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Digital astro-geodetic camera system for the measurement of the deflections of the vertical: tests and results

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ABSTRACT

This study introduces the new results of a novel low-cost digital zenith camera system operated in Turkey that uses astronomical and geodetic instrumentation. Currently, it is possible to determine deflections of the vertical (DoV) components by using a vast amount of information gathered from geo-referenced star images, tilt measurements, and Global Navigation Satellite System technology. This new design of an astro-geodetic camera system is used for calculating DoV components with 12 independent solutions on a test station in Istanbul, and additional observations were performed to investigate the external accuracy of the system on a test network. A specific leveling method is developed to align system toward the zenithal direction. The final results of the observations on a test station located in Istanbul indicate that the accuracy of the system is about ±0.19 arc-seconds in latitude and ±0.28 arc-seconds in longitude determination. The system has been further tested on a network with 4 control points that have averagely 20 km baselines. At the test network, the root mean square of the average value of the vertical deflections is calculated as ±0.36 arc-seconds. Furthermore, DoV components are compared with the values that are calculated using global geopotential models.

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KEYWORDS
Geodetic astronomy; geoid; digital zenith camera system

1. Introduction

Geoid as a reference surface for the global height system can be considered as a fundamental research area, because it forms a natural link between physical and mathematical quantities. Geodesy uses several observational and theoretical methods in order to define local, national, and global interpretation of the geoid such as gravimetric, combination of GNSS (Global Navigation Satellite System) measurements and sprit leveling technique (GNSS/Lev), global geopotential models, and geodetic astronomy. Besides, astronomic and geodetic coordinates can be used to derive the deflection of the vertical components from the astro-geodetic technique that provides an independent observational approach for the direction of the plumb line. Deflections of the vertical (DoV) can be defined as the angle between ellipsoidal normal and the direction of Earth's gravity vector. Geodetic astronomy determines local and regional definitions of Earth's gravity field by providing DoV components as measurements. In this context, a rapid and efficient technique for geodetic astronomy applications becomes a scientific challenge for earth observations.

The invention of CCD (Charged Coupled Devices) sensors and the widespread usage of GNSS lead major developments in both astronomical and geodetic applications. Therewith, traditional optical–mechanical instruments have been redesigned and updated with CCD sensors, GNSS

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receivers, and precise tiltmeters. As a result, digital zenith camera systems (DZCS) were designed during the beginning of 2000s (Burki, Muller, and Kahle 2003; Gerstbach and Pichler 2003; Hirt 2004; Kudrys 2007, 2009; Ogrizovic 2009; Abele et al. 2012; Tian et al. 2014), and in this way the determination of astro-geodetic deflection of the vertical components has become more efficient. Each of these systems provide unique design in terms of hardware components and automation software.

Leaning on this background, this paper introduces the first DZCS in Turkey, which is designed and tested within the scope of a research project conducted by Istanbul Technical University and Bogazici University in Turkey (Halicioglu 2015). This study provides techniques and tools for geodetic astronomy as the first study to conduct in Turkey. The system designed and tested in this study differs from the previously published systems in terms of the hardware used, and the way the components were integrated as well as the observation method. It is also a unique study that integrated, commonly used, astronomical and geodetic instrumentation with specially designed mechanical connectors. The components used in this system are widely used astronomic and geodetic hardware. Thus, collective experience and knowledge are available worldwide for the components used in this system. Furthermore, this study also aims to define a standard procedure for astro-geodetic measurements in order to use the instrumental infrastructure of the various scientific fields such as astronomy and geodesy. The hardware (telescope, tiltmeter, and GNSS receivers) used in this study are mainly available in laboratories of astronomy, geodesy, and geoscience departments. Thus, it can be possible to construct a new DZCS by using the design offered in this study as it provides a standard procedure in terms of using available instrumentation.

The software specially designed and developed in this study coordinates the instruments to achieve astro-geodetic observables and determine DoV components. This paper also introduces the final design and the new results achieved on a test station and a test network. The new results on the test station shows the internal accuracy of the system, whereas the test observations on the network investigate the external accuracy of the observations. System-derived DoV components were compared with global geopotential models. This study also includes the comparison of geoid heights and geoid height differences with the ones that were calculated using GNSS/Lev geoid.

2. Observation principle and data processing

Astronomical coordinates (Φ, Λ) define the direction of plumb line that is calculated by equatorial coordinates of stars (α, δ) given in star catalogs. For a star exactly located at zenith, astronomical and equatorial coordinates of a station point can be linked with Greenwich Apparent Sidereal Time (θ) using the following equation:

$$\Phi = \delta, \quad \Lambda = \alpha - \theta. \tag{1}$$

The observation method requires collection of the images near zenith via a DZCS, and to interpolate the zenithal direction using time-dependent position information of reference stars (Figure 1). The positions for reference stars captured on each image should be transformed into apparent positions, in order to extract epoch-dependent information of observations. These transformations require precise catalog information as well as accurate earth orientation parameters, precession, and nutation models. In order to derive apparent star positions, IAU2006-P03 precession model (Capitaine, Wallace, and Chapront 2003) and IAU2000A nutation models (Mathews, Herring, and Buffett 2002) are implemented to the calculations.

The stars on the zenithal star field have to be identified using information in appropriate star catalogs such as USNO CCD Astrograph Catalogs (UCAC). The star identification approach was processed implementing astrometry software to the ADAPS such as SExtractor (Bertin 2006), Pinpoint Astrometry Engine libraries of DC-3 dreams, and astrometry.net (Lang et al. 2010), in order to produce image-specific files for further calculations. Image identification process follows astrometric

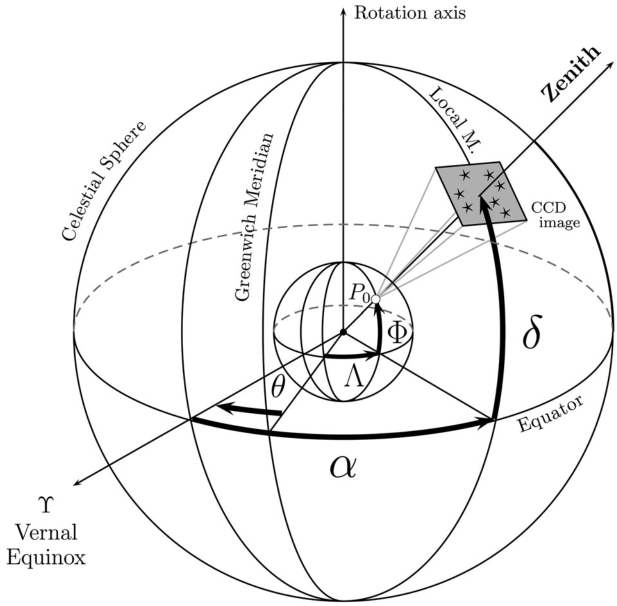

Figure 1. Zenithal star field and direction of the local plumb line (modified from Hirt et al. 2010).

plate reduction procedures (Smart 1977). It is not possible to link position information of the stars (x, y) directly to the image coordinate system with equatorial coordinates (α, δ) that are defined in celestial sphere. The tangential coordinates (ξ, η) of identified stars need to be calculated by projecting spherical coordinates onto a plane which is tangent at an approximate zenith direction $(\alpha, \delta)_0$ where q is an auxilary quantity (Equation (2)). Determination of tangential coordinates was introduced in previous works (Hirt et al. 2010: Halicioglu, Deniz, and Ozener 2012a, 2012b):

$$\cot q = \cot \delta \cos(\alpha - \alpha_0)$$
$$\xi = \frac{\tan(\alpha - \alpha_0) \cos q}{\cos(q - \alpha_0)},$$
$$\eta = \tan(q - \delta_0).$$

The relation between tangential coordinates and image coordinates can be formed using projective transformation using Equation (3). Least square adjustment is used, in case of having more than four common stars in both systems, which are adequate for estimating transformation parameters:

$$\xi = \frac{ax + by + c}{kx + ly + 1},$$
$$\eta = \frac{dx + ey + f}{kx + ly + 1}.$$

Possible stars are detected using centroiding algorithms (i.e. point spread function) and identified using star catalogs such as UCAC2 (The Second U.S. Naval Observatory CCD Astrograph Catalog) (Zacharias et al. 2004). Star catalogs contain position information for stars including equatorial coordinates, proper motions, position errors, and magnitude for each star in a reference epoch (J2000.0). The software package (ADAPS – Astro-geodetic DAta Processing Software) developed in this study

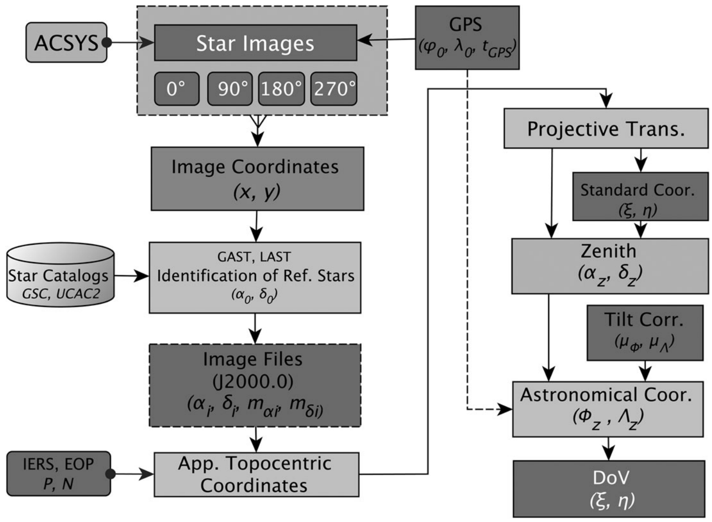

Figure 2. Data processing steps of ACSYS.

creates image files that contain the catalog information of identified stars for each captured image. Figure 2 shows the simplified steps of the data processing.

First, star images need to be time/geo-tagged using GPS signal, thereafter the tangential coordinates are related to image coordinates through the projective transformation (Ogrizovic 2009). The image files are used as input to the Naval Observatory Vector Astrometry Software (NOVAS) package (Bangert et al. 2011) that is integrated in ADAPS, in order to calculate apparent places of imaged stars at the observation epoch. Using the standard coordinates for each image star, the coordinates of the approximate zenith point are calculated. Astronomical coordinates of zenith point are derived using Equations (4) and (5) after the tilt corrections are applied for four different instrumental directions. The coordinates of direction of projection center can be calculated using the inverted formula (Gessler 1975):

$$\alpha_z = \alpha_0 + \arctan\frac{\xi_z}{\cos\delta_0 - \eta_z \sin\delta_0} \tag{4}$$

$$\delta_z = \arctan\frac{(\eta_z) + \tan\delta_0 \cos(\alpha_z - \alpha_0)}{1 - \eta_z \tan\delta_0} \tag{5}$$

The variables $(\alpha, \delta)_0$ represent the approximate coordinates of zenith point which is taken as tangent point, $(\alpha, \delta)_z$ shows the equatorial coordinates of reference stars, and $(\xi, \eta)_z$ are tangential coordinates in equation (4) and (5). The position of the zenith is interpolated through an iterative process. Finally, DOV components (ξ, η) are calculated using astronomical coordinates (Φ, Λ), and ellipsoidal coordinates (ϕ, λ):

$$\xi = \Phi - \phi, \qquad \eta = (\Lambda - \lambda)\cos\varphi. \tag{6}$$

3. DZCS of Turkey

In the scope of this study, a transportable fully automated instrument, the Astro-geodetic Camera SYStem (ACSYS) is designed and tested. Several test observations with different hardware combinations were performed in 2014 in Istanbul. In order to achieve this design, we have tested various

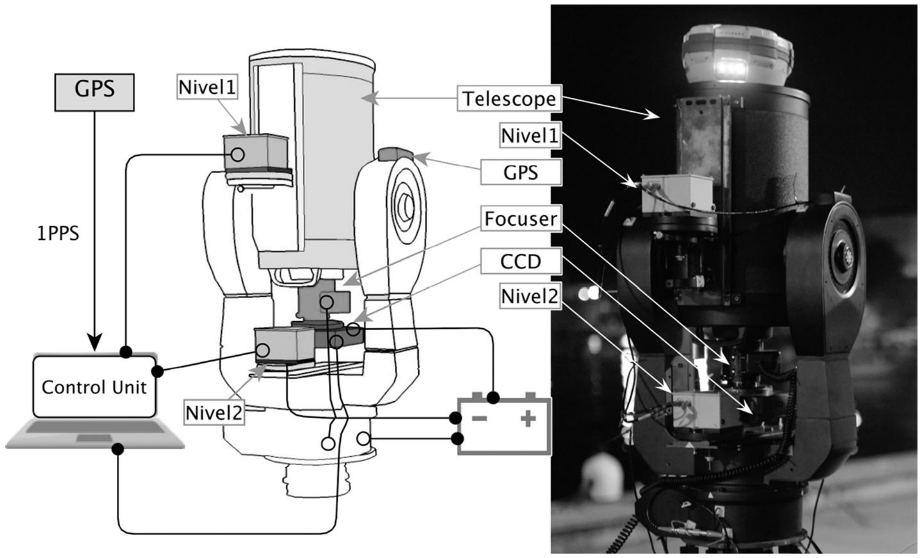

Figure 3. DZCS of Turkey.

hardware and observation methods that were defined at Halicioglu, Deniz, and Ozener (2012a, 2012b).

The final design of the system is operated with 8″ apertured Schmidt–Cassegrain type telescope, digital inclinometers, CCD camera, and GPS receivers (Figure 3). The optical component of the system has a focal length of 2000 mm with a focal ratio of f/10 (Table 1). The CCD has a peak quantum efficiency of 86% at 610 nm of visible light spectrum. Therefore through using CCD/telescope combination, it is possible to acquire a sufficient number of stars on zenithal images, which is averagely 100–150 for each image at short exposure intervals (0.4–0.5 s).

The system is operated on a control unit and the whole observation process is automated. The test observations were performed at the zenith camera observatory, which is specially designed for this system in Kandilli Observatory and Earthquake Research Institute in Istanbul. ACSYS is capable of capturing a frame on celestial sphere with the dimensions of $17.2' \times 25.5'$, which corresponds to the field of view (FoV) of$0.12\,\mathrm{deg}^2$.

4. Test observations and results

Conventional astronomical observations define two different faces of the instrument as a single observation series. In this study, observations were performed in 4 different positions of instrument with 5–10 (on some observation nights 20–40 images) single observations, which is defined as one series. The leveling accuracy of system is generally below 0.1 arc-second for each instrumental direction. An iterative process is developed and performed in this study in order to align the

Table 1. Specifications of ACSYS.

Component	Specification
Telescope	Meade LX200 GPS (8″, f/10)
CCD camera and sensor	Apogee 32 and Kodak KAF3200ME
Pixel size	$6.8\mu m \times 6.8\mu m$
FoV	$25.5' \times 17.2'$ ($0.12\,\mathrm{deg}^2$)
Tilt sensors	Leica Nivel 210
GPS	Trimble 5700 and CNS Clock II

ACSYStoward the zenith, which is defined as *iterative leveling*. During the iterative leveling process, the system is steered toward four azimuthal directions of 0°, 90°, 180°, and 270° and the tilt values are observed. The trace of the main axis of the system is recorded by tiltmeters, and needs to have a radial symmetric behavior around the zenith if the axis conditions between optical and tilt systems are formed. The radius of the best fitting circle in least squares manner is calculated using tilt coordinates for four azimuthal directions. Afterwards, the ACSYS is re-aligned toward the zenith direction using the radius of the tilt circle by the help of the adjustable substructure of the tiltmeters and the system separately. The whole procedure is repeated until the correction value can be considered negligible, which corresponds to an approximate radius value of 10 arc seconds, and is generally fulfilled in 3–4 iterations. Generally, the tiltmeters are fixed to the substructure (Burki, Muller, and Kahle 2003; Hirt 2004; Kudrys 2007, 2009) or to the optical system (Abele et al. 2012; Tian et al. 2014) in other DZCS designs, whereas in this study we used tiltmeters on substructure and optical systems separately in order to control the leveling procedure and satisfy the axis conditions. Moreover, this design uses adjustable tiltmeter substructures, which make possible to work in high-precision range of tilt sensors that yields us more accurate tilt reading.

The aim of iterative leveling is to minimize the radius of the best fitting tilt circle, which is below 10 arc seconds. Figure 4 shows the tilt values of 12 instrumental directions with 30° angular separation in the unit of milliradians. During the test observations, CCD and telescope calibrations, shutter latency measurements, suitable epoch determination, and image quality test were also performed. Shutter latency effect was measured using MaxIM DL shutter latency test measurements and the result was calculated as average delay of 0.02 s, which was set as the observation time to the image header information. Figure 5 shows the total number of images and stars processed during this study including calibration and test observations. The test observations showed that on a suitable meteorological observational night, it is possible to calculate coordinates of zenithal points up to 16 K stars.

DoV components derived from 12 independent series of observations are calculated with an internal accuracy of ±0.2–0.3 arc-seconds. DoV components that were derived using ACSYS are compared with the DoV components that were calculated using global geopotential models such as EGM08 (Pavlis et al. 2012) and GGMplus (Hirt et al. 2013). Table 2 shows the calculated and observed deflection of the vertical values in the unit of seconds at the observation site Kandilli (KNDL).

EGM08 global geopotential model is complete to spherical harmonic degree and order 2159, and contains additional coefficients extending to degree 2190 and order 2159. GGMplus is constructed as a composite gravity field model that is based on GRACE and GOCE information that is detailed in Hirt et al. (2013). GGMPlus provides North–South (ξ) and East–West (η) components of deflection of the vertical in Helmert's definition using latitude and longitude derivatives of disturbing potential, respectively. The accuracy of GGMplus is about 3–5 arc-seconds over regions that have limited ground gravity data availability such as Asia, Africa, and South America. The accuracy over well-surveyed areas of North America, Europe, and Australia, reaches to the level of 1 arc second for DoV components.

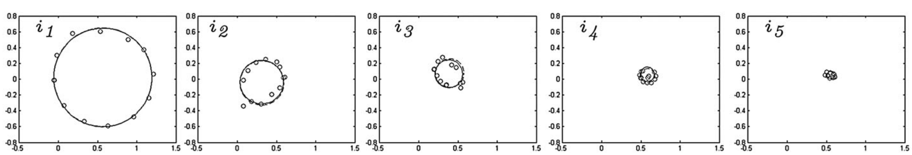

Figure 4. The iterative leveling procedure developed in this study. Small circles show the data collected for each azimuthal direction of the system which is 30°, and the best fitting circle is calculated in least squares sense shown in larger circles. The iteration numbers are given as i_i, and units are in milliradians where the accuracy of the tiltmeters is 10^{-3} milliradians that corresponds to 0.2 arc seconds.

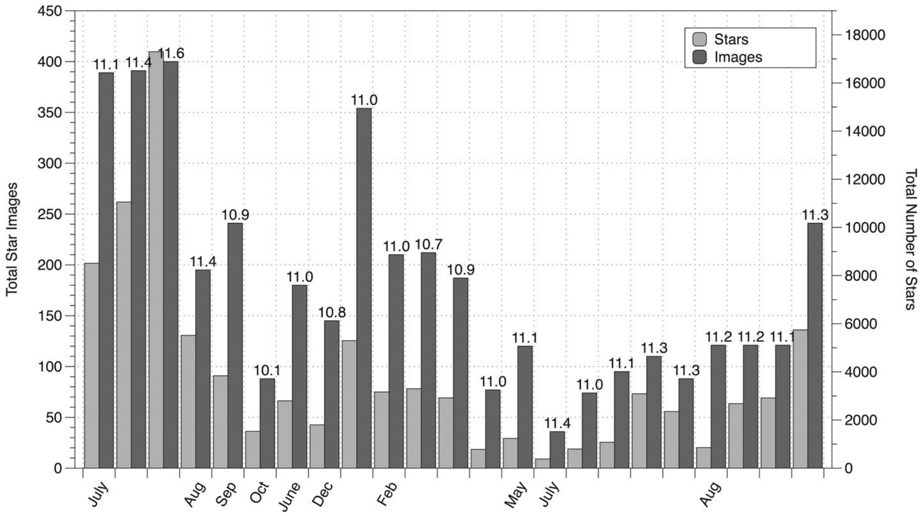

Figure 5. Total number of images and stars processed.

The results that were calculated using ACSYS observations are in a good agreement with those that were calculated using global geopotential models (Table 2). Test observation results reveal the internal accuracy of the system. The external accuracy of ACSYS should be investigated using a network approach, and by comparing the observed and modeled geoid height differences. Using GPS/Lev and EGM08 data, which is available for a test area, can be used for this comparison. GPS/Lev geoid was modeled by Ayan (2006), and geoid heights were calculated with an accuracy of ±3.5 cm for Istanbul. Istanbul geoid is a local geoid model and referenced to the national height datum, thus it includes the distortions of national height system. Due to this fact, comparing geoid height differences is more reliable and correct than comparing geoid heights. The geoid height differences that are calculated using surface DOV components, and geoid height differences calculated using geometric leveling and GPS observations can be compared without any theoretical discrepancy.

The test network is located at the eastern (Anatolian) part of Istanbul, which has an average of 20 km baselines with 4 points including the test station (Figure 6). The results at the test network indicate that the root mean square of the average value of the North–South and East–West components of the vertical deflections is calculated as 0.35″ and 0.37″, respectively.

The geoid height differences between control points of the test network were calculated using the astronomical leveling procedure (Torge and Müller 2012). The GPS/Lev and ACSYS derived heights of the test network are also compared in this study. The analysis of the height differences of the stations calculated using different weighting approaches ($1/S$ and $1/S^2$, where S is the distance between control points), the root mean square of determining the geoid undulations for 1 km length

Table 2. Comparison of DOV components derived using ACSYS and global geopotential models averaged for three different epochs.

	ACSYS		ACSYS-EGM08		ACSYS-GGMPlus	
Method	ξ''	η''	$\delta\xi''$	$\delta\eta''$	$\delta\xi''$	$\delta\eta''$
1	1.49	2.41	0.36	0.64	−0.36	0.80
2	1.10	2.47	−0.03	0.70	−0.75	0.86
3	1.28	2.99	0.15	1.22	−0.57	1.38
Ave	1.29	2.62	0.16	0.85	−0.56	1.01
EGM08	1.13	1.77				
GGMPlus	1.85	1.61				

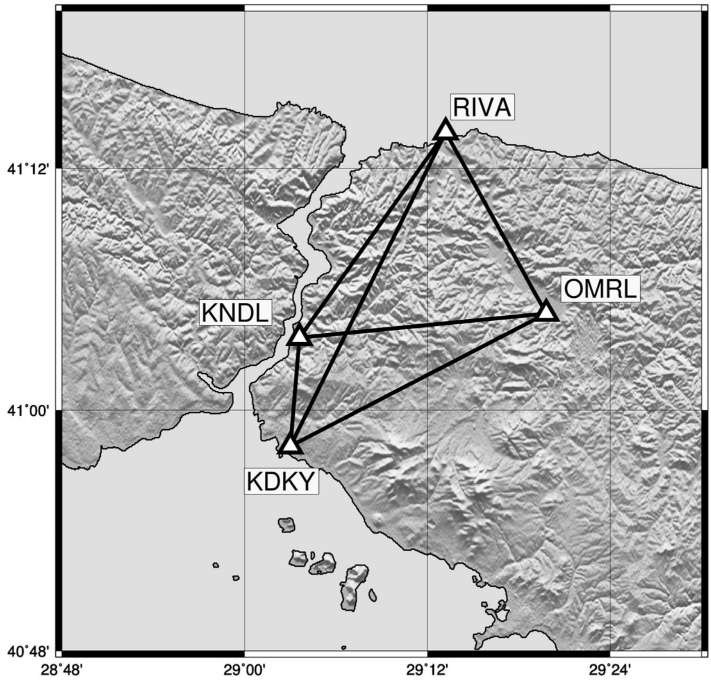

Figure 6. Test network.

Table 3. The geoid height differences calculated using DoV and comparison with GPS/Lev.

St_i	St_j	DoV (m)	GPS/Lev (m)	GPS/Lev-DoV comparison (m)
KNDL	RIVA	−0.810	−0.921	−0.111
KNDL	OMRL	−0.344	−0.484	−0.140
KNDL	KDKY	−1.106	−0.108	−0.002
RIVA	OMRL	0.549	0.437	−0.112
KDKY	OMRL	−0.381	−0.376	+0.005
KDKY	RIVA	−0.685	−0.813	−0.128

is calculated as ±14.7 mm/km for $P_{\Delta N} = 1/S\,\text{km}$ and ±2.9 mm/km for $P_{\Delta N} = 1/S^2\,\text{km}$. The geoid height differences were calculated at the test network through using least squares adjustment, depending on the geoid height of the Kandilli station, and the root mean square of the sample of system observations with $P_{\Delta N} = 1/S\,\text{km}$ is ±17.6 mm/km and with $P_{\Delta N} = 1/S^2\,\text{km}$ is ±3.6 mm/km. Table 3 shows the comparison of geoid height differences calculated in this study with the ones derived from GPS/Lev geoid published by Ayan (2006).

5. Conclusions

Determining astro-geodetic DOV using DZCSs has some advantages and disadvantages over the other conventional methods defined above. The astro-geodetic technique is rapid, and the digital data captured is easy to handle. In order to determine a cm-geoid using the astro-geodetic method, fewer reference points (5–10 points/1000 km^2) are needed with respect to the gravimetric technique (Gerstbach 1996). A DZCS can also be used to monitor atmospheric refraction (Hirt 2006). It does not have any boundary effects, nor does it require data outside the working area. Moreover, the DoV components are less influenced by subsurface density variations than gravity anomalies. On the other hand, temperature deviations, humidity, wind, precipitation, and cloud coverage directly reverberate the observations and prevent from acquiring solutions. Thus, the astro-geodetic method requires clear sky view, and suitable meteorological conditions.

In this study, a transportable system is produced by mechanically integrating a CCD/telescope system, tilt sensors, and a GPS receiver. Star images that are captured by a CCD camera and tilt values system are synchronized with GPS time to calculate latitude and longitude of the station point. A new approach is presented in order to align system toward the zenith direction called *iterative leveling*. Observation and calculation processes are fully automated. The precision of processing star images is about ±0.1–0.2 arc-seconds. Leveling precision of the system is reached to ±0.4 arc-seconds and the system is averagely leveled within a circle with 10 arc-seconds radius. The precision of latitude determination is ±0.19 arc-seconds and longitude determination is ±0.28 arc-seconds at the test station located in Istanbul, Turkey. The root mean square of the average value calculated at test network is 0.35″ for north–south component and 0.37″ for east–west component of vertical deflection. The results achieved on the test network show that the system is capable of determining geoid undulations better than ±3 mm/km. The results obtained in this study indicate that zenith camera observations can be used to improve reliability of GPS/Lev geoid and to eliminate the systematic errors in leveling networks. The system designed and tested in this study can also be used for the modernization of the national height system of Turkey.

Advances in sensor technology provide more precise observation and monitoring equipment. Therefore, an optimization should be designed to combine the best possible hardware to increase the accuracy of the results. Studies on modern astro-geodetic technique indicate that the observation strategy is built on operator-independent systems especially in digital zenith camera observations. Using robotic/gyro substructures, the exposure times of captured images can be longer, which yields capturing more stars on zenithal star field. The improvements planned on the system include the substructure of the system, temperature compensated focusing, robotic leveling, real-time processing, the updating of the control-processing, and adaptation to latest versions of star catalogs.

The inferences from this study's results regarding the effects of optical and mechanical components of the system should be improved in terms of shortening the observation time and increasing the precision. Recently, the outcomes of this study are used to define more precise local gravity field determination in Istanbul, which yields tests on a larger network and includes instrumental updates. Thus, the improvement of the system is still an ongoing process.

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Disclosure statement

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