The Digital Zenith Camera - A New High-Precision and Economic Astrogeodetic Observation System for Real-Time Measurement of Deflections of the Vertical

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Abstract. During the last few years, new developments in the field of geodetic astronomy have been sparsely published. This might be due to the fact that the determination of deflections of the vertical still required relatively large efforts, both in time and in manpower, thus keeping the costs per point at a high level. Recently, the development of new high performance image sensors (CCD) at a reasonable price level enabled and initiated fundamental improvements in astrogeodetic observation instrumentations in terms of efficiency, automation, accuracy, and real-time capability. This promising development leads to a revitalization of astrogeodetic methods and offers very encouraging prospects for local high-precision astrogeodetic gravity field and geoid determinations.

In this paper, two slightly different versions of the digital zenith camera, initially developed at the Institut für Erdmessung, University of Hannover, are presented as high-precision state-of-the-art instruments. Using modern CCD technology for imaging stars and a GPS receiver, these systems allow the direct determination of the direction of the plumb line and thus its deflection from the ellipsoidal normal within a fully automated procedure in real-time. In addition to a description of the system's design and performance, the processing steps are presented: image data acquisition, data transfer and processing giving deflections of the vertical immediately after measurement.

Keywords. Digital zenith camera, CCD, plumb line, deflection of the vertical, astrogeodetic geoid determination

1   Introduction

The impact of astrogeodetic methods has experienced a steadily decreasing importance in modern geodesy during the last two decades. This is caused by several circumstances. A first reason is related to the intensive growth of geodetic space techniques such as VLBI, SLR, and GPS taking over most of the tasks traditionally covered by the geodetic astronomy. A second reason is based on the fact that the determination of deflections of the vertical by means of classical methods requires not only dedicated equipment, but also well trained and skilled observational personnel. The latter argument could be mitigated by applying impersonal photographical observing systems such as transportable zenith cameras developed at Universities in Europe (Gessler 1975; Wissel 1982; Chesi 1984; Wildermann 1988; Bürki 1989). These systems have been successfully applied in many geodetical and geophysical projects in countries all over Europe, North-, and South-America.

These instruments provided extremely valuable contributions to local gravity field and precise geoid determinations. However, astrogeodetic methods required a high input with regard to the manpower thus keeping the costs per point still at a relatively high level. These disadvantages might be the cause for the fact that most geoid determinations at a continental or global scale are mostly based on gravity, altimetry, and to some extent on GPS-levelling data. Nevertheless, it has been shown that deflections of the vertical are still indispensable for precise geoid determinations in mountainous areas such as the European Alps. They are also useful as a check on gravimetric geoid computations or can be implemented in combined solutions e.g. by least squares collocation. New geoid solutions based on astrogeodetic data have been carried out (e.g. Marti 1997) or are under preparation (Sünkel 1995; Erker et al. 1996). Deflections are also required to reduce survey data (Featherstone and Rüeger 2000).

Because of the development of large CCD image sensors which are able to replace the photographic films by digitally readable arrays, this situation has been improved dramatically in the late 1980's and early 1990's. The first CCD sensors have been applied primarily in the field of astronomy in general

and astrometry in particular (Mackay 1986; Schildknecht 1994; Ploner 1996). Presumably due to the fact that the prices of CCD sensors stayed at an extremely high level, the applications in geodetic astronomy remained quite rare. However, in the 1990's first applications in the field of geodetic astrometry and astro-geodesy were published (Ploner 1996; Bretterbauer 1997) thus triggering a new era in astro-geodetic levelling (Hirt 2000, 2001, 2002; Hirt and Seeber 2002).

The aim of this paper is to describe and introduce two systems which were developed initially at the Institut für Erdmessung (IfE) at the University of Hannover, Germany. The second instrument was purchased by the Geodesy and Geodynamics Laboratory (GGL) at the Swiss Federal Institute of Technology, ETH Zurich, Switzerland. Both systems have been utilized widely in several international projects aiming at the determination of the direction of the gravity vector and its deflection of the vertical. Some of the projects have been carried out in cooperation with teams and additional equipments from Austria and Italy (e.g. Bürki 1989). After some years of low activity, these instruments have been re-activated and modified from the analogue to the digital CCD technique. Hence they represent a modern tool for economic and cost-effective determination of deflections of the vertical.

2 Instrumental Design

The digital zenith camera system (Figure 1) consists of a lens which is directed to the zenith, a CCD-sensor used for imaging stars, a GPS-receiver for the determination of geodetic coordinates and timing purposes, plus a pair of electronic tiltmeters in order to get reference to the plumb line. The system is completed by a computer which is used both for device steering including data flow control, as well as for on-line data processing with powerful software.

Most of the mechanical and optical parts of the two systems are identical, however there are some differences: The levelling of the zenith camera TZK2-D used at IfE is operated by means of three manually handled levelling screws and two electronic tiltmeter. The change of orientation to the opposite position is done manually, whereas all activities concerning the steering of the CCD camera including the time keeping (determination of the epochs of the exposures) by means of suitable GPS equipment are automatically monitored by the computer. The motorization of the system similarly to the one realized by GGL is planned.

Figure 1. The transportable digital zenith camera TZK2-D

The system TZK 2000 as operated by GGL has been upgraded in the way that the control of the system consisting of levelling, azimuthal attitude control, focus compensation, and time-keeping by GPS is automatically monitored by the computer. In order to perform the required functions, a total of five motors were implemented in the system. They carry out the following tasks: three motors are mounted in vertical position above the levelling screws. With their help, the computer performs an automated levelling. The levelling procedure starts with a first readout of the two electronic levels indicating the angle between the optical axis of the camera and the vertical. Depending on these values the camera is then automatically aligned into the direction of the vertical by means of the three levelling motors. The achieved spatial attitude of the system after the levelling procedure corresponds to about 1 to 3 arcseconds with the true vertical. Furthermore, two motors are used in order to automate the focussing procedure before measurement as well as the azimuthal rotation between first and second camera position during observation. In addition to an improvement in efficiency, influences on the measuring system caused by the operator can be completely avoided.

2.1 Mechanics

The zenith camera's body is compounded of a fixed substructure being mounted on a tripod and a turnable superstructure consisting of lens, CCD-sensor and electronic levels (Figure 1). The superstructure is separated from the substructure by a special ball bearing that can be rotated by 180 degrees az-

imuthally in order to realize first and second camera position. Measurements in two opposite positions allow the impact of the eccentricity of the CCD and the zero offsets of the electronic levels to be eliminated.

2.2 Lens and CCD-sensor

A Mirotar lens by Zeiss is used as optical component with an aperture of 200 mm and a field of view of about 3.5 degrees. It achieves 1020 mm focal length by shortened architecture (similar to Maksutov-Cassegrain) and is characterized by its low distortion. As an integral part for imaging stars, a CCD-sensor is located in the focal plane and replaces the photographic plate used in the former versions of the zenith camera. The main improvement of using CCD technology is the instantaneous availability of image data enabling image data processing digitally and directly after data acquisition. Due to the enhanced light-sensitivity of CCD-sensors compared with photographic plates, stars up to a magnitude of 14.0 mag are imaged by the combination of lens and CCD, whereas the photographic version of the zenith camera only achieved stars up to 10.0 mag. The CCD-sensor is equipped with an electro-mechanical shutter controlling the exposure time (typically between 0.5 and 1.0 sec) by means of TTL pulses with a raising edge to +5V as trigger signals. These signals are steered by the computer. A two-stage Peltier cooling element is integrated in order to reduce dark current as essential error source of the CCD chip.

2.3 GPS Equipment

GPS is an ideal tool for timing purposes in many applications, in particular in geodetic astronomy. Thanks to the high accuracy of GPS time signals, the timing capability of GPS can be used in order to determine the epochs of the exposures. GPS system time is related to Universal Time Coordinated (UTC) via an offset (presently +13 sec). By taking the Earth Orientation Parameter dUT1 into account, the epochs of the exposures can be converted from UTC to UT1. This time scale is linked to Greenwich Mean Sidereal Time (GMST) and Greenwich Apparent Sidereal Time (GAST) which is required in geodetic astronomy.

To start an exposure of the CCD camera, a logical TTL pulse is sent to the electronic shutter of the CCD in order to trigger the integration time. The rising edge of the TTL pulse, which marks the beginning of the exposure, is routed via hardware link from the control unit of the CCD to the GPS-receiver. The shutter movements are stamped on the GPS time scale and transferred to the computer. By taking sys-

tematic time delays of the shutter into account, the implemented timing procedure provides an accuracy potential of approximately 1 millisecond. This accuracy is mainly restricted by the mechanical behaviour of the shutter.

In addition to time measurements, the dedicated GPS timing receivers are used for determining geodetic coordinates in differential mode, thus providing an accuracy of ellipsoidal longitude and latitude of less than 1 m corresponding to an error of $\sim$0.03 arc-seconds.

2.4 Tiltmeter

Preceding the exposure, a pair of high-resolution tiltmeters (HRTM) in orthogonal orientation are used to level the zenith camera. After the levelling process, usually minor deviations between the rotation axis of the zenith camera and the plumb line remain. They are measured and stored during the exposure in order to determine the camera's orientation with respect to the plumb line. The analogue voltage signals provided by the HRTM are digitized with a scan frequency of 100 Hz using a data acquisition card. In order to refer inclination measurements to exposure intervals, the TTL provided by the CCD control unit is sampled synchronously.

System	TZK2-D	TZK 2000
Developer	IfE, Hannover	GGL, Zurich
CCD	KX2E, Apogee	Chroma C^3, DTA
Sensor	KAF 1602E, Kodak	KAF 6303E, Kodak
Array size	1530x1020 px.	3088x2056 px.
Pixel size	9 μm x 9 μm	
Pixel scale	1.85 arcsecs/Pixel	
Field of view	47.2x31.5 min	95.2x61.2 min
Exposure time	0.5 - 1.0 sec	
Read-out time	3 sec	4 sec
GPS	Z12, Ashtech	Modell 521, Novatel
Tiltmeter	HRTM, Lippmann	
Accuracy	< 0.05 arcsec	

Table 1. Specifications of sensors used in the digital zenith camera systems TZK2-D and TZK 2000

3 Data Acquisition

After levelling and focussing the digital zenith camera, a fully automatic computer-controlled data acquisition procedure is executed.

The procedure begins by opening the CCD's electronic shutter in order to image the zenithal star field. Simultaneously, the epochs of the exposures are measured using the GPS receiver, as described. The tilt signals provided by the two tiltmeters as well as the TTL pulse for the synchronization are sampled using the data acquisition card. After transferring image data from the CCD and time information from the GPS receiver to the computer, the superstructure of the zenith camera is rotated azimuthally by 180 degrees into the second position, either manually or automatically. The data acquisition procedure is repeated and ends by determining geodetic coordinates with GPS. One complete measurement for each camera position lasts approximately 10 seconds.

4 Processing

In this section, the basics steps of automatic astronomical positioning are briefly explained. Further information on processing digital zenith camera measurements can be found in (Hirt 2001; Hirt and Seeber 2002).

4.1 Basic Principle

Astronomical coordinates (Φ, Λ) describe positions on the Earth's surface and equatorial coordinates (δ, α) define positions of stars on the celestial sphere (Figure 2). Both coordinate systems are linked by GAST (= angle Θ being the Greenwich hour angle of the vernal equinox) regarding the Earth's rotation.
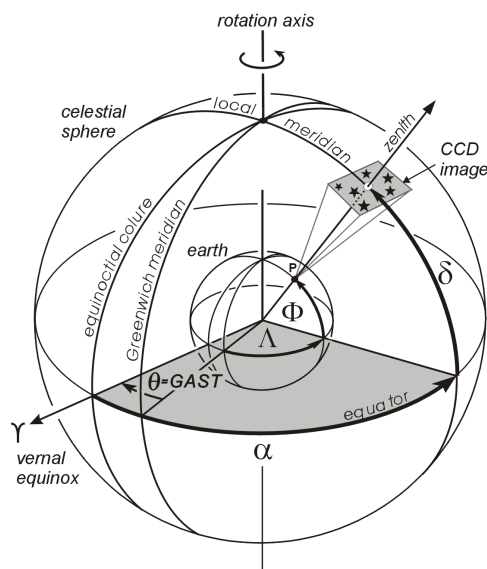

Figure 2. Basic principle of the determination of the plumb line (Φ, Λ) by imaging the stars in zenith direction

Geodetic astronomy uses the equivalence of astronomical coordinates (Φ, Λ) and equatorial coordinates (δ, α) for a star located at local zenith. The star's declination δ equals the astronomical latitude Φ and the astronomical longitude Λ is identical to the difference of the star's right ascension α and the observation epoch Θ

$$\Phi = \delta \qquad\qquad \Lambda = \alpha - \Theta \qquad (1)$$

Accordingly, a star (δ, α) being located in zenith at time Θ directly gives the unknown astronomical coordinates (Φ, Λ). Since the zenith point is not marked by a corresponding star, the direction of the zenith (which is identical to the direction of the local plumb line) has to be interpolated into the field of circumjacent zenithal stars imaged by the CCD.

4.2 Processing in a Nutshell

Star extraction. The data chain starts with the processing of the digital zenith images implicitly containing direction measurements to zenithal stars. The procedure of star extraction comprises the automatic detection of star images followed by measuring coordinates of their centers. Star images are characterized as pixel groups whose grey values significantly contrast to surrounding pixels belonging to the dark sky. The detection of stars is easily performed by applying segmentation-based image processing techniques (Hirt 2001). The center (x, y) of every segment extracted is determined with an accuracy of approximately 0.4 arcseconds by averaging and weighting image coordinates (x_i, y_i) with the grey value g for each pixel within an extracted segment.

Star catalogues. The further astrometric processing requires equatorial coordinates for stars extracted from digital zenith images. Equatorial coordinates serve as a reference and can be taken from a digital star catalogue such as e.g. Tycho-2, GSC, or UCAC. Due to the camera's high light-sensitivity, allowing to image approximately 14 million stars up to 14 mag, dense and extensive star catalogues are necessary. Catalogues meeting this requirement are listed in Table 2 (Hirt 2001).

Catalogue	Stars [Mio]	Accuracy [arcsecs]	Remarks
Tycho-2	2.5	<0.1	low density
GSC	19.0	0.5-1.0	low accuracy
UCAC	80.0	<0.1	in progress

Table 2. Star catalogues used for data processing

Functional model. After the process of identification of the extracted stars using reference stars from a star catalogue (e.g. Hirt 2001), the functional model can be set up. Since *plane* image coordinates (x, y) of extracted stars cannot directly be linked with *spherical* equatorial coordinates (δ, α) taken from the star catalogue, *plane* tangential coordinates $(\xi, \eta)^1$ are introduced as an intermediate step. Tangential coordinates (ξ, η) are equivalent to equatorial coordinates (δ, α). They are obtained by projecting the spherical coordinates (δ, α) onto a tangential plane touching the celestial sphere in a common point (δ_0, α_0). Coordinates (δ_0, α_0) are given by Eq.1 using exposure epoch Θ and introducing ellipsoidal values for $(\Phi_0, \Lambda_0) := (\varphi, \lambda)$ determined with GPS. The tangential coordinates ξ and η are obtained by

$$
\begin{aligned}
\cot q &= \cot \delta \cos(\alpha - \alpha_0) \\
\xi &= \frac{\tan(\alpha - \alpha_0) \cos q}{\cos(q - \delta_0)} \\
\eta &= \tan(q - \delta_0)
\end{aligned}
\quad (2)
$$

The tangential coordinates (ξ, η) of the reference stars are related to the image coordinates (x, y) through formulae of the projective transformation

$$
\xi = \frac{a_1 + b_1 x + c_1 y}{1 + dx + ey} \qquad \eta = \frac{a_2 + b_2 x + c_2 y}{1 + dx + ey} \quad (3)
$$

The eight transformation parameters $a_1, a_2, b_1, b_2, c_1, c_2, d$ and e, needed for interpolation of the zenith point, are determined in a least squares adjustment. This functional model is a well-known standard astrometric model (e.g. Seeber 2003). It approximates physical reality of the imaging process sufficiently.

Interpolation. The interpolation is performed for each camera position by transforming initial image coordinates of the zenith point into tangential coordinates (Eq.3) and equatorial coordinates (inverted Eq.2). Averaging the results of both interpolations gives the final zenith direction after 2 or 3 iterations, due to the approximate character of the initial values.

Corrections. A minor deviation between the rotation axis of the camera and the zenith direction is measured by means of the electronic tiltmeters and corrected for. Taking the mean value of both observation epochs Θ into account, the equatorial coordinates (δ, α) of the zenith point can be transformed into astronomical coordinates (Φ, Λ) using Eq.1. Astronomical coordinates depend on the influence of polar motion; they vary in time. This influence is

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^{1}Not to be confused with deflections of the vertical (ξ, η).

corrected for by applying standard formulae given in (Torge 2001).

Deflections of the vertical. Finally, deflections of the vertical (ξ, η) are derived by comparing ellipsoidal coordinates (φ, λ) determined with GPS and astronomical coordinates (Φ, Λ)

$$
\xi = \Phi - \varphi \qquad\qquad \eta = (\Lambda - \lambda) \cos \varphi \quad (4)
$$

4.3 Processing System AURIGA

All processing steps described above are implemented in the processing software AURIGA (Automatic Realtime Image Processing System for Geodetic Astronomy). The system has been developed at the Institut für Erdmessung (Hirt 2000, 2001). The software package consists of executable programs (C,C++) for data calculation and graphical user interfaces (scripting language Tcl/Tk) for data input, data flow control, data visualization and project data management. After data acquisition, the software computes deflections of the vertical in a fully automated process within 3 - 5 seconds based on integrated star catalogues GSC, Tycho-2 and UCAC (Table 2).

5 Experiences and Applications

First experiences have shown that one needs about 30 minutes per station to determine the direction of the vertical. After completing software and hardware handling details, this procedure can be shortened to about 15 to 20 minutes per station.

Principally, one observation in both camera positions is sufficient for computing the local plumb line's direction (Φ, Λ) and its deflection of the vertical (ξ, η). In order to increase precision and reliability, at least 5 observations in both camera positions are carried out. Since real-time data processing is possible, internal precisions are calculated online from repeated measurements. Repeated measurements also considerably reduce the impact of atmospheric scintillation on imaged stars.

Tests of the digital zenith camera systems performed in Hannover and Zurich have shown an internal accuracy (precision) of approximately 0.1 - 0.2 arcseconds. Current research activities are dedicated to equalize internal and external accuracy of the systems. The main topics of this work concern instrumental calibration and mitigation of anomalies of zenithal refraction.

Compared to the former analogue systems, digital zenith camera systems open new applications in local gravity field and geoid determinations since no further data processing steps, which usually followed the field work, are necessary anymore. There is no

doubt that in mountainous areas a reliable determination of the fine structure of the geoid at the 1 cm accuracy level is extremely difficult to reach without deflections of the vertical. This challenge is the most important area in which this type of equipment can be applied.

The geoid plays an extremely important role in the field of combined geodetic networks, incorporating the link between the classical gravity field related world of orthometric heights and ellipsoidal heights representing the pure geometrical world of space-related techniques such as GPS. In this context, the accuracy of the geoid is probably the limiting factor regarding the connection of GPS and levelling networks. An improved and densified network of accurate deflections of the vertical could help to mitigate these problems. This is in agreement with the Resolution No. 2 from the Symposium EUREF'2000 of the IAG Subcommission for Europe (EUREF) in Ponta Delgada, Azores, Portugal. Considering this situation, the determination of deflections of the vertical with the aim to strengthen local geoid determinations will be a main application of such systems.

6 Conclusions and Outlook

The revival of the astrogeodetic methods as described in this paper opens new possibilities for the determination of the Earth's gravity field in general, and geoid determination in particular. This is of special interest in areas where the gravity field is dominated by mountains or by intracrustal density anomalies. The grade of automatism will perform a much higher efficiency thus reducing the costs per station remarkably. Depending on the distances, 4 to 8 stations per night or even more in local areas can be observed. By observing numerous very short-distant stations ($\leq$ 50 m) along a profile, the digital zenith camera systems are ideal instruments to meet highest requirements for astrogeodetic geoid determinations in engineering projects concerning accuracy and resolution. In addition, these systems can be applied for investigations on refractivity issues. By observing the direction of the vertical continuously during clear nights, one can get important information on changes and fluctuations in the zenithal refractivity.

In conclusion, the availability and support of highly efficient and accurate CCD camera systems is of great interest for the geodetic community.

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