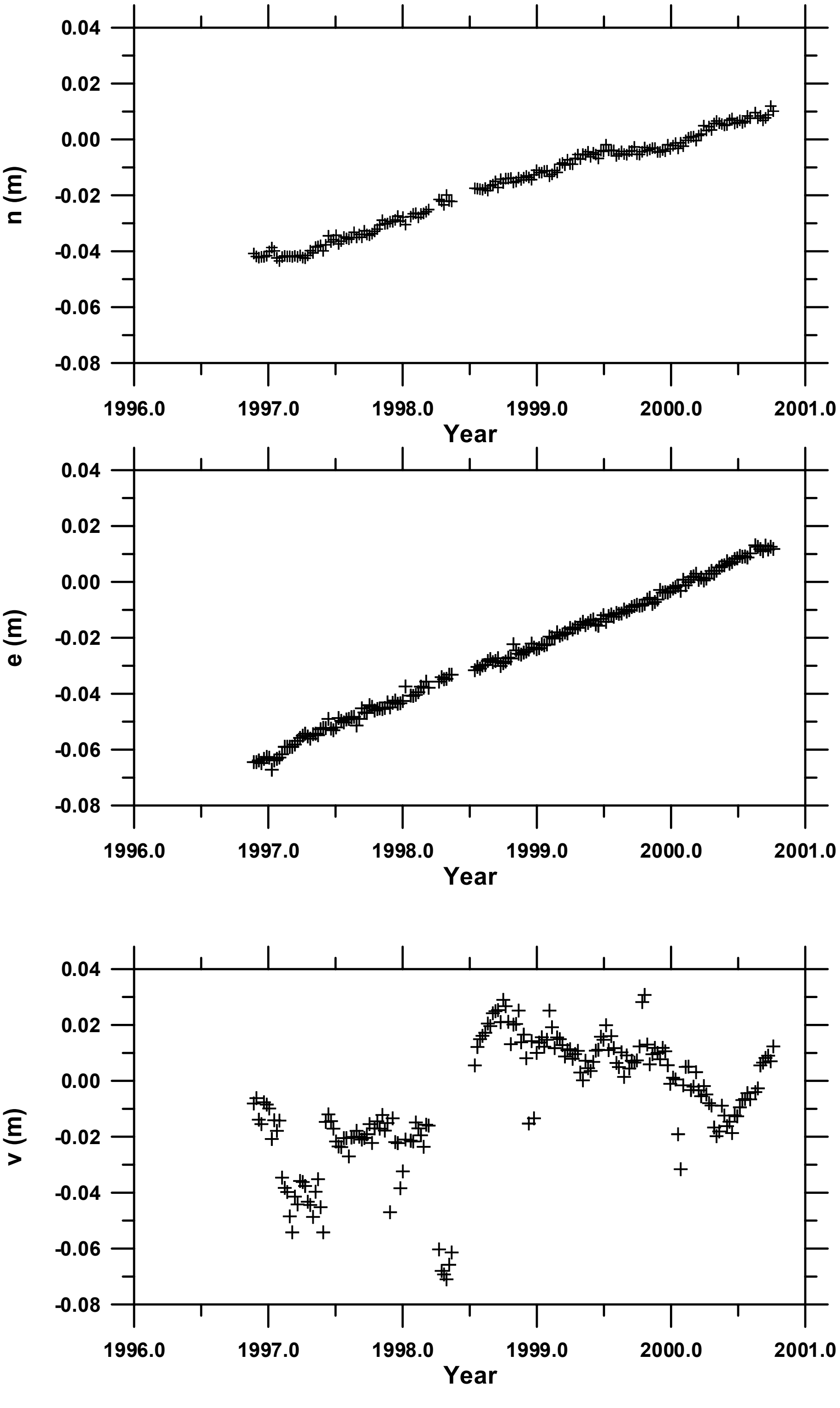


**Fig. 3.** Evolution of MOPI EUREF local coordinates in three components: north-south ($n$), east-west ($w$) and up ($v$). The relative scale is given on the $y$-axes

The horizontal components $n$ and $e$ exhibit a uniform linear trend reflecting the systematic drift of the movement of the Eurasian tectonic plate towards north-east. The gap in data around 1998.5 occurred because the MOPI station was temporarily excluded from the combined EUREF solution due to problems with radome manipulation that caused unexpected jumps in the height component. The small variations with respect to the linear trend are mainly due to changes in the implementation of reference system at the EUREF Analysis Center.

The vertical component $v$ is much noisier compared to the horizontal components. Three main sources are responsible for the variations observed:
- changes in implementation of the reference frame,
- installation and manipulation with the radome placed over the GPS antenna,
- temporary layers of snow and frost on the radome during winter periods.

Tab. 1 summarises the dates when the set of reference stations was changed to implement the terrestrial reference frame in the EUREF Analysis Center.

Tab. 2 summarises the manipulations with the radome over the GPS antenna at the MOPI site. The radome installation was followed by the apparent lowering of the height of MOPI of about 4 cm. This was anticipated because the plastic material of the radome (a width of 5 mm) affected the velocity of the L1 and L2 carriers. What was unexpected and unexplained was that the shifting of height of the radome over the GPS antenna also caused changes in the MOPI's height determination. The result of the radome reinstallation on 1997.459 was that the height became approximately the same as without the radome. The removal and new installation in 1998.199 caused an apparent lowering in height of about 5 cm. This significant was detected in the coordinates of the EUREF processing and stimulated the new shifting of the radome in height to reach the original position of 1997.459. The jump in height jump towards the previous position has been observed again; however the MOPI's height is about 2 cm over the value expected. We found that the radome shifting in height causes unpredictable apparent changes in $v$ component; therefore, the radome was fixed on the pillar. The physical cause for the effect of the radome's shifting on the determination of ellipsoidal height at MOPI remains unexplained.

To remove the effects of the changes in the reference frame implementation as well as the effects of the radome's installation and removal we computed a regression of the coordinates $y_i$ plotted on the graphs in Fig. 3. The general formula applied was

$$y_i = \bar{y} + v \cdot (t_i - T_0) + \sum_j a_j \cdot \delta_j(t_i) + \sum_k b_k \cdot \delta_k(t_i) + s \cdot \sin[2\pi(t_i - T_0)] + c \cdot \cos[2\pi(t_i - T_0)] \tag{1}$$

where

| | |
|---|---|
| $\bar{y}$ | mean value of $y$ for epoch $T_0$ |
| $v$ | annual velocity of $y$ |
| $a_j$ | value of jump due to change in reference sites at $t_j$ |
| $b_k$ | value of jump due to MOPI radome manipulation change $t_k$ |
| $\delta_j(t_i)$ | = 1 if $t_i > t_j$ otherwise = 0 |

$\delta_k(t_i)$ = 1 if $t_i > t_k$, otherwise = 0

$s$, $c$ amplitude coefficient of annual periodic change of $y$

Fig. 4 shows the residuals from the regression according to (1) for the $n$, $e$, and $v$ components. The standard deviations of the unit weight representing the uncertainty of the weekly coordinate component are $\sigma_{0n}$ = 1.2 mm, $\sigma_{0e}$ = 1.2 mm and $\sigma_{0nv}$ = 4.9 mm. In the plot of the $v$ component, the outliers below –20 mm are due to snow and frost layers on the antenna radome during the winter periods. The values for days corresponding to when frost was documented by meteorological observations were excluded from the processing.

The estimated velocities $v_n$, $v_e$ and $v_v$ are summarised in Tab. 3. Also given for comparison are the MOPI velocities estimated from the CERGOP 1994-1997 campaigns (Hefty, 1998), the velocities from CERGOP 1994-1999 and EXTENDED SAGET 1998 campaigns (Hefty, 2000), and from ITRF96 and ITRF97 (Boucher, et al., 1999). The velocities from this paper and the CERGOP velocities mutually agree as to the estimation procedures considering effects of the radome. The height component of the ITRF97 velocity is biased, most probably due to not accounting the radome manipulations.

Tab. 4 shows the estimated jumps in local coordinates related to the radome's installation and manipulation. The values in Tab. 5 represent the estimated corrections due to the effects of the radome's installation and removal. The corrections have to be added to the local coordinates according to the period given in the first column to obtain the initial position without the radome. It is worth mentioning that since May 21, 1998, the radome position remained unchanged. The effect of the radome on the zenith angle-dependent antenna phase centre variations is analysed in (Hefty, 1999).

The annual seasonal term is significant only for the height component $v$ with the estimated sine and cosine coefficients $s_v$ = -6.9 ± 0.7 mm and $c_v$ = -2.2 ± 0.6 mm. The reason for annual height variation with the 8 mm amplitude can be associated with the troposphere induced effects on GPS signal propagation. However a number of other phenomena have to be considered, such as variation in height due to atmospheric loading or ground water storage variations.

**Table 1.** Reference stations used to implement the ITRF reference frame for the EUREF permanent network

| GPS weeks | Period in years | ITRF | Reference sites |
|---|---|---|---|
| 0860 - 0946 | 1996.47 - - 1998.16 | ITRF94 | BRUS, GRAZ, KOSG, MATE, METS, ONSA, WTZR, ZIMM |
| 0947 - 0981 | 1998.18 - - 1998.83 | ITRF96 | BOR1, GRAZ, KOSG, MATE, ONSA, POTS, REYK, WTZR, ZIMM, ZWEN, VILL |
| 0982 - 1020 | 1998.85 - - 1999.57 | ITRF96 | BOR1, GRAZ, KOSG, MATE, ONSA, POTS, REYK, WTZR, ZIMM, ZWEN, VILL, GRAS, |
| 1021 - 1056 | 1999.59 - - 2000. 26 | ITRF97 | BOR1, GRAZ, KOSG, MATE, ONSA, POTS, REYK, WTZR, ZWEN, VILL, GRAS, NYA1, TRO1, THU1 |
| 1057 - | 2000.28 - | ITRF97 | BOR1, GRAZ, KOSG, MATE, ONSA, POTS, REYK, WTZR, VILL, GRAS, NYA1, TRO1, THU1 |

**Table 2.** Installation of the radome, removals and manipulations at MOPI GPS site

| Date | Date in years | Action |
|---|---|---|
| 02-FEB-1997 10:00 UT | 1997.089 | Radome installation |
| 02-JUN-1997 09:30 UT | 1997.418 | Radome removal (CERGOP campaign) |
| 17-JUN-1997 08:30 UT | 1997.459 | Radome installation in new position |
| 13-MAR-1998 07:30 UT | 1998.195 | Radome removal (experimental measurements) |
| 14-MAR-1998 11:50 UT | 1998.199 | Radome installation in new position |
| 21-MAY-1998 09:30 UT | 1998.387 | Radome removal due to its reinstallation |
| 21-MAY-1998 10:00 UT | 1998.387 | Radome installation close to the position of 1997.089 |

**Table 3.** Estimated annual velocities of MOPI

| Reference | Interval (years) | Observa-tions | $v_n$ (mm/year) | $v_e$ (mm/year) | $v_v$ (mm/year) |
|---|---|---|---|---|---|
| This paper | 3.8 | perm. | 14.4 ± 0.4 | 21.1 ± 0.4 | 3.3 ± 2.3 |
| CERGOP 94-97 | 3.0 | epoch | 11.8 ± 1.4 | 21.6 ± 1.3 | 0.4 ± 1.4 |
| CERGOP 94-99 & EXT.SAGET 98 | 5.0 | epoch | 13.2 ± 0.7 | 19.2 ± 0.6 | 4.8 ± 0.7 |
| ITRF96 | 1.3 | perm. | 2.1 ± 3.2 | 19.5 ± 3.6 | 1.2 ± 3.2 |
| ITRF97 | 2.3 | perm. | 11.5 ± 9.3 | 21.0 ± 3.9 | -13.7 ± 9.5 |

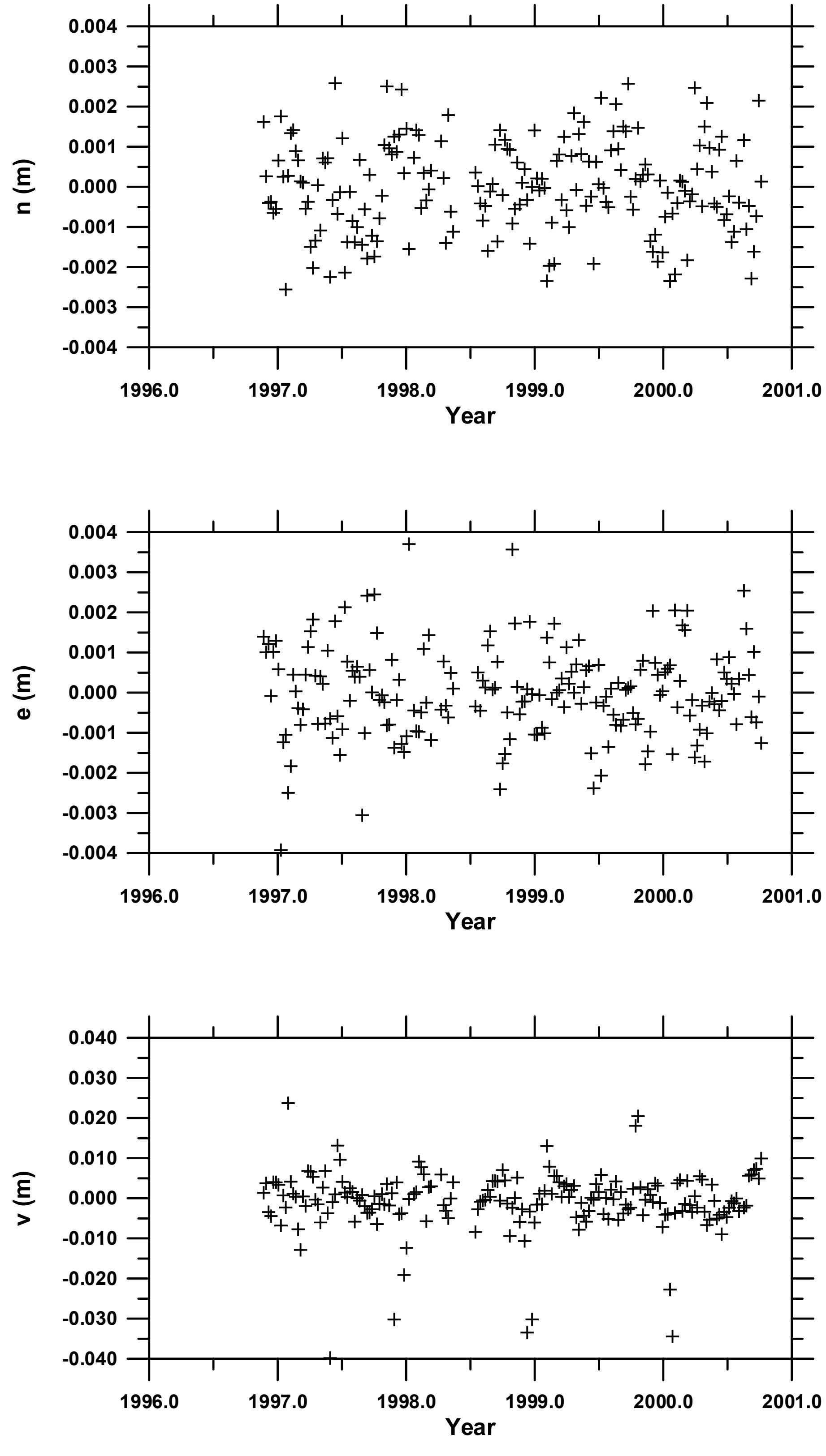


**Fig. 4.** Evolution of residuals from regression according to (1) in components: north-south (*n*), east-west (*e*) and up (*v*).

**Table 4.** Estimated jumps due to the effects of the radome's installation and removal on the local Cartesian MOPI coordinates

| Date | $n$ (mm) | $e$ (mm) | $v$ (mm) |
|---|---|---|---|
| 1997.09 | -3.9 ± 0.5 | 1.8 ± 0.5 | -21.5 ± 2.2 |
| 1997.42 | 0.6 ± 0.8 | 1.6 ± 0.8 | 26.5 ± 3.8 |
| 1997.46 | 1.3 ± 0.5 | -0.7 ± 0.5 | -15.3 ± 3.8 |
| 1998.20 | 1.4 ± 0.9 | -0.4 ± 0.8 | -46.2 ± 3.6 |
| 1998.39 | 0.6 ± 0.7 | -1.9 ± 0.7 | 72.6 ± 2.9 |

**Table 5.** Estimated local coordinate corrections to the initial position without the radome. The changes are due to the effects of the radome's installation and removal.

| Period | $n$ (mm) | $e$ (mm) | $v$ (mm) |
|---|---|---|---|
| 1997.09 - 1997.42 | 4.2 ± 0.5 | -1.5 ± 0.5 | 21.5 ± 2.2 |
| 1997.42 - 1997.46 | 3.6 ± 0.9 | -3.3 ± 0.9 | -5.5 ± 4.2 |
| 1997.46 - 1998.20 | 2.8 ± 0.6 | -1.8 ± 0.6 | 10.3 ± 2.7 |
| 1998.20 - 1998.39 | 0.7 ± 0.9 | -2.2 ± 0.9 | 48.2 ± 4.0 |
| after 1998.39 | -0.1 ± 1.1 | -0.9 ± 1.1 | -24.4 ± 4.6 |

## 4. SHORT-TERM COORDINATE VARIATIONS OF MODRA-PIESOK

The short-term behaviour of the MOPI coordinates will be analysed from the daily solutions performed at SUT since 2000.0. The daily data used are an output from the analysis of the Central European regional GPS network described in (Hefty & Kártiková, 2000). The applied method of analysis uses rules similar to the EUREF permanent network strategy. The network, which is comprising of 15 Central European EUREF permanent sites, is processed as a free network fixing to ITRF97 through the actual ITRF97 position of GRAZ.

The evolution of the MOPI daily local coordinates for days 001-277 is shown in Fig. 5. The dominant feature of horizontal components $n$ and $e$ is the linear trend due to Eurasian plate motion without any significant jumps or variations. The RMS of the unit weight for the residuals from the linear regression are $\sigma_{0n}$ = 2.6 mm, $\sigma_{0e}$ = 2.3 mm and $\sigma_{0nv}$ = 11.0 mm. The daily values observed reflect the variations both at the MOPI and GRAZ sites, as the ITRF97 GRAZ position was fixed in the processing. The above 10 mm residuals in the horizontal position that exceed the 99% confidence are remarkable. For the height component the negative height values of about –40 mm around the DOY 50 are due to the frost layer on the antenna radome. The reason for other outliers in $v$ is inexplicable. The handling of the troposphere in the network processing can be associated with these phenomena.

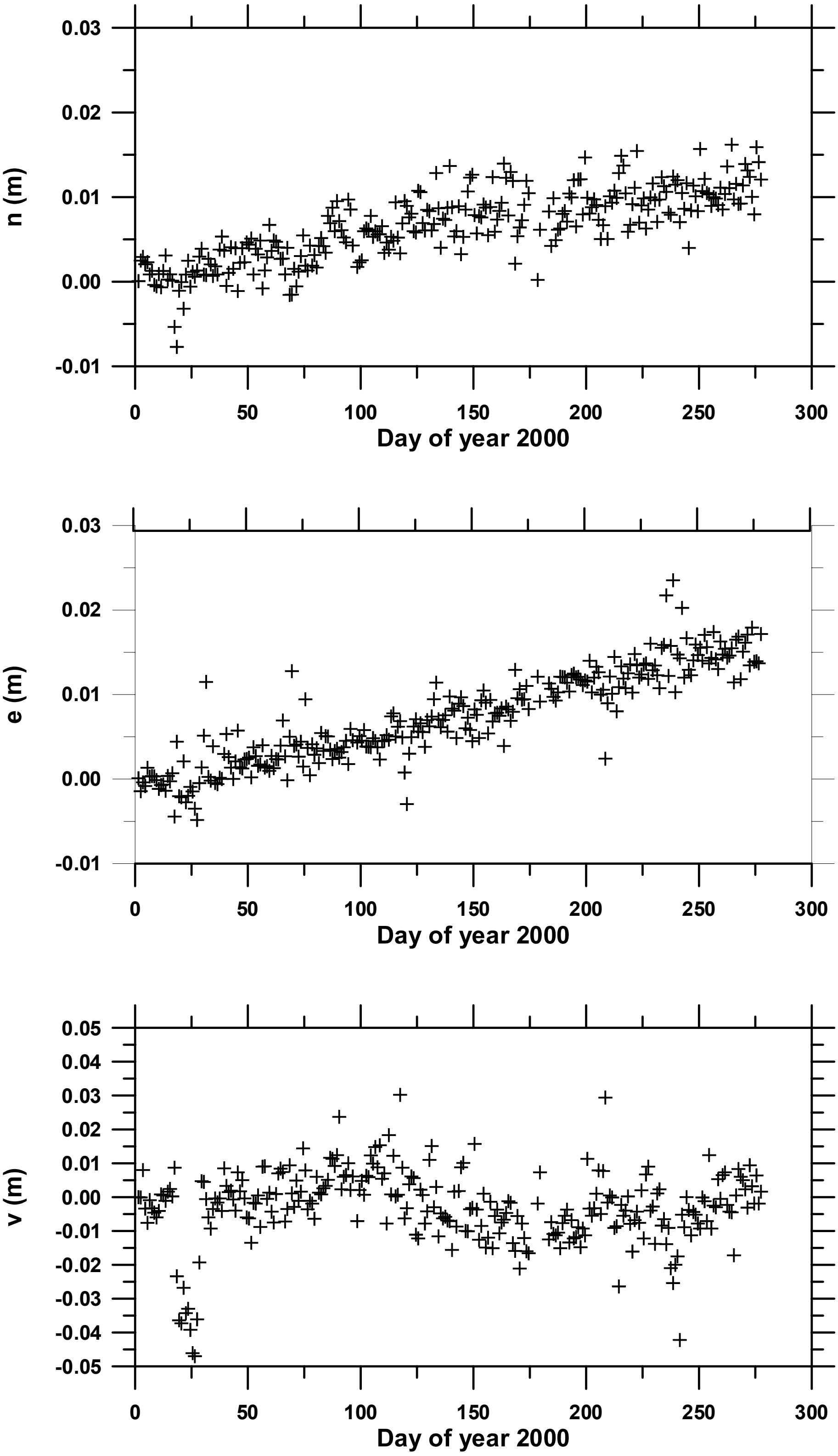


**Fig. 5.** Evolution of MOPI daily coordinates for GPS days 001-277 of 2000. Three components: north-south (*n*), east-west (*e*) and up (*v*) are displayed. The relative scale is given on the *y*-axes.

To obtain representative data not affected by the implementation of the reference frame we will use the time evolution of baseline which are coordinate independent. Two baselines MOPI-GRAZ (197 km) and MOPI-BOR1 (434 km) are shown in Fig. 6. The different behaviour of the two time series is visible. The MOPI-GRAZ baseline oscillates around its mean value; the scatter the in spring period (≈DOY 50-100) is smaller when compared to the summer and autumn periods. The effect of the frost layer on the radome around DOY 50 is clearly visible. The MOPI-BOR1 baseline exhibits long-term variations of about 10 mm, probably with annual period. A spectral analysis will be possible after the accumulation of more than a 1-year interval. The RMS of the unit weight for both baselines is 3 mm.

## 5. CONCLUSIONS

The Modra-Piesok permanent GPS station is the reference for GPS activities in Slovakia. The more than four-year interval of observations has proved the good quality and stability of the reference site, GPS antenna and receiver. The problems with the unexpected effects of the radome manipulation that occurred in 1997 and 1998 no more affect the station coordinates. The radome was fixed in May 1998, and no unexpected jumps in the coordinate time series have occurred. The additional continuous observations of meteorological parameters at MOPI started in 2001. The 1-hour GPS data transfer and 1s data GPS sampling will be possible only after improving the Internet connection to the Modra-Piesok observatory.

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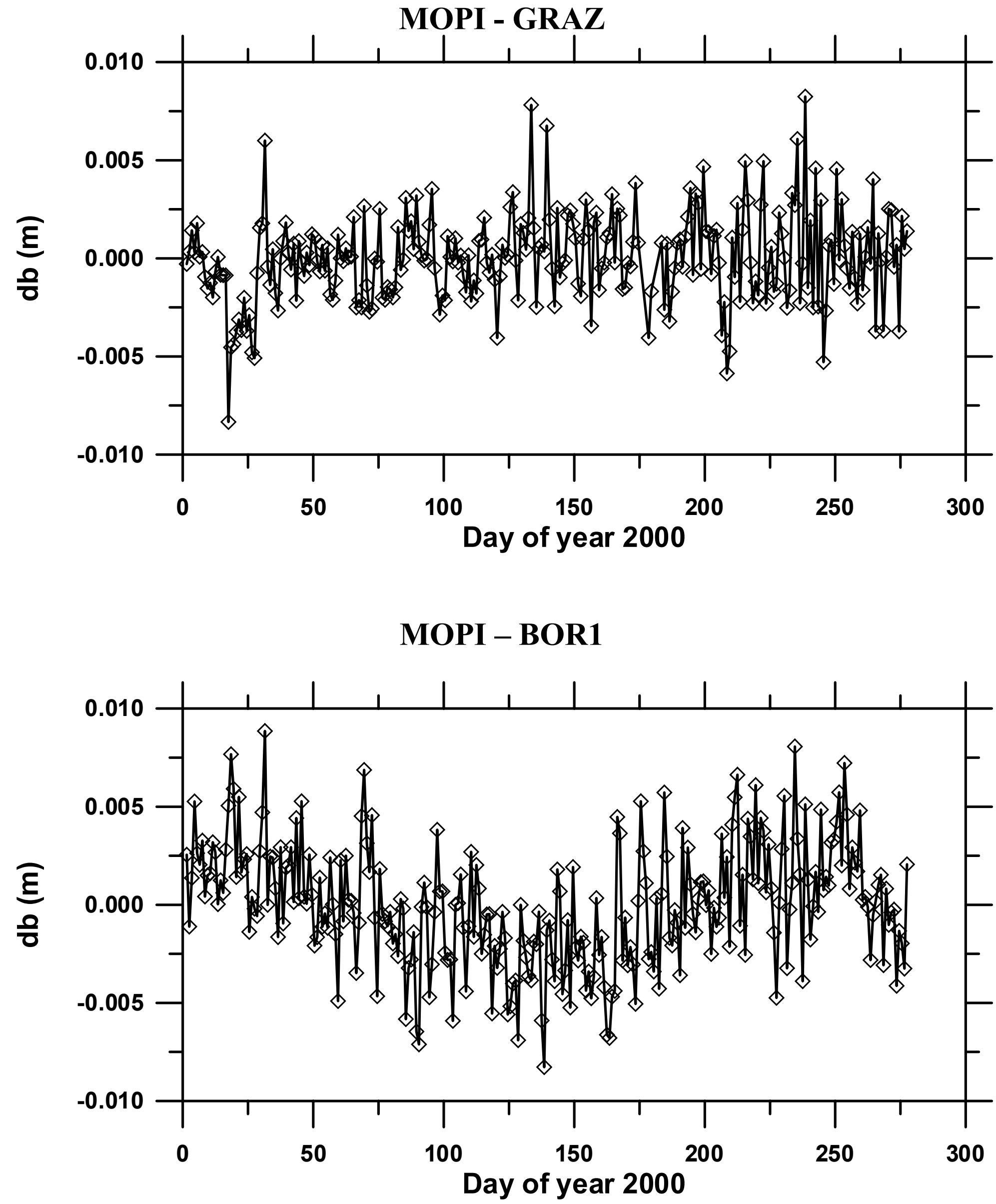


**Fig. 6**. Evolution of Modra-Piesok – Graz (197 km) and Modra-Piesok – Borowiec (434 km) baselines

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