Digital Zenith Camera's Results and Its Use in DFHRS v.4.3 Software for Quasi-geoid Determination

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***Abstract*—The design of digital zenith camera was started in 2010 by Institute of Geodesy and Geoinformatics. Since then the prototype of digital zenith camera has been developed. Now, after improvements of design and manufacturing of the second version, it has reached operational status. This paper describes the construction of zenith camera and features of its control software. The results of vertical deflections' measurements are discussed. At the moment measurements are done in Riga region and are used in DFHRS software in order to check and improve local quasi-geoid model. It is a new method of quasi-geoid model determination and has not been used in Latvia before. DFHRS (Digital Finite-Element Height reference surface (HRS)) software has been developed by Karlsruhe University, Institute of Applied Research (IAF). It is based on parametric modeling of the HRS as a continuous polynomial surface, which allows direct conversion of GNSS-heights h into normal heights H.**

Keywords—astrophysics; geodesy; geophysics; geosciences; level measurement.

I. INTRODUCTION

The use of vertical deflections data in DFHRS software gives an opportunity to improve quasi-geoid model independently from GNSS/levelling data. It is possible to use both observations from digital zenith camera, and derivatives from global geopotential models (GGM) in this software. The aim of this research is to check observations from digital zenith camera, and compute quasi-geoid model for Riga region using DFHRS v. 4.3 software [11]. It is a new method of quasi-geoid model determination and has not been used in Latvia before. The project concerning 1 cm precision quasi-geoid model for eastern part of Latvia has been successfully fulfilled without using vertical deflection observations, but still there are places that have some discrepancies and should be checked and improved by digital zenith camera. This paper discusses the advantages of new implemented measurements and improvement of quasi-geoid model. Another advantage of vertical deflection measurements in comparison to gravity acceleration measurements, is that a smaller number of observations is required, (especially in mountain areas) and densification of region of interest can be done much easier. On the other hand, the instrument requires night work and favorable weather conditions.

II. VERTICAL DEFLECTIONS

Astronomical coordinates (Φ, Λ) define positions on earth surface and equatorial coordinates (δ, α) define positions of stars on the celestial sphere (Fig. 1).

Both coordinate systems are linked by Greenwich apparent sidereal time – GAST (the hour angle of the vernal equinox) regarding the Earth's rotation [5]. The astronomic latitude Φ and longitude Λ determine the direction of the tangent to the plumb line and is defined by digital zenith camera and the geodetic coordinates (φ, λ) define the direction of the ellipsoid normal using GNSS techniques [3], [8]. The principle of determination of vertical deflections - related to the vertical direction at the earth surface, namely in the ellipsoidal height h (see also (7a,b) - is depicted on Fig. 2.

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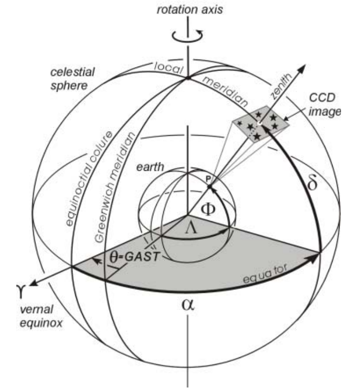

Fig. 1. Basic principle of the determination of the plumb line (*Φ*, *Λ*) by imaging the stars in zenith direction [5].

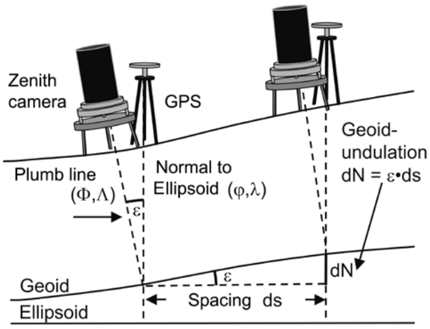

Fig. 2. The principle of determination of vertical deflections by digital zenith camera and GNSS techniques [7].

Deflection of the vertical is the angular difference between plumb line direction and normal to the surface and consists of north and east component (ξ, η) [1]. Deflections of the vertical can be calculated using astronomical coordinates (Φ, Λ) and geodetic (ellipsoidal) coordinates reading [12]:

$$\xi = \Phi - \varphi,\ \eta = (\Lambda - \lambda)\cos\varphi \tag{1}$$

The component ε in the azimuth α can be computed using ξ and η components**:**

$$\varepsilon = \xi\, cos\alpha + \eta \sin\alpha \tag{2}$$

Equations (1) and (2) are valid for all definitions of the deflection of the vertical.

The differential relationship between geoid height and deflection of the vertical is defined through the following formulae [4], [13]:

$$-dN = \varepsilon.ds \text{ or } \varepsilon = -\,dN/ds \tag{3}$$

By combining formulae (2) and (3) we obtain:

$$-\,dN/ds = \xi\, cos\alpha + \eta \sin\alpha \text{ or} \tag{4}$$

$$-\Delta N/\Delta s \approx \xi\, cos\alpha + \eta \sin\alpha \tag{5}$$

In case of the DFHRS-software 4.3 the height reference surface is modelled by mesh-wise (i= mesh index), but overall continuous polynomials $\mathbf{p}_i$. So we have [9]:

$$\begin{aligned} N_i &= [1 \,|\, B, L \,|\, B^2, BL, L^2 \,|\, B^3, B^2L, BL^2, L^3 \,|\, ..] \cdot \\ &\quad [p_{00} \,|\, p_{10}, p_{01} \,|\, p_{20}, p_{11}, p_{02} \,|\, p_{30}, p_{21}, p_{12}, p_{03} |..]_i^T = \mathbf{f}(B,L)^T \cdot \mathbf{p}_i \end{aligned} \tag{6}$$

In (6) the parameters (B, L) mean the ellipsoidal latitude and longitude at position P.

Considering that in case of computing a quasi-geoid (N_{QG}), we have to use surface vertical deflections instead of the Helmert type (Fig. 2). These are related - according to the Molodenski theory - to the so-called Telluroid point Q_j, which is in a height $h_{Q,j} = h_{P,j} - N_{OG,j}$ below the surface point P_j. For the j-th couple of vertical deflections measured in the i-th mesh, we arrive at the the following observation equations:

$$\xi_{j,i} = -\frac{\partial N_{QG}}{\partial B_j} \cdot \frac{\partial B_j}{\partial s_N} = -\frac{\partial B_j}{\partial s} \cdot \frac{\partial N_{QG}}{\partial B_j} = \frac{-1}{(M_j + h_j)} \cdot \mathbf{f}_{B_j}^T \cdot \mathbf{p}_i \tag{7a}$$

$$\eta_{i,j} = -\frac{\partial L_j}{\partial s} \cdot \frac{\partial N_{QG}}{\partial L_j} = \frac{-1}{(N_j + h_j) \cdot \cos B_j} \cdot \mathbf{f}_{L_j}^T \cdot \mathbf{p}_i \tag{7b}$$

M and N mean the radius of the curvature of the ellipsoid to the direction of the meridian and the prime vertical, respectively. In the latest DFRHS version 5x, the parametric representation of the height reference surface related to the regional gravity potential W. W is modelled by adjusted spherical cap harmonic parameters with coefficients $(C_{n(k),m}, S_{n(k),m})$ of degree and order (k, m) [2]. In that case, the DFHRS software 5.0 can also parametrize gravity measurements [9], [14]. With the disturbance potential T=W-U (U=reference potential (GRS80)) and according to the theorem of Bruns and the Quasi-Geoid theory of Molodenksi [10] we have for the deflections from the vertical the following observation equations:

$$\xi_j = -\frac{-1}{\gamma_{Q_j} \cdot (M_j + h_j)} \cdot \left(\frac{\partial T(C_{n(k),m}, S_{n(k),m})}{\partial B_j}\right)_{P_j} \tag{8a}$$

$$\eta_j = \frac{-1}{\gamma_{Q_j} \cdot (N_j + h_j) \cdot \cos B_j} \cdot \left(\frac{\partial T}{\partial L_j}\right)_{P_j} \tag{8b}$$

Following a Quasi-Geoid computation, where the measured vertical deflections at the earth surface can be used without reductions, and surface gravity values only have to be rotated by approximate vertical deflections - e.g. using EGM2008 - to the sphere. A computed Quasi-Geoid can always be transformed point or grid-point wise, respectively, by

$$N_G = N_{QG} + \frac{\bar{g}-\bar{\gamma}}{\bar{\gamma}} \cdot H \qquad (9)$$

to a geoid N_G model.

III. Construction of Digital Zenith Camera

The design of digital zenith camera was started in 2010 by Institute of Geodesy and Geoinformatics. Zenith camera consists of a rotating assembly, placed on a roughly (a few arc minutes) leveled platform (see fig. 3). Any rotation position can be used. Camera assembly is leveled with a few arc second accuracy in each rotation position using 3 linear actuators. After that a number of zenith area star images are obtained together with high resolution tiltmeter readings. An on-board GNSS receiver is used to obtain geocentric site coordinates and support accurate image timing. Hardware control and data acquisition is done by an on-board control computer. An observation session typically lasts 20-40 minutes. The accuracy of obtained vertical deflection value is usually in the range of 0.1-0.2 arc seconds.

Fig. 3. Digital Zenith camera.

IV. Control Software for Vertical Deflection Determination

The data and control processing software is designed as a single program under Windows system. It can be run either in measurement or post-processing mode. Difference between modes is mainly in data acquisition hardware treatment. On-board control process is monitored and controlled by remote terminal via “RemoteDesktop” connection.

Though data processing and vertical deflection determination can be done in real time, this kind of mode is considered to be time-consuming and not practical. Generally, measurement data are saved in file system and processed later using post-processing mode. Exceptions are some critical data quality indicators, such as tiltmeter data dispersion and quality of star images on CCD image, which always are calculated in real time. A number of control parameters, involved in measurement process, are stored in software configuration file and can be adjusted by operator [15].

V. DFHRS v.4.3 Software

DFHRS (Digital Finite element Height reference surface (HRS)) v4.3. software has been developed by Karlsruhe University, Institute of Applied Research. It is based on parametric modeling of the HRS as a continuous polynomial surface. The access to the parametric HRS model is enabled by DFHRS_DB data-bases and access-software, which allow direct conversion of GNSS-heights h into physical normal heights H. DFHBF_DB stores polynomial parameters p. The principle of a GNSS-based height determination H requires submitting the GNSS-height h to the DFHRS(B,L,h)-correction N, reading [16]:

$$H=h-N=h-DFHRS(p|B,L,h)=h-NFEM(p|B,L,h) \qquad (10)$$

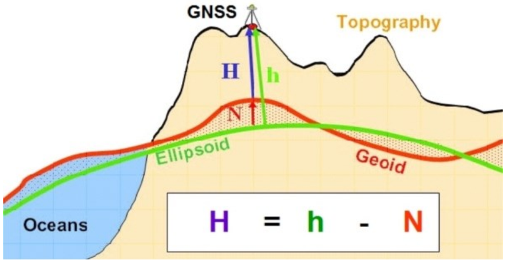

Fig. 4. The principle of GNSS-based height determination [16].

The region of interest is devided into finite elements, or so called meshes and *p* polynomials are computed. These *p* parameters are stored in DFHRS_DB database in order to get an access to parametric HRS model. In order to reduce an effect of medium-wave or long-wave length, DFHRS concept allows to subdevide region of interest into patches or so called “geoid-patches”. Each patch has a datum and associated transformation parameters *d.* Continuity conditions should also be considered, boundaries between two meshes should be the same, so that meshes represent the whole continuous area [14]. DFHRS v4.3 includes all types of geometrical input data: both ellipsoidal and normal/orthometric heights, geoid/quasi-geoid heights, vertical deflections, derived from Earth Gravitational Model (EGM2008) or grids, and observed vertical deflection measurements from digital zenith camera, as well as gravity data derived e.g. from EGM2008 [17].

VI. THE RESULTS

The residuals of standard deviations are depicted in Table I. As it is seen from the Table I the difference of the solutions is equal to 0.0001 m if we compare the results computed using EGM2008 model and EIGEN6C4 model. It can be explained by the fact that the same terrestrial data for these models were used in the territory of Latvia. The use of vertical deflection observations from digital zenith camera improves standard deviation twice. This shows favorable tendency for quasi-geoid improvement and also sustainability of digital zenith camera.

TABLE I. DIFFERENT SOLUTIONS FOR RIGA REGION QUASI-GEOID

Used data	**Standard deviation (m)**
EGM2008 model + observations from digital zenith camera	0.0050
EGM2008 model	0.0109
EIGEN6C4 model	0.0110
EGM2008 model with derived vertical deflections	0.0127

The residuals of some vertical deflections measurements are depicted in Table II.

TABLE II. THE OBSERVATIONS AND RESIDUALS OF VERTICAL DEFLECTIONS FROM DFHRS V 4.3. SOFTWARE

Point number	$\xi('')$	$\varepsilon(\xi'')$
	$\eta('')$	$\varepsilon(\eta'')$
Riga	1.40	-0.060
	5.60	-0.086
Daug	-0.45	0.075
	6.30	0.226
Iks1	-1.40	-0.100
	5.00	-0.014
Iks2	-1.15	0.029
	5.15	-0.009
Luni	1.80	0.162
	6.30	-0.311
Kang	-0.40	-0.016
	6.72	0.059
Ceku	-1.72	-0.094
	6.55	0.108
Salp	-1.18	-0.087
	5.88	0.011
Vaiv	2.90	0.042
	8.20	-0.022
Zalv	1.55	0.053
	6.20	-0.059

The mean standard deviation after estimation is found to be about 0.11".

VII. CONCLUSIONS

The observations from digital zenith camera will be continued in order to cover whole territory of Latvia and all "suspicious" places will be checked. At the moment, these places are the North of Latvia and Kegums territory, as GNSS/levelling points have high residuals in these places and need to be checked by zenith camera in order to find the reason of discrepancies: Either the normal heights are incorrect or derivatives of gravity acceleration from GGM models have some errors. Further research will concern western region of Latvia in order to compute quasi-geoid model for the whole country. It is known that GNSS/levelling points in western part are not so well condensed and the use of digital zenith camera would allow to use vertical deflections in these places what would compensate the lack of fitting points. It is planned to make about 200 observations by digital zenith camera to be used in Latvia.

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