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AUTOMATIC DETERMINATION OF THE DEFLECTIONS OF THE VERTICAL – FIRST SCIENTIFIC RESULTS

Jacek KUDRYS

AGH University of Science and Technology, Faculty of Mining Surveying and Environmental Engineering, Al. Mickiewicza 30, 30-059 Kraków, Poland
Corresponding author's e-mail: jkudrys@agh.edu.pl

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ABSTRACT
The astrogeodetic method of detailed geoid determination need astronomical observations of longitude and latitude. Together with GPS observations it may be used to vertical deflections determination. In the article the portable system for automatic determination of astrogeodetic vertical deflection components developed at AGH University of Science and Technology is described. The design, main error sources, and preliminary results of the test measurements are presented.

KEYWORDS: deflection of the vertical, CCD observation, geoid determination

INTRODUCTION

The problem of the geoid or quasi-geoid determination is a subject of scientific researches and executive works for many years. Interest with the geoid about the accuracy of 1 cm ties in with the development of satellite technologies to which determination of the ellipsoidal height with accuracy of 1 cm is possible. Having the geoid (quasi-geoid) model with the accuracy of 1cm it is possible to determine orthometric (normal) heights with similar accuracy (Rogowski, 2008). The astrogeodetic geoid can be obtained by integration of deflections of the vertical along a profile. Deflection components determination consist in the comparison of astronomical coordinates: latitude and longitude and ellipsoidal coordinates of the same point (Hofmann-Wellenhof and Moritz, 2006). A disadvantage of this method is the labor intensity of astrometric measurements. However, is this only method letting in to determine the absolute directions of normal to the geoid (directions of the plumb line).

At the AGH University of Science and Technology in Krakow, the system for automatic determination of the deflections of the vertical is realized. The system design is based on the portable photographic zenith telescope equipped with the CCD camera. At present, devices of this type make possible to determine the vertical deflection components with accuracy of 0.05" (Hirt and Burki, 2006).

MEASURING DEVICE

Within the framework of the project the apparatus for automatic determination of astronomical coordinates of the point was designed (Fig. 1). The base of the system is mechanical construction letting on turning the kamera together with the lenses around its optical axis. For the inclination of the instrument's rotation axis measurements one electronic inclinometer is used. It forced special manner of the registration of star images in several position of the lenses (Kudrys, 2007).

METHOD OF THE ZENITH POINT DETERMINATION.

For the purpose of the zenith point determination against the background of stars image the well-known

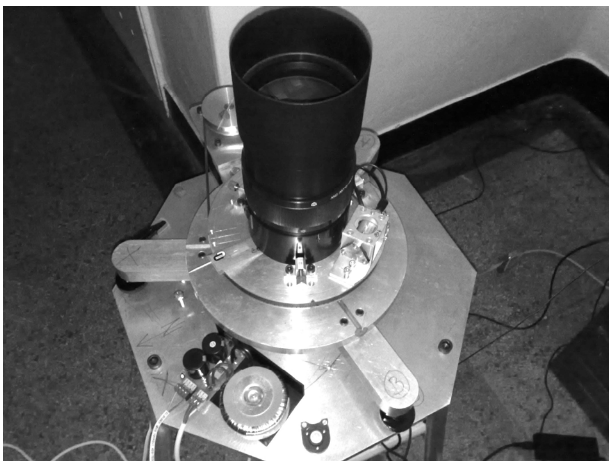

Fig. 1 The apparatus for automatic determination of astronomical coordinates.

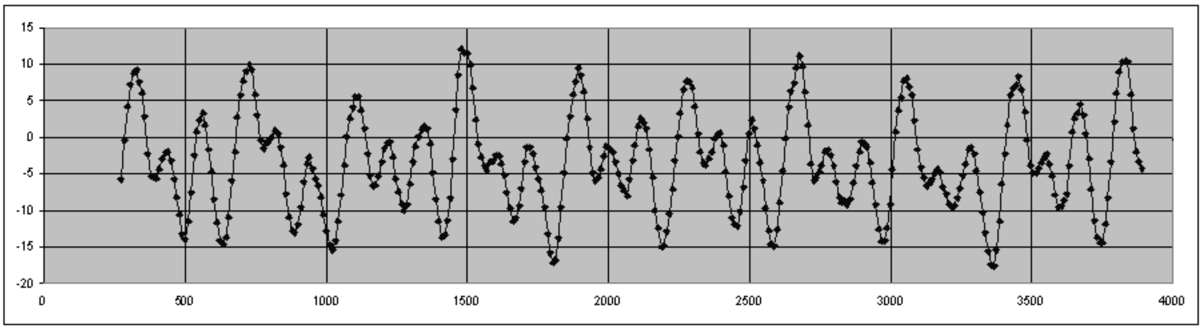

Fig. 2 Inclination of the apparatus rotation axis during 9 turns.

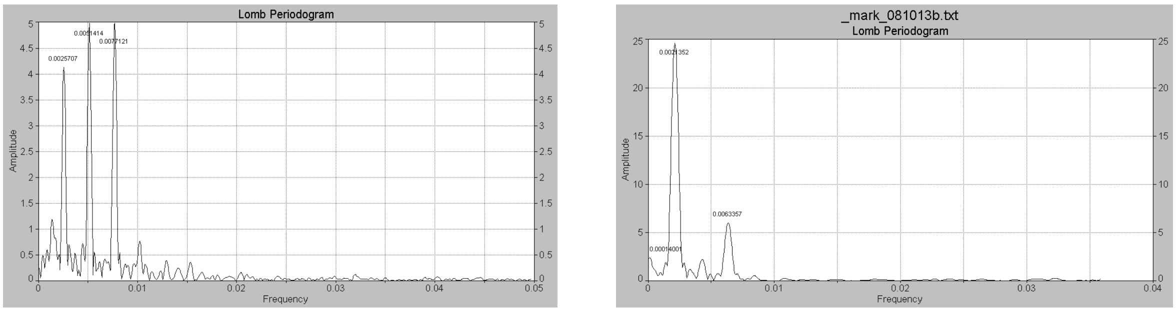

Fig. 3 Spectral analysis of the inclinometer readings during turns in the laboratory and field tests.

method from the theory of the photographic zenithal telescope was adopted (cf. Opalski and Cichowicz, 1980). The method consists in zenithal star observations in two positions of the lenses differing about 180° in azimuth with the simultaneous measurement of the rotation axis inclination to the plumb line. By use of the only one inclinometer at the construction of the measurement system, the two additional observations in the perpendicular plane to previous positions of the lenses is necessary. However, upon test measurement the instability of the rotation axis of the instrument was found. It showed with characteristic oscillations in values of the registered inclination during the turns (Fig. 2). The oscillations due to instable axis of rotation, are caused by imperfectness of the rolling bearing used and misleveling of the rotating base during measurements.

The spectral analysis of the inclinometer readings on both laboratory and field points showed that the signal consists of three harmonic frequencies of periods 1, 1/2 and 1/3 the full turn (Fig. 3). In order to model variations of the axis of rotation the observational procedure was changed so the star image and the inclination were performed in at least 6 positions of the lenses. In the test measurements described it was performed in 36 positions at 10° in azimuth.

Method of the zenith point determination is illustrated in Figure 4. Performing zenith stars images in several positions of the lenses we are able to describe the change in the position of the arbitrary chosen point in the picture. In case of the perfectly horizontal measuring system, stable axis of rotation and all star images reduced to the common epoch, a track of chosen point will be the circle of the spherical radius dependent on the difference of spherical coordinates of the rotation center (the zenith) and spherical coordinates of the given point on individual images. In case of equatorial coordinates this dependence is expressed as follows:

$$\cos r_i = \sin\delta_0 \sin\delta_i + \cos\delta_0 \cos\delta_i \cos(\alpha_i - \alpha_0) \qquad (1)$$

where r_i – the spherical distance to the center of rotation, α_i, δ_i – equatorial coordinates of chosen point, α_0, δ_0 – equatorial coordinates of the center of rotation.

If the axis of rotation is not stable, and the inclination from the plumb line is registered for every image, readings of the inclinometer i_i must be taken into account:

$$r_i - i_i = \arccos\left(\sin\delta_0 \sin\delta_i + \cos\delta_0 \cos\delta_i \cos(\alpha_i - \alpha_0)\right) \qquad (2)$$

TEST OBSERVATIONS

First laboratory test observations were performed at the beginning of the year 2007. These measurements were to confirm a stability of the instrument. Earlier, the test measurements of the

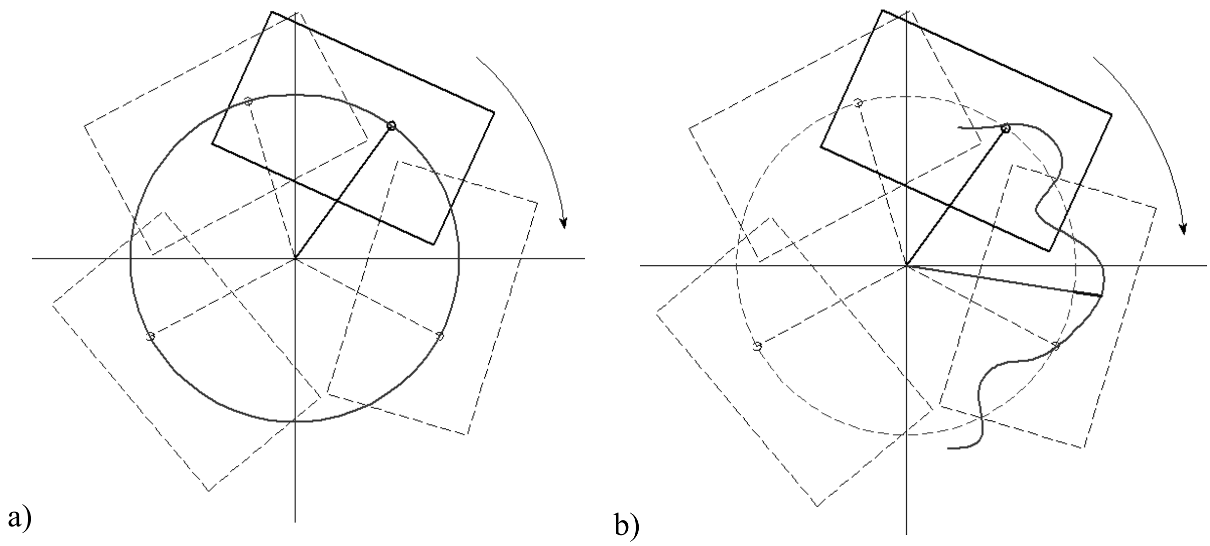

Fig. 4 Method of the zenith point determination: stable a) and instable b) axis of rotation case.

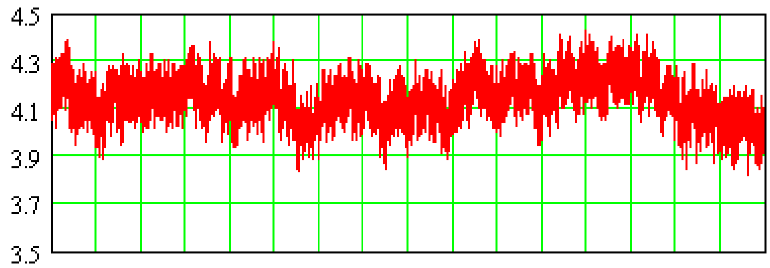

Fig. 5 Inclinometer readings in arc seconds, during 16 hours of observations.

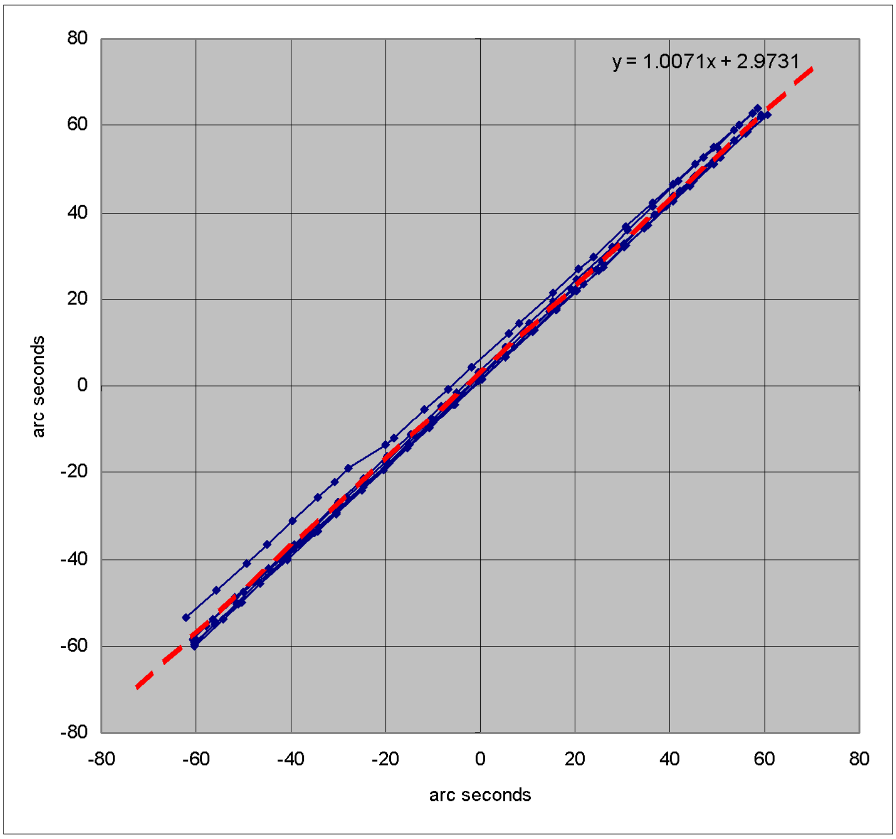

Fig. 6 Inclinometer vs. laser interferometer readings during test measurements.

inclinometer were performed. The inclinometer readings was compared to the laser interferometer set up for angle measurements (Kudrys, 2008). They confirmed its sufficient accuracy, stability in time and linearity within the range –60” – 60” (Figs. 5, 6). In the laboratory tests, photographed object was the chart with coordinate frame marked in the form of lines or points. Field tests had to confirm possibilities of optical sets of a MTO-11CA lenses. In the next stage, algorithms of the processing and calibrations star images were elaborated. Despite the short exposure time of 1 second, it is advisable to remove the “dark-frame”. In order to avoid random noise increase the “master dark frame” – average of 9 single dark frames – are used. This procedure allows image thermal noise reduction. In order to increase the range of imaged stars, it is possible to use 2x2 pixels binning (grouping of pixels in the grid 2x2), or stacking of several images taken in the same position of the lens. Both methods let on the registration of weaker objects, but first results in a reduction in the image resolution and the other requires longer observation time. In tests, the images are stored in full resolution of 3024x2016 pixels and for further processing as more convenient to works the 2x2 binning is performed.

STARS IDENTIFICATION

In order to recognize objects in the image and identify them as the stars the software using the PinPoint Astrometric Engine library is developed. The software makes possible stars recognition with 4 different methods, and identification with star catalogue. To identify the stars the Tycho-2 catalogue is used.

CALCULATION OF THE INTERMEDIATE POSITION IN THE IRS SYSTEM

The algorithm of the calculation of the intermediate (apparent) positions of the stars in the Celestial Intermediate Reference System (CIRS) is realized in the following steps:

- correction due to proper motion (International Celestial Reference System to Barycentric Celestial Reference System transformation)
- generalized Lorentz transformation (Barycentric Celestial Reference System to Geocentric Celestial Reference System transformation including corrections due to annular parallax, light deflection, aberration)
- IAU2006 precession-nutation model applying (GCRS to CIRS transformations).

Individual stages of calculations are realized in accordance with procedures described into the Rocznik Astronomiczny IGiK (Kryński and Sękowski, 2008) and using the SOFA library. At this stage of development, coordinates are not corrected for the polar motion.

PROJECTION OF SPHERICAL COORDINATES α, δ ON PLANE COORDINATES X, Y

Practical implementation of the transformation of spherical coordinates to the image frame is performed in two stages:

- gnomonic projection of spherical coordinates α, δ to the plane coordinates x’, y’,
- affine transformation the x’, y’ coordinates to the image plane coordinates x, y.

Both stages are carried out in accordance with the well known equations (cf. Śledziński, 1978; Kovalevsky and Seidelmann, 2004):

$$x'_i = \frac{\sin\delta_i \cos\delta_0 - \sin\delta_0 \cos\delta_i \cos(\alpha_i - \alpha_0)}{\sin\delta_i \sin\delta_0 + \cos\delta_0 \cos\delta_i \cos(\alpha_i - \alpha_0)} \tag{3}$$

$$y'_i = \frac{-\cos\delta_i \sin(\alpha_i - \alpha_0)}{\sin\delta_i \sin\delta_0 + \cos\delta_0 \cos\delta_i \cos(\alpha_i - \alpha_0)} \tag{4}$$

$$x = ax'_i + by'_i + Tx \tag{5}$$

$$y = cx'_i + dy'_i + Ty \tag{6}$$

where:
α_0, δ_0 – spherical coordinates of the plane x’, y’ frame origin,
α_i, δ_i – star intermediate coordinates (right ascension, declination),
a, b, c, d – affine transformation parameters,
Tx, *Ty* – translation parameters.

TIME SYNCHRONIZATION

To register the epoch of image exposure a portable computer is used that is synchronized with 1PPS signal from the GPS receiver. The PC clock is synchronized by the Tac32 software in 1 minute interval with accuracy of millisecond, which is sufficient for the purposes of the project.

ERRORS AFFECTING THE ASTRONOMICAL COORDINATES DETERMINATION

The change of the inclination of the rotation axis under performed measurement is precisely registered with the electronic inclinometer. Laboratory tests show the good agreement between the inclinometer indications and the given model (equation 2). In case of field tests the agreement is considerably smaller. Moreover, jumps in the position of the point on the image are visible (Fig. 7). The jumps are caused by errors in star identification algorithm and time of exposure recording procedure.

EPOCH OF EXPOSURE

The CCD camera is equipped with an electronic shutter which is characterized with latency between triggering an exposure and capturing an exposure. The CCD camera controlling software based on the MaximDL environment makes possible to record

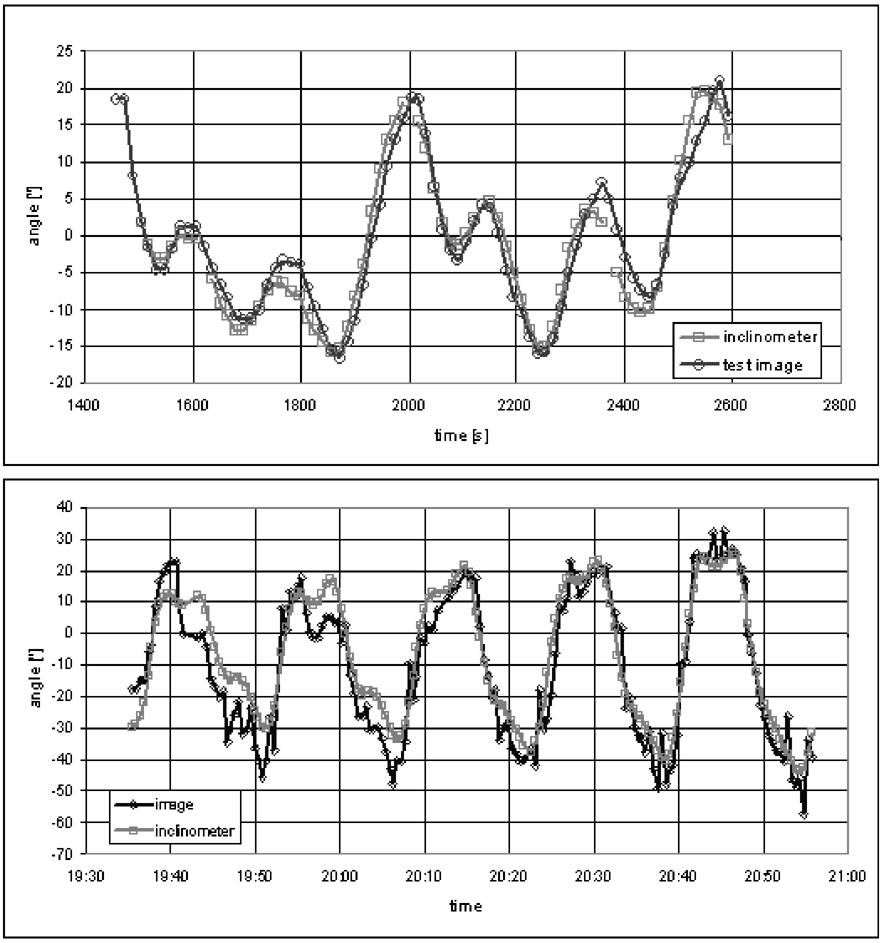

Fig. 7 Variation of the arbitrary chosen point position on the image compared to inclinometer reading on laboratory (top) and field (bottom) tests.

the epoch of triggering (*exp_beg*) and the end of the exposure (*exp_end*). Time difference:

$$exp\_end - exp\_beg = latt + exp\_time \quad (7)$$

is the sum of shutter latency (*latt*) and exposure time (*exp_time*). In the measurements conducted, the *exp_end – exp_beg* values was not a constant and the difference between nearby values was exactly 1/64 sec within the range from 151/64 sec to 158/64 sec. In some cases the difference gained the value 184/64 sec. In order to obtain accurate astronomical coordinates this error must be eliminated.

STARS IDENTIFICATION

Stars identification is performed with the Pin Point Astrometric Engine library. Since the exposure time is 1 second, the images of stars are trailed due to Earth rotation. This may cause problem with accurate star centroid determination, resulting in additional errors in stars coordinates determination. In this case, shorten the exposure time or change in the star identification algorithm should verify an error source.

FIRST RESULTS OF THE DEFLECTION OF THE VERTICAL COMPONENTS DETERMINATION

In progress of the project realization about 20 surveys for the astronomical coordinates determination has been performed. On the Figure 8 the astronomical coordinates of the same point determined 8 times consecutively during one night are presented. Single observation last less then 20 minutes. Based on conducted observations, the repeatability of the astronomical latitude determination is of 2-3 arc second between individual values. In case of astronomical longitude the repeatability is much worse. The time registration procedure and shutter latency seems to be the dominant error sources. After their elimination the improvement of accuracy of astronomical coordinates is expected.

Fig. 9 shows the values of the deflection of the vertical components ξ, η calculated from equations (Hofmann-Wellenhof and Moritz, 2006):

$$\xi = \Phi - \varphi \quad (8)$$

$$\eta = (\Lambda - \lambda)\cos\varphi \quad (9)$$

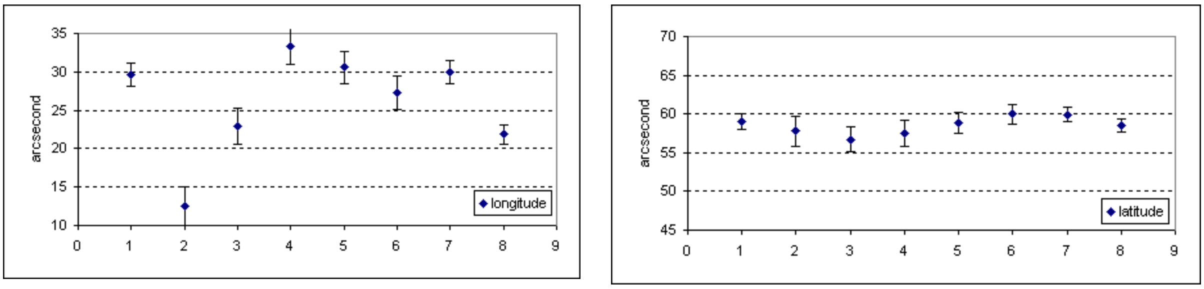

Fig. 8 Latitude and longitude determined during 2.5 hour survey.

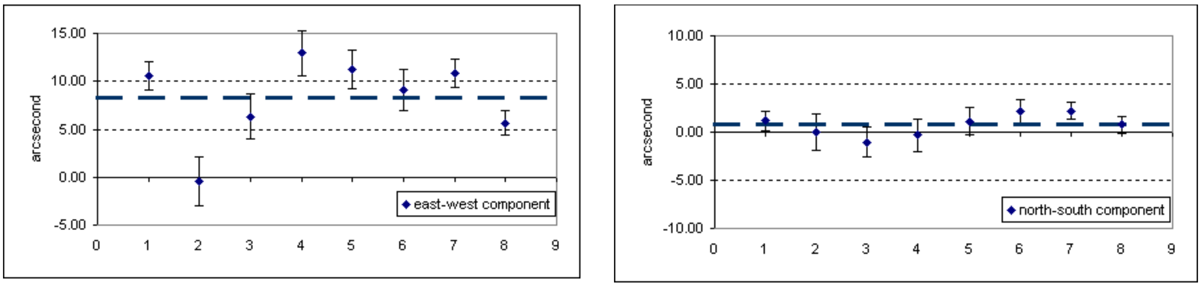

Fig. 9 Deflection of the vertical components determined during 2.5 hour survey.

where φ, λ - ellipsoidal coordinates obtained from GPS measurements, Φ, Λ - astronomical coordinates of the same point.

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