Digital Zenith Cameras – State-of-the-Art Astrogeodetic Technology for Australian Geodesy

Christian HIRT, Beat BÜRKI, Sébastien GUILLAUME and Will FEATHERSTONE

Key words: digital zenith cameras, vertical deflections, geodetic astronomy, geoid, quasigeoid

SUMMARY

Over recent years, significant progress has been made in astrogeodetic research with the development of digital zenith camera systems (DZCSs) at ETH Zurich, Switzerland, and the University of Hanover, Germany. The use of charged coupled device (CCD) sensors for star imaging improved the degree of automation, accuracy and efficiency of this modern astrogeodetic instrumentation. With DZCSs, vertical deflection determinations usually take about 20 minutes, including highly-redundant observation and data processing. Depending on the distance between field stations, DZCSs allow collection of vertical deflections at 10 or even more stations per night. This is a considerable improvement over the earlier time-consuming astrogeodetic techniques (e.g., analogue zenith cameras or astrolabes). Between 2003 and 2008, the Hanover and Zurich DZCSs have been used to observe vertical deflections at about 900 new stations in several European countries. The accuracy of DZCS vertical deflections is 0.1 arc-seconds and better. The main applications of DZCS vertical deflections are local and regional highly-precise geoid/quasigeoid determinations, but they can also be used to connect geometric and natural/astronomic coordinate systems.

The present paper starts by giving an overview on key aspects of DZCS technology, these being instrumental design, field routine, data processing and accuracy. Then, results of completed and ongoing DZCS field projects in Europe are presented. Based on the experiences gained from these applications, a link is presented to potential future applications of DZCS technology in Australia. Potential application fields include validation and improvement of Australia's national quasigeoid model, analysis of errors inherent in the Australian Height Datum, contributions to precise GNSS heighting, and supplementation of local ties at co-located geodetic sites. We analyse the attainable accuracy of quasi/geoid heights from astronomical levelling at regional and continental scales, which is relevant for some applications over Australia. As a general conclusion, Australian geodesy could benefit in various ways from these advancements in DZCS technology.

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1. INTRODUCTION

At the beginning of the 21st century, considerable advancements were made in geodetic astronomy at ETH Zurich, Switzerland, and at the University of Hanover, Germany, with the development of digital zenith camera systems (DZCSs) for determining highly precise and accurate vertical deflections. Digital imaging sensors (charge coupled devices; CCD) are the key improvement of the new camera generation, automating the observation of the direction of the plumbline and its vertical deflection from the ellipsoidal surface normal.

Between 2001 and 2003, previously used analogue zenith cameras were re-designed and equipped with CCD technology for star imaging (Hirt and Bürki 2002). These works were supplemented by the development of automated control and processing software (e.g., Hirt 2001, 2004). These efforts yielded two very similar DZCSs at Hanover and Zurich, both of which have been in operational use since 2003. Between 2003 and 2008, the Hanover and Zurich DZCSs were used in geodetic field surveys for collection of vertical deflection data at about 900 new stations in Europe (e.g., Müller et al. 2004, Hirt and Seeber 2007, Hirt and Flury 2008, Hirt et al. 2008, Somieski 2008). The main application for vertical deflections from DZCSs is local and regional geoid/quasigeoid determination at the mm to cm level (e.g., Hirt and Flury 2008, Hirt et al. 2010). In Europe, other research groups have since started similar instrumental developments; e.g., Kudrys (2009) in Poland and Ogrizovic (2009) in Serbia. However, no such technology has been used or developed in Australia.

The present paper outlines the instrumental design of the two DZCSs (TZK2-D at Hannover and DIADEM at Zurich), and describes the practical field routines. It gives an overview of the data processing and accuracy of DZCS vertical deflection data. The focus is placed on applications of DZCS in gravity field determination, engineering projects and vertical control. A summary of completed and ongoing projects in Europe is given. Based on the results and experiences gained from these projects, the paper presents a link to potential future applications of DZCS technology in Australia. The attainable level of accuracy of astronomical levelling for quasigeoid computation over continental profiles is estimated and discussed. We address areas such as gravity field modelling over Australia and the Australian Height Datum (AHD) which might benefit from DZCS technology, as well as local ties at co-located geodetic observatories.

2. DIGITAL ZENITH CAMERAS

2.1 Instrumental Design

The Hannover TZK2-D (Transportable Zenitkamera 2 – Digitalsystem; Hirt 2004) DZCS and the Zurich DIADEM (Digital Astronomical Deflection Measuring System; Bürki et al. 2004, Somieski 2008) DZCS are quite similar instruments (Figure 1). Both basically consist of an objective directed to zenith, a CCD sensor used for star imaging, a GPS receiver deployed for the observation of geodetic coordinates as well as time tagging, and an orthogonal pair of high-precision tilt sensors.

Both DZCSs employ dedicated mechanics. A motorised superstructure, consisting of lens, CCD and tilt sensors, forms the upper part of the system and can be rotated by 180° in azimuth, allowing observations in two opposite camera directions. A precision ball-bearing separates the superstructure from the substructure, which is a motorised tripod. Three electric actuators connected to a stable base-plate enable automatic levelling of the instrument. An integrated field computer is used for device and data-flow control, data storage and on-line data processing, and which completes the astrogeodetic measuring system.

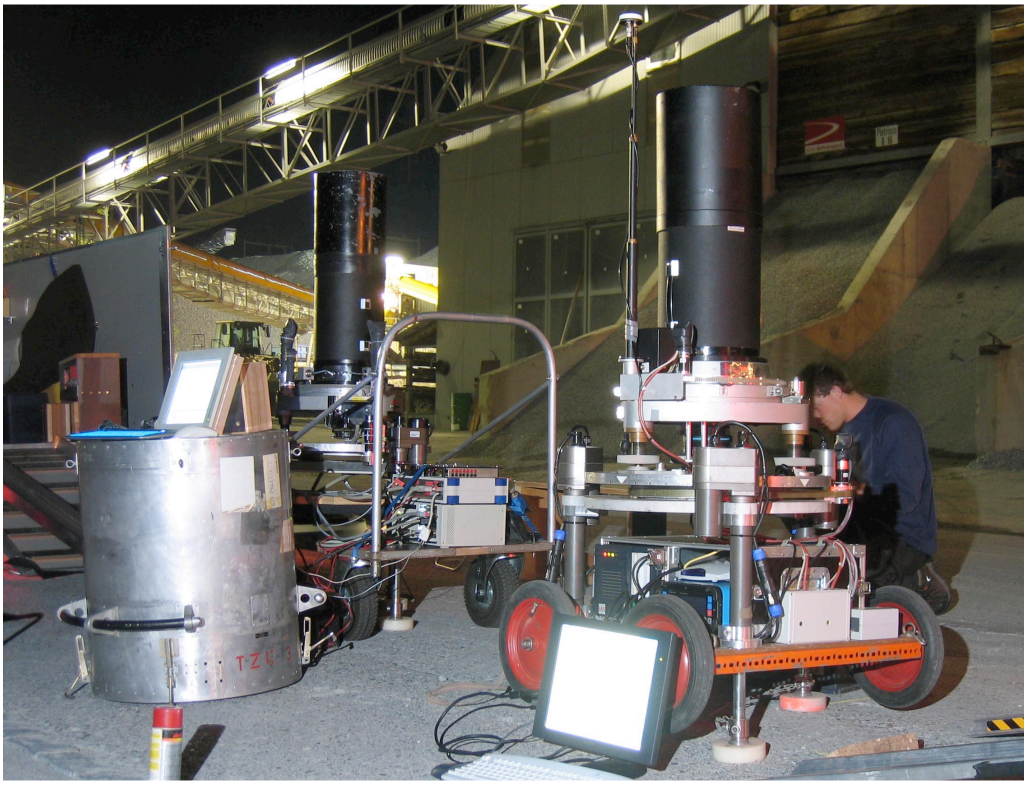

Figure 1. Digital Zenith Camera System DIADEM (left) and TZK2-D (right) during parallel vertical deflection measurements in the AlpTransit Network (Switzerland), summer 2005.

The objective (a Zeiss Mirotar lens-mirror combination with a 20 cm aperture) achieves a focal length of 102 cm along with a compact architecture (about 40 cm overall length). The CCD imaging sensor (a Kodak KAF full frame transfer sensor) used for star imaging has an array size of 1.5 million pixels (for TZK2-D) or 6 million pixels (for DIADEM). The pixel size is identical for both cameras (9 µm, which equates an angular scale of 1.86" per pixel). The field of view (FOV) of the DZCSs is about 0.42 deg^2 (for TZK2-D) and 1.68 deg^2 (for DIADEM).

In most cases, a sufficient star count (at least 10 or more stars) is obtained using the 1.5 million pixel CCD in TZK2-D. However, the larger sensor used in DIADEM has some advantages, e.g., in the case when thin clouds appear at zenith. Unlike most other telescopes used for astrometry, the DZCS is a non-tracking instrument and requires a very stable set up during operation. Due to the optical specifications, a limiting star brightness of about 13-14 magnitude is obtained after short exposure times of 0.2 - 0.5 s. Such a limiting magnitude corresponds to a total star count of about 10 million stars available on the sphere for processing of DZCS vertical deflection measurements.

In order to time-tag the epoch of exposure, the control unit of the shutter is linked to the GPS receiver and synchronised to the GPS time-scale. At the beginning of each zenith camera exposure, a logical signal (TTL pulse) is directed simultaneously from the CCD control unit to the shutter and to the GPS receiver, marking the exposure epoch. The epoch registration is necessary for connecting the celestial and terrestrial reference systems.

Tilt measurements are performed in order to refer the DZCS's optical axis to the plumbline. Pairs of recently developed pendulum tilt sensors, called HRTM (High Resolution Tiltmeter from the Lippmann Company for Geophysical Instruments, Germany), have been installed in orthogonal orientation on the DZCSs. They are used to align the camera to the zenith direction before observation. During observation, the tilt sensors monitor small, but inevitable, deviations between the plumbline and camera axis. Differential carrier-phase GPS is used for measuring the geodetic coordinates of the camera.

2.2 Field Routines

All DZCS components are installed on a small trolley or integrated into a hanger, both of which can be conveniently transported by van or station wagon to the field stations. Above the observation site, the electric actuators of the tripod are extended so that the DZCS is lifted into a stable position. Prior to the observation, automated procedures are carried out to set up the instrument. The levelling of the zenith camera is accomplished using an automated control routine, which steers the length of the actuators depending on the readings of the tilt sensors. The levelling procedure automatically aligns the camera axis with the plumbline accurate to 2-3 arc seconds. A motorised focus unit moves the CCD sensor vertically into the focal plane of the objective. The instrumental set-up usually takes only a few minutes for an experienced operator.

The automatic data acquisition involves digital star imaging, GPS-based time-tagging and digitisation of tilt signals, as well as transfer and storage of the observation data on the steering computer. DZCS measurements are always carried out in two opposite telescope directions in order to reduce the impact of the zero offsets of the CCD and tilt sensors. As a refinement, data acquisition series are generally performed in camera positions I-II-II-I, eliminating any linear variation of the instrumental zero offsets (e.g., Hirt et al. 2010). The azimuthal rotation of the telescope is motorised, which allows for completely automated observation programs.

A single observation consists of two images, taken in opposite camera directions, as well as the epoch registrations and tilt measurements. In most cases, 20 to 50 stars (for TZK2-D) and 80 to 200 stars (for DIADEM) are contained in a single image. These numbers are exceeded when the galactic plane (Milky Way) is transiting zenith (e.g., in autumn or winter in Central Europe). Only in rare cases will the star count fall short of 10 stars (for TZK2-D) or 40 stars (for DIADEM), e.g., when sky regions near the galactic poles are up. In order to enhance the observational accuracy and redundancy, usually sequences of 40-50 single observations are acquired at each field station. This takes a total of about 20 minutes' observation time. As a result, the vertical deflection at a single field station relies on several 1000 observations of stars contained in the digital image data.

Depending on the distance between field stations, DZCSs usually allow vertical deflection data to be collected at 10 or more stations per night. This is a significant improvement over the earlier time-consuming astrogeodetic techniques (e.g., analogue zenith cameras or astrolabes), where several hours of observations and processing were needed per station, sometimes over several nights. Moreover, the DZCS is more precise than the analogue instruments (e.g. Hirt et al. 2010), see also Section 2.4.

2.3 Data Processing

Digital imagery, as obtained from the CCD sensor of a DZCS, contains information on directions to stars near zenith. Digital image processing algorithms are used for extraction and measurement of star coordinates. Methods such as image moment analysis or star image fitting with point spread functions deliver the star coordinates accurate to 0.2-0.4" (cf. Hirt 2004, Hirt et al. 2010). Star catalogues (described below) provide equatorial coordinates (declination and right ascension) as the celestial reference for the imaged stars.

For the reduction of DZCS star images, the Tycho-2 (Høg et al. 2000) and UCAC (Zacharias et al. 2004) high-precision and dense catalogues are suitable. Both catalogues are densifications of the HIPPARCOS astrometry space mission (ESA 1997) and contain reference positions for several million stars (14 magnitude and fainter), accurate to 0.02-0.1". For future DZCS applications in the Southern Hemisphere, it is important to note that the accuracy of star positions in the Southern and Northern celestial spheres are fairly similar (e.g., Zacharias et al. 2004). Therefore, no degradation in accuracy is to be expected for DZCS observations in Australia with respect to the European observations described later.

As part of the astrometric data reduction, the process of star identification establishes the relation between star image coordinates and star catalogue positions. The direction of the plumbline (the counterpart of the zenith direction) is then obtained through interpolation of the camera's optical axis into the field of zenithal stars (for details see, e.g., Hirt et al. 2010). This process, done separately for the image data of both camera orientations, converges after 2-3 iterations. The final interpolation results are then corrected by the measured tilt values and the impact of polar motion.

As the last processing step, vertical deflections are computed as the difference between the direction of the plumbline and the camera's geodetic coordinates from differential carrier-phase GPS, scaled for meridional convergence. The accuracy of vertical deflection values from one single measurement (in two camera orientations) is about 0.2-0.3" when 10-20 stars are available per image. Processing a single vertical deflection measurement normally takes a few seconds using the fully-automated AURIGA software system that was developed at University of Hannover.

2.4 Accuracy

Since the development of DZCSs, considerable efforts have been placed on determining the accuracy of vertical deflection measurements (e.g., Hirt and Seeber 2008). First, the vertical deflection of a selected test site near the University of Hannover was observed repeatedly over 107 nights between 2003 and 2006. Second, about 220 vertical deflection stations in test areas at Steinhude (near Hannover), the Harz Mountains (Germany) and the Bavarian Alps (Germany) were observed twice on different nights, allowing the computation of standard deviations from repeated observations. Third, parallel measurements using the Hannover and Zurich DZCSs were carried out (cf. Figure 1). Fourth, comparison measurements at sites with independent deflection data were performed.

Based on this range of experiments, the accuracy of DZCS's vertical deflections was found to be about 0.08-0.10". This applies to data from measuring periods of about 20 min (equivalent to 40-50 single solutions and a total of 2,000-5,000 processed stars). Extended observations over periods of about 60 min yield an accuracy of 0.05" for vertical deflections (Hirt and Seeber 2008, Hirt et al. 2010). An extension of observation time, however, does not significantly reduce the observation noise further. This is due to residual atmospheric refraction effects.

Anomalous atmospheric refraction is a small yet systematic astronomical refraction effect in the zenith direction (contrary to general belief, this direction is not free of refractivity!). It currently places limitations on further accuracy improvement of optical vertical deflection measurements. Anomalous refraction originates from small horizontal temperature gradients occurring, e.g., at land-sea transitions, in strongly sloped terrain, due to air mass convection (atmospheric gravity waves) or passing weather fronts (e.g., Ramsayer 1967, Sugawa and Kikuchi 1979, Hirt 2006, Taylor 2009).

Although anomalous refraction may exhibit amplitudes of 0.05-0.2" at time-scales of several minutes to some hours, it behaves like a random error source to DZCS observations at different stations in the course of the night (Hirt 2006). A study by Sugawa and Kikuchi (1979) indicated that anomalous refraction may occur seasonally at regional scales with amplitudes of some thousands of arc seconds. Section 3.2 explains why such small residual systematic effects have to be treated with some care in regional and continental DZCS applications.

3. PROJECTS AND APPLICATIONS

The 'product' of DZCS measurements is accurate astrogeodetic vertical deflections. The main field of application for vertical deflections is the highly-precise local and regional determination of the geometry of the quasigeoid or equipotential surfaces such as the geoid. The precise determination of quasi/geoid heights is of ever-increasing relevance in vertical control as the quasi/geoid connects ellipsoidal heights from GNSS (Global Navigation Satellite Systems) and physical heights used for most applications in geodetic practice.

With respect to gravimetric methods usually applied in quasi/geoid determination (e.g., Stokes's integral), astrogeodetic vertical deflections are independent and complementary (cf. Featherstone 2006, Hirt et al. 2008). As such, they are of particular value both for validation of and combination in gravity field computations. With vertical deflections from DZCS measurements, the classical technique of astronomical levelling delivers precise information on the geometry of the gravity field between points or along profiles.

In astronomical levelling, vertical deflections are numerically integrated along a path, yielding height differences of the quasigeoid, geoid or other equipotential surfaces (see, e.g., Torge (2001) for the theoretical aspects). The precise application of astronomical levelling requires densely-spaced ('quasi-continuous') vertical deflections along the integration path. When the astrogeodetic deflections are not densely arranged (say, down to 50 m or 100 m), a dense arrangement can achieved by means of interpolation that uses computed vertical deflections from high-resolution terrain models, i.e., astronomical-topographic levelling, (cf. Hirt and Flury 2008). Subsequently, we summarise results of completed and ongoing astrogeodetic projects in Europe and outline potential areas of application in Australia.

3.1 Completed and ongoing projects in Europe

In complex terrain, e.g., in Switzerland, precise astrogeodetic vertical deflections are known to substantially reinforce gravimetric geoid computation (e.g., Marti 1997). Therefore, the Hannover and Zurich DZCSs were deployed throughout Switzerland to collect vertical deflections at around 70 scattered locations (Müller et al. 2004). These data have been used in the latest computation of the Swiss geoid model, CHGeoid2004 (Marti 2004). Further to this, the Zurich DZCS was applied for deflection measurements in rugged parts of Portugal in 2004 and Greece in 2006 (Müller et al. 2006, Somieski 2008).

Vertical deflections are required for the precise reduction of terrestrial survey data to the geodetic ellipsoid (Featherstone and Rüeger 2000), as well as for highly-accurate connection between heights from GNSS and spirit levelling in local areas (Hirt and Bürki 2002, Bürki et al. 2007). This holds particularly in complex terrain. In 2005, the Hannover and Zurich DZCSs were deployed for observation of vertical deflections in the high-precision geodetic control network of Switzerland's AlpTransit project, a 57 km long railway tunnel passing beneath the Alps (Bürki et al. 2007).

DZCS astronomical levelling was successfully applied for determination of quasigeoid and equipotential profiles with mm and cm accuracy in several German and Swiss test areas (e.g., Hirt and Seeber 2007, Hirt et al. 2008, Hirt and Flury 2008). Due to the efficiency of the DZCS, peak productivity values of 10-22 stations were attained over clear nights, thus allowing the collection of large sets of vertical deflections within short observation campaigns. Table 1 provides an overview of the characteristics of all recent vertical deflection profiles measured with these DZCSs in Europe.

Table 1. Characteristics of vertical deflection profiles available from DZCS observations in Germany and Switzerland.

Area and region	**Epoch of observation**	**Length of profile [km]**	**# DZCS stations**	**Spacing [km]**	**Level of accuracy [mm]**
CERN (Western Switzerland)	2009-	0.7	70	0.01	sub mm
Steinhude (Northern Germany)	2005-2006	7	144	0.05	sub mm
Isar Valley (Bavaria, Southern Germany)	2005	23	103	0.23	1-1.5 mm
Elbe (Northern Germany)	2006	6	20	0.2	1 mm
Benthe (Northern Germany)	2004	10	26	0.36	1 mm
Susten summit (Central Switzerland)	2007	32	22	1.5	few mm
Harz Mountains (Northern Germany)	2006	67	102	0.65	2 to 3 mm
Germany North-South	2006-2007	600	137	2.5-5	few cm
Germany East-West	2007-2008	500	133	2.5-5	few cm

In the test area Steinhude (Germany), experimental vertical deflection measurements were performed along a 7 km profile with a dense 50 m spacing between adjacent stations, while DZCS observations at even shorter spacings of 10 m are currently being carried out at CERN in Switzerland (Ph.D. thesis of Sébastien Guillaume). The data sets are used for analysis of the fine structure of the gravity field. It was demonstrated that astronomical levelling is capable of accessing the sub-mm accuracy level for height differences of equipotential surfaces over profile lengths of a few km (e.g., Hirt and Seeber 2007). This is of relevance to meet extraordinarily high accuracy requirements associated with the alignment of future particle accelerators, perhaps including the Australian synchrotron in Melbourne.

In the Bavarian Alps, vertical deflection data were collected along a 23 km traverse at fairly densely spaced stations (230 m). In the Harz mountains, DZCS measurements were performed along a 65 km long traverse with the vertical deflection stations spaced at 650 m. High-resolution elevation data were used in both areas for precise interpolation of vertical deflections between astrogeodetically observed vertical deflections. Analysis showed that the quasigeoid height differences are accurate to 0.5-1 mm over a 10 km profile length (Hirt and Flury 2008, Hirt et al. 2008). The resulting profiles of quasigeoid height differences were successfully used for validation of national gravimetric quasigeoid models in Germany (Hirt et al. 2007, 2008).

With larger station spacings ranging between 2.5 km and 5 km, DZCS astronomical-topographic levelling was used over several 100 km distance for the validation of regional and global gravity field models and GPS/levelling points (Voigt et al. 2007). The accuracy of quasigeoid height differences was assessed to be at the level of few cm over the entire profile lengths.

3.2 Potential applications in Australia

Over Australia, only a set of 1080 scattered vertical deflections, originating from historical observations, is available (Figure 2). With a crudely estimated level of accuracy of 1" (Featherstone and Lichti 2009), this data set is less suited for precise astrogeodetic gravity field determination in Australia. However, the availability of DZCS technology could open up a number of beneficial applications and yield answers to some of the challenges of Australian geodesy. In essence, most of the previous example applications, successfully completed in Europe, are of interest to future Australian geodesy. For instance, astrogeodetic vertical deflections from DZCS observations could be used for the determination of precise quasigeoid profiles on regional and even continental scales, reinforcing and validating Australia's vertical control data sets.

3.2.1 Astronomical-topographic levelling on continental scales

For potential applications in Australia, it is worthwhile to assess the potential accuracy of DZCS quasigeoid profiles at continental scales (say, 2000 km length in North-South direction). With such profile lengths, adjacent vertical deflection stations would have a spacing of some km, still allowing the completion of field projects in a timely manner. In order to keep interpolation errors small, astronomical-topographic levelling (and not the simple astronomical levelling) would be an appropriate method (cf. Hirt and Flury 2008).

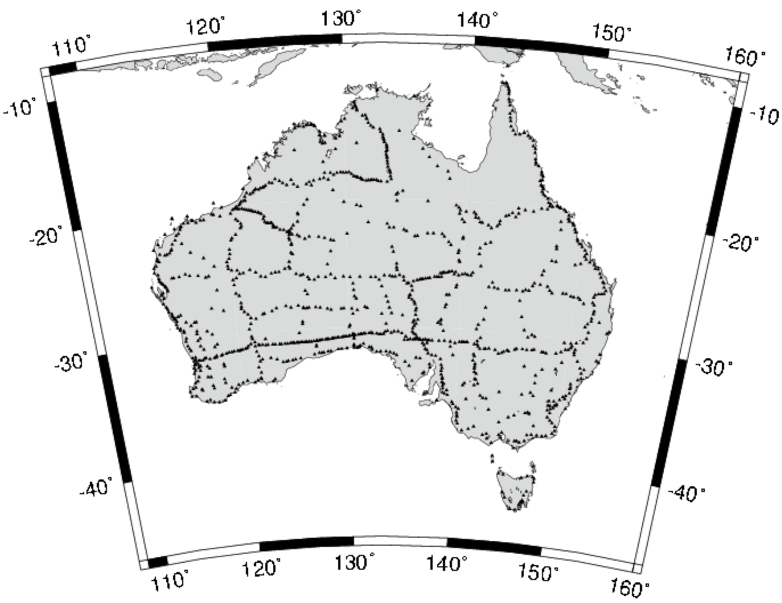

Figure 2. Coverage of the 1080 astrogeodetic vertical deflections [Lambert projection];

From Featherstone (2006, corrigendum)

Since vertical deflections are being integrated along a path, random and systematic errors accumulate with increasing distance. Qualitatively, the error propagation in astronomical-topographic levelling is quite similar to conventional spirit levelling, in that, random errors increase with the square root of the length of the profile, while systematic errors propagate linearly with the distance.

Therefore, in contrast to short profiles (say 20 km or 30 km), undetected small systematic errors will be particularly crucial in astronomical-topographic levelling at continental scales. The impact of residual systematic errors in the deflection data may be assessed using a well-known rule of thumb (1 arc second translates into 4.8 mm quasigeoid height over 1 km, cf. Hirt and Seeber 2007). On the other hand, the magnitude of residual systematic errors is very difficult to assess, e.g., because high-order comparison data is not available. We cautiously estimate the magnitude of systematic errors to be a few 0.001", e.g., due to small systematic refraction influences (cf. Sugawa and Kikuchi 1979) or residual unmodelled instrumental errors. Note that systematic errors always add up to supersede the random error effects over longer distances.

The spacing between the DZCS observation stations is a very important parameter. The larger the spacing between the observed astrogeodetic vertical deflections, the more economic is the application of astronomical-topographic levelling. However, a large spacing of say 5 km or 10 km results in a degradation of accuracy because the Earth's gravity field is not fully sampled (signal omission error). This holds even if topographic data is used for interpolation (cf. Hirt and Flury 2008).

We take into account both random and systematic errors in our error analysis of quasigeoid heights from astronomical-topographic levelling (Figure 3). The impact of random errors (including signal omission) is computed as a function of the parameters length of profile and spacing between astrogeodetic stations, from the empirical propagation law of random errors. This empirical law was derived based on an analysis of densely-spaced DZCS vertical deflections in the Bavarian Alps (Isar Valley, cf. Table 2), an area with complex topography and significant local gravity field variations. As such, it should not give too optimistic values for most other types of topography (cf. Hirt and Flury 2008). The empirically derived error propagation law is in good agreement with error estimates for quasigeoid height differences in the Harz Mountains (65 km profile) and regional Germany (a 500 km North-South profile); see the previous section for details.

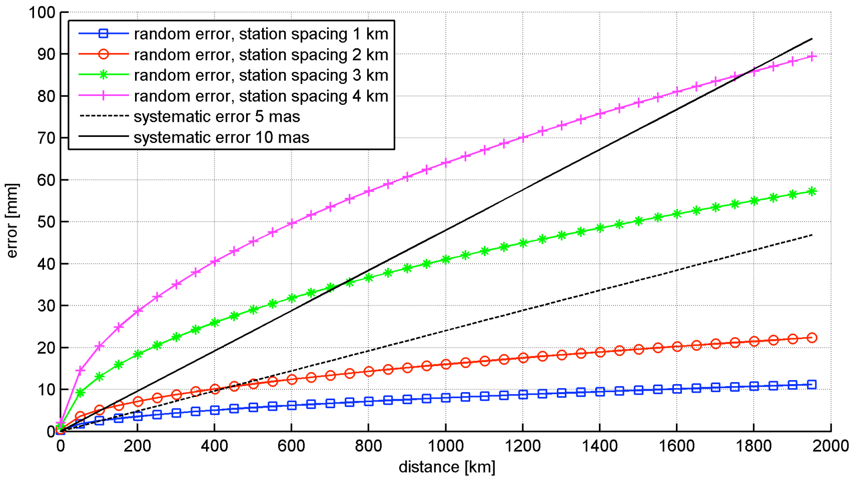

Figure 3 Error of quasigeoid heights from astronomical-topographical levelling in regional and continental applications (distances to 2000 km) as a function of profile length and spacing between adjacent stations. The random error graphs are based on the error propagation law derived by Hirt and Flury (2008, p. 245). The impact of (fictitious) systematic errors of 5 mas and 10 mas (1 mas = 1 milli arc second) on the quasigeoid heights is shown in black.

Figure 3 indicates that for regional applications (profiles of some 100 km length and 2 km spacing), quasigeoid heights may be determined at the level of a few cm, both in terms of systematic and random errors. Over sections of some 100 km length, profiles of precise vertical deflections could be a valuable independent check on Australian gravimetric quasigeoid models, and also the integrity of the AHD. In particular, the fine structure of the gravimetric quasigeoid model could be validated from astrogeodetic vertical deflections. With respect to distortions inherent in the Australian Height Datum (AHD), astrogeodetic quasigeoid undulations may be used for a validation of recent GNSS/levelling points and – in regions with reliable GNSS heights available –for analysis of errors in Australia's spirit levelling data set.

For continental applications, residual systematic errors may come into play, as seen in Figure 3. Over a 2000 km distance, quasigeoid information may be determined accurate to 1-2 dm when a spacing of 4 km between astrogeodetic stations is used. Such a continental profile would be very helpful as independent check on the ~ 1 m North-South slope in the AHD (cf. Featherstone 2004, 2006). Also, such a data set could be used for constraining the gravimetric quasigeoid model, as proposed by Featherstone and Lichti (2009). With a spacing of 4 km between adjacent stations and 10 stations normally observable over clear nights, a 100 km profile section would take three nights of net observation time. The observation of a continental vertical deflection profile would require an estimated net time of 2 months, using modern DZCS observation systems. These pre-calculations show that DZCS could be applied within acceptable time frames to support Australia's vertical control.

It should be noted that, particularly for precise determination of continental profiles, further research would be required to correctly assess and to reduce small residual systematic errors, possibly contained in the DZCS vertical deflection data. Digital weather models could be a suitable means for investigating and modelling refraction anomalies on regional scales. In this context, it is demonstrated how a (fictitious) systematic error of 10 mas would contaminate the accuracy of astronomical levelling on continental scales (Figure 3).

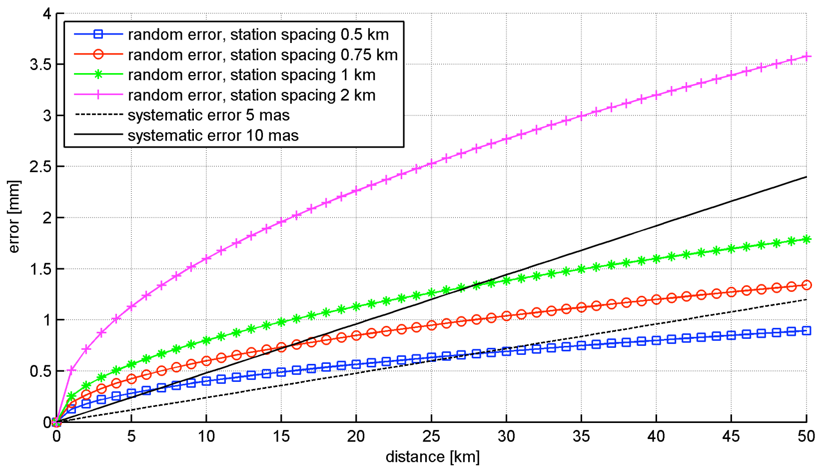

Figure 4 Same as Figure 3, but restricted to distances to 50 km and shorter spacings between the astrogeodetic observation stations.

3.2.2 Astronomical-topographic levelling on local scales

In local applications (working areas up to 10-20 km), astronomical-topographic levelling can be used for gravity field determinations at the 1 mm accuracy level. Over profile lengths of some km, gravity field information is obtained at the sub-mm level (cf. Figure 4 and Table 1). DZCSs can be used to supplement local ties at co-located geodetic sites (e.g., GNSS, SLR and VLBI), where the terrestrial observations must be accurately related to an ellipsoidal reference frame (e.g., Johnston et al. 2005).

A further possible application of DZCS is seen in relation with the currently ongoing modernisation of GNSS networks in Australia (e.g., Featherstone 2008). A levelling variant called geometric-astronomical levelling, i.e., astronomical levelling combined with precision spirit levelling, could be used to derive ellipsoidal height differences at the mm accuracy level. These could serve as valuable external check on GNSS-heighting in local test networks, allowing better analysis of GNSS errors and GNSS processing models. Such tests are of some relevance for precise GNSS-based heighting in Australia.

As a general conclusion, precision heighting over Australia could benefit in various ways from the advancements in zenith camera technology.

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BIOGRAPHICAL NOTES

Dr Christian Hirt, born in 1975, studied Geodesy at University of Hannover (Germany) from 1995 to 2000. From 2001 to 2006, he specialised at University of Hannover in digital zenith camera technology and astrogeodetic gravity field determination. He received a PhD in Geodesy in 2004. From 2006 to 2008, he was employed as Associate Professor for Surveying and Adjustment Theory at HafenCity University Hamburg (Germany). Since 2009, Christian has been working in gravity field modelling at the Western Australian Centre for Geodesy, Curtin University of Technology, Perth. His other research interests involve precision heighting, sensor technology, and refraction influences in geodesy.

CONTACTS

Dr **Christian Hirt**
Western Australian Centre for Geodesy
Curtin University of Technology
GPO Box U1987
Perth, WA 6845, Australia
Tel. : +61 8 9266 2218
Fax : +61 8 9266 2703
Email: c.hirt@curtin.edu.au; chris.hirt@web.de

Dr **Beat Bürki** and **Sébastien Guillaume**
ETH Zürich, Institut für Geodäsie und Photogrammetrie
Schafmattstr. 34
CH-8093 Zürich, Switzerland
Email: beat.buerki@geod.baug.ethz.ch
Email: guillaume@geod.baug.ethz.ch

Prof. Dr **Will Featherstone**
Western Australian Centre for Geodesy
Curtin University of Technology
GPO Box U1987
Perth, WA 6845, Australia
Email: w.featherstone@curtin.edu.au