Status of Geodetic Astronomy at the Beginning of the 21st Century

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Abstract

At the beginning of the 21st century, a significant technological change took place in geodetic astronomy. The use of digital imaging sensors strongly improved the degree of automation, efficiency and accuracy of methods for the observation of the direction of the plumb line and its vertical deflection. This paper outlines the transition of astrogeodetic techniques and applications from the analogue to the digital era and addresses instrumental developments and recently completed projects. Particular attention is given to Digital Zenith Camera Systems representing astrogeodetic state-of-the-art instrumentation. Moreover, accuracy issues, present application examples for highly-precise astrogeodetic gravity field determinations and some future applications are described.

1 Introduction – Review of Astrogeodetic Tasks and Methods

The most important objective of geodetic astronomy is the determination of astronomical longitude Λ and latitude Φ at selected points on the Earth's surface by measuring directions to celestial bodies, primarily stars. Astronomical longitude Λ and latitude Φ represent the orientation of the local gravity vector g in space and hence the direction of the local plumb line. The local gravity vector **g** is completed by the gravity acceleration g (Torge 2001):

$$\mathbf{g} = -g \begin{pmatrix} \cos\Phi\cos\Lambda \\ \cos\Phi\sin\Lambda \\ \sin\Phi \end{pmatrix} . \tag{1}$$

A second objective is to determine astronomical azimuths A of terrestrial points by combining direction measurements to terrestrial and celestial targets.

Geodetic astronomy is the only discipline which provides methods for the *direct* observation of the direction of the plumb line. Until the middle of the last century, exclusively astrogeodetic methods allowed the absolute determination of longitude and latitude related to the global terrestrial coordinate system. Essential early applications were navigation at sea, positioning (e.g. on expeditions), determination of Earth dimensions (historical arc measurements), orientation of geodetic networks or reference ellipsoids, determination of geoid profiles using the method of astronomical leveling and the observation of Earth orientation parameters.

With the evolution of satellite-based positioning techniques, particularly the U.S. Global Positioning System GPS, an essential part of traditional astrogeodetic tasks was taken over (details are given e.g. by Seeber 2003 and Beutler 2006 in this volume). Satellite-based positioning and navigation – available at all times, everywhere and independent of weather conditions – established itself as flexible and easily applicable universal geodetic technique.

Optical astrogeodetic methods were applied for determining Earth orientation parameters (pole coordinates and time) from 1900-1990. Up to the 1950's, observations using (optical) zenith telescopes of the International Latitude Service (ILS) and Bureau International de l'Heure (BIH) were visually performed. Subsequently, stationary Photographic Zenith Tubes (PZT) automated the optical observation procedure. The PZTs operated within the framework of the International Polar Motion Service (IPMS). Later modern space geodetic techniques like Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and GPS were combined for monitoring Earth rotation by the International Earth Rotation and Reference Systems Service (IERS). The space geodetic techniques replaced the optical astrometric methods by the end of the 1980's.

While disadvantageously for pure positioning purposes, the direction of the plumb line and its vertical deflection provides information on the structure of Earth's gravity field – as seen from a physical point of view. For several decades, astrogeodetic observations were primary gravity field observables and used for astrogeodetic geoid determinations (e.g. Helmert 1913 in the Harz mountains, Northern Germany; Heitz 1968 in Germany; Bomford in Europe (1971) – just to mention some of the classical works). Observations were performed visually; therefore requiring not only dedicated instruments (DKM3A, T4, Astrolabes) but also well-trained and skilled observers. Major improvements of these observation techniques could be achieved since the 1970's when transportable photographic zenith cameras (named TZK1,2,3, see Figure 1-3) were successfully designed and constructed at the University of Hannover (cf. Gessler and Pilowski 1972, Gessler 1975, Seeber 1978, Wissel 1982, Torge and Seeber 1985, Wildermann 1988 and Bürki 1989). Similar developments took place in Italy (Birardi 1976) and Austria (Chesi 1984). Thanks to a fully automated registration of exposure epochs and level readings, this new instrumental type overcame the problem of personally influenced results (personal equation effects) to a large extent. Moreover, compared to classical visual techniques, the zenith cameras allowed a significantly accelerated and simplified observation procedure. Such automated instruments were extensively applied in European and American countries (Switzerland, Austria, Germany, Denmark, Italy, Spain, Portugal, Greece, France, Norway, Canada, Brazil, Venezuela) for local and regional geoid determination and geophysical applications up to the nineties of the 20th century.
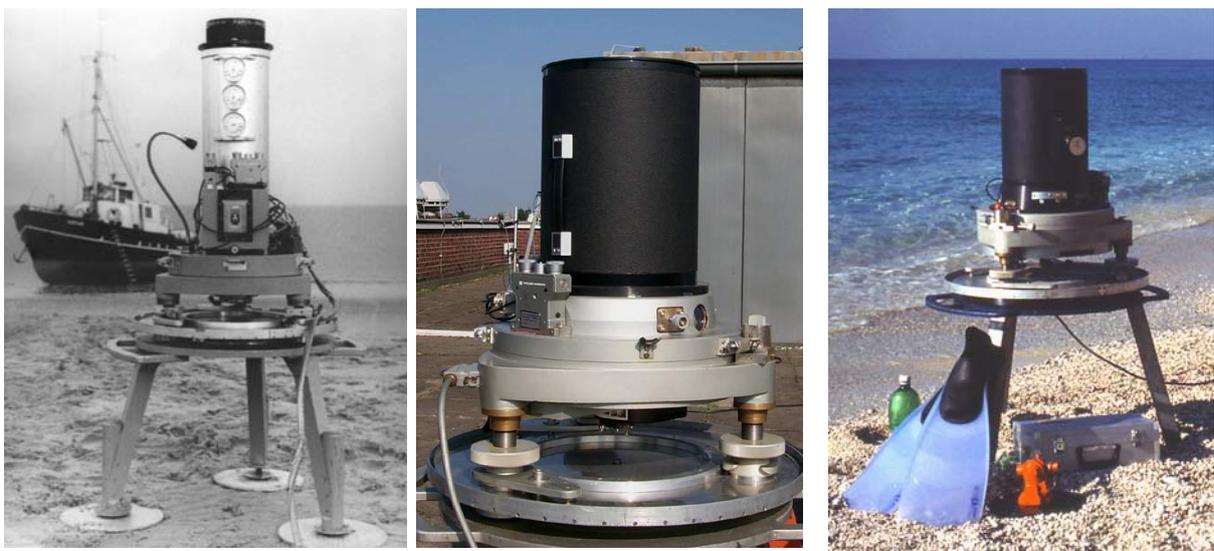

Figure 1-3: Transportable Zenith Cameras TZK1 (1976), TZK2 (2000) (both cameras operated by the Institut für Erdmessung, University of Hannover) and the twin model of TZK2, called TZK3 (1986), operated by the Geodesy and Geodynamics Laboratory of ETH Zurich.
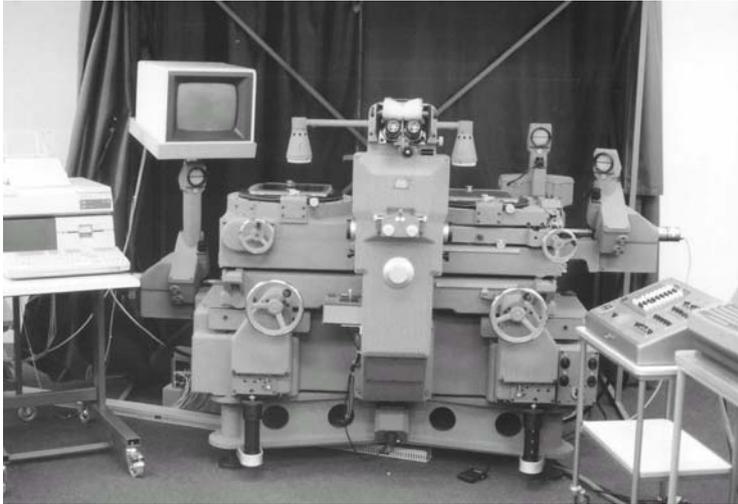
Figure 4: Comparator (Type Wild STK1) used for semi-automated star coordinate measurements at ETH Zurich (1989-2000).

Compared with current geodetic standards, the main drawback of the (analogue) photographic technique was the acquisition of star coordinates which was performed manually or semi-automated using a comparator (Figure 4, see also Wissel and Seeber 1979). The processing of a single station usually lasted 3-5 hours thus requiring man-power and keeping the costs of astrogeodetic measurements at a relatively high level. In addition, due to the increasing number of available gravity observations and satellite data, gravimetric computation techniques advanced with the result that more gravity field models based on gravimetric techniques became available (e.g. Denker 1988, Geiger 1990). As a consequence, the significance of astrogeodetic methods for the determination of the Earth gravity field decreased considerably in the 1990's.

2 Digital Era of Geodetic Astronomy, Today's Instrumentation

The invention of extremely light-sensitive digital imaging sensors (CCD) which are able to replace the analogue photographic techniques has revolutionized observational astronomy in general and astrometry in particular (e.g. Smith 1976, Buil 1991, Janesick 2001). Also the field of geodetic astronomy did not remain unaffected by these developments. CCD-sensors used for digital imaging of stars basically provide the image data directly after observation which is indispensable for online-processing. This way the conceptual disadvantage of photographic observations – the chemical development of the photo and the need for manual evaluation by means of a comparator – could be completely overcome so that the efficiency of astrogeodetic methods increases significantly.

First developments at the beginning of the digital era were published in the field of direction measurements to artificial satellites more than one decade ago (Schildknecht 1994, Ploner 1996). In consequence of this new technique, concepts for the automated observation of the plumb line were presented by research groups in Munich (cf. Eissfeller und Hein 1994, Schödlbauer 2000) and Vienna (Gerstbach 1996, Bretterbauer 1997). First instrumental approaches were published by e.g. Fosu (1999), however, without progressing to field-capability yet. This requires robust implementation of hardware and electronic components, the development of suited processing software and proper calibration procedures.

At the Institut für Erdmessung (IfE), University of Hannover and the Geodesy and Geo-dynamics Laboratory (GGL), ETH Zurich, intensive research in astrogeodetic use of CCD-technology has started at the beginning of the 21st century. The existing photographic zenith cameras TZK2 and TZK3 were re-designed and equipped with CCD imaging sensors to

Digital Zenith Camera Systems (DZCS). The digital development, which was initiated by Prof. Günter Seeber at the Institut für Erdmessung, is called TZK2-D (Transportable Zenitkamera 2 – Digitalsystem), whereas the DZCS implemented at ETH Zurich is named Digital Astronomical Deflection Measuring System (DIADEM). Both systems are shown in Figure 5.

The results already obtained in the development phase have been encouraging as they clearly indicated the potential of automated astrogeodetic methods for local gravity field studies (Hirt 2001, Hirt and Seeber 2002, Hirt and Bürki 2002). In 2003, hardware and software details of both DZCSs were completed and full field-capability was achieved for the first time. The performance of this new generation of astrogeodetic instruments for the determination of vertical deflections could be successfully demonstrated during a first common field campaign in the frame of the "European Combined Geodetic Network (ECGN)" which took place in Switzerland in autumn 2003 (Müller et al. 2004, Brockmann et al. 2004, Hirt 2004). In the sequel, both systems have been extensively used for local and regional gravity field determinations in Switzerland, Greece, Portugal, Northern Germany, Bavaria and the Netherlands at more than 450 new field stations (for details see section 5).
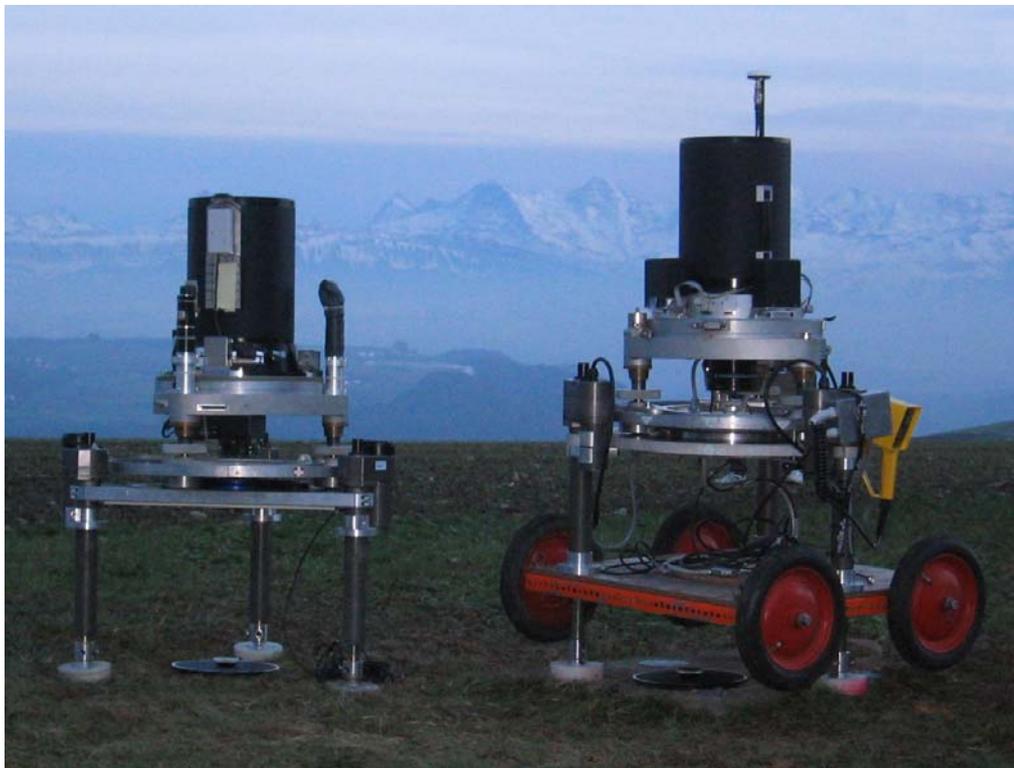

Figure 5: Digital Zenith Camera Systems TZK2-D (IfE) and DIADEM (GGL), depicted on the left side, during parallel observations at the Geostation Zimmerwald in Switzerland, autumn 2003.

Today, in the digital era of geodetic astronomy, the determination of vertical deflections using the digital zenith camera systems DIADEM and TZK2-D requires just "one mouse click". This is due to the completely automated observation process – including leveling, exposure, data acquisition and data transfer – and processing. The observation of a single vertical deflection takes about half a minute. Under normal conditions about 50 single observations are carried out at field stations requiring a total of 20 min observation time. Depending on the accessibility of the station, station spacing and duration of darkness, about 5 to 20 vertical deflection stations can be observed during one night. If compared to the analogue era, the accuracy of astrogeodetic observations remarkably improved from about 0.4-0.5" to 0.05-0.1" (cf. section 4). In comparison with modern satellite positioning, the new astrogeodetic

observation technique has achieved a similar degree of automation, ease and real-time capability as such complying with today's geodetic standards. For technical details on the Swiss observation system DIADEM, the reader is referred to Bürki et al. (2004) and Müller et al. (2004). Details on the realization of the system TZK2-D are given in the PhD thesis of Hirt (2004), which includes a comprehensive description of instrumental calibration procedures and algorithms used for automated data processing.

System ICARUS for on-line deflection and azimuth measurements

At the GGL, ETH Zurich, a theodolite measurement system called ICARUS has been developed which allows an almost fully automated determination of *astronomical azimuths A* and the direction of the plumb line (Φ,Λ). The equipment consists of a motorized total station TCA 1800 by Leica Geosystems, a small GPS receiver for timing and geodetic positioning, a field computer, and the online-processing software ICARUS/AZIMUTH. Once the orientation has been realized by pointing to a star (in most cases to α Ursae Minoris/Polaris) the system moves its telescope automatically towards the terrestrial target, and to the chosen star, respectively. The observer's only task is to center the telescope towards the star, and once to the target. The related accuracy of ICARUS azimuth observations and vertical deflection measurements is about 0.5". Recent projects focus on the use of CCD sensors instead of the human eye in order to minimize the impact of the personal equation and to enhance the efficiency.

3 Observation Principle, Status of Astrogeodetic Observables and Related Techniques

The simple astrogeodetic observation principle remained – in essence – unchanged throughout the decades: The direction of the plumb line (Φ,Λ) is obtained by means of *direction measurements* to celestial objects, primarily stars, whose equatorial coordinates right ascension α and declination δ are given in the International Celestial Reference System ICRS.
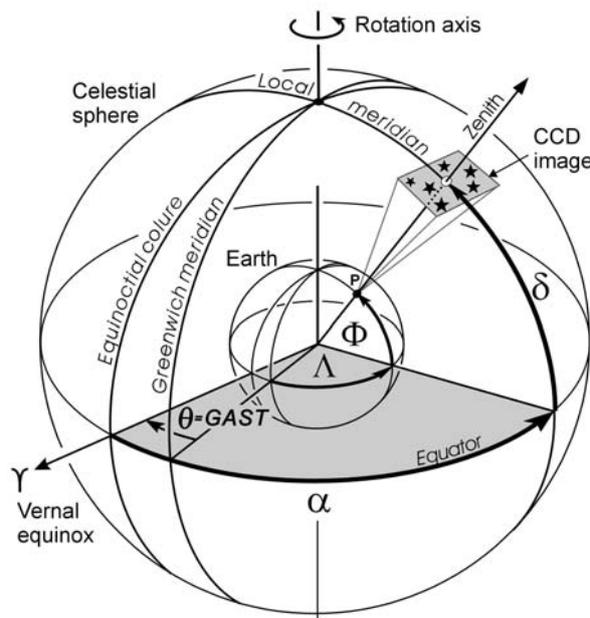

Figure 6: Basic principle of the direct determination of the plumb line's direction Φ,Λ (figure from Hirt and Bürki 2002).
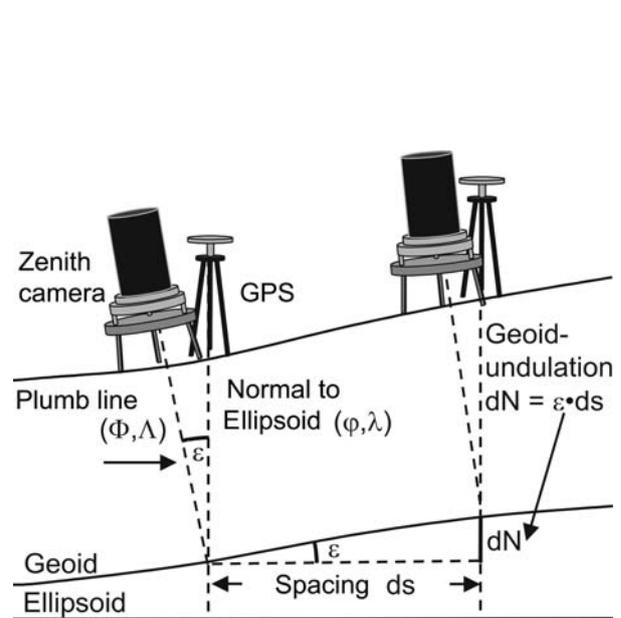
Figure 7: Basic principle of determination of vertical deflections (ξ, η) measurements by combining zenith camera and GPS in the context of astronomical leveling (figure from Hirt 2004).

The astronomical coordinates longitude Λ and latitude Φ define the spatial direction of the plumb line with respect to the International Terrestrial Reference System ITRS (see Figure 6). ITRS and ICRS are linked by Greenwich Sidereal Time GAST being a measure for Earth's rotation angle. Astrogeodetic methods use the equivalence of astronomical coordinates (plumb line Φ,Λ) and equatorial coordinates (zenith direction α,δ) for a star exactly located in zenith:

$$\Phi = \delta \qquad\qquad \Lambda = \alpha - \text{GAST.} \qquad\qquad (2)$$

Since a corresponding star is usually *not exactly* transiting through zenith, the star field surrounding the zenith is imaged on a CCD and used for interpolation. Vertical deflections (ξ, η) are easily obtained by calculating the difference between the local plumb line and the camera's geodetic coordinates (φ,λ) to be determined with GPS (see Figure 7):

$$\xi = \Phi - \varphi \qquad\qquad \eta = (\Lambda - \lambda) \cos \varphi. \qquad\qquad (3)$$

A closer look onto the observation principle and processing chain leads to an extended observation equation which schematically shows the quantities needed for data processing. The equatorial coordinates (α,δ) of the zenith point depend on the star catalogue applied, measured directions, transformation model, Earth Rotation Parameters (ERP), and, last but not least, on refraction. The tilt correction accounts for small angular deviations between the plumb line and the true alignment of the instrument during observation. GAST computed on the basis of GPS-based time measurement depends on ERP (DUT1 and celestial pole coordinates). The extended observation equation now reads:

$$\Phi = \delta \text{ (catalogue, ERP, x,y, model, refraction) + tilt,} \qquad\qquad (4)$$
$$\Lambda = \alpha \text{ (catalogue, ERP, x,y, model, refraction) + tilt – GAST (GPS-time, ERP).}$$

In the following, the above quantities are analyzed in terms of availability, presently obtainable accuracy, and the technique used for acquisition in special consideration of DZCS.

- **Geodetic coordinates:** Today, the determination of geodetic coordinates $(\varphi,\lambda$, related to a reference ellipsoid) of the instrument by using GPS is certainly the less critical part. Using differential positioning techniques, the related accuracy is on the order of some centimeters (= order of milli arc seconds, mas) thus playing a negligible role in the error budget of vertical deflection determination.

- **Star catalogues:** They incorporate the celestial reference system for astrogeodetic observations, hence they are of major importance for data reduction. In 1993, ESA's successful Hipparcos astrometry space mission laid the foundation for today's geodetic astronomy by producing the 1-mas-Hipparcos catalogue being the high-precision standard realization of the ICRS in the optical domain (ESA 1997). In the following, the highly-densified catalogues Tycho-2 (Hog et al. 2000) and UCAC (Zacharias et al. 2004) were compiled. Both catalogues provide reference data for a couple of million stars (14. magnitude and even fainter) at an (external) accuracy level of 0.02-0.10" (cf. Zacharias et al. 2000). Without a doubt, Tycho-2 and UCAC substantially contribute to the renaissance of geodetic astronomy as they enable the zenith camera observations to be processed adequately. ESA's planned GAIA astrometry mission to be launched in 2012 is designed for accessing even the *micro arc second* accuracy domain (ESA 2006). As a result, star catalogue data will be practically free of variance – provided that the GAIA mission will succeed.

- **Earth Rotation Parameters ERP:** Earth orientation plays an important part in geodetic astronomy as it connects the celestial and terrestrial reference frame. Nowadays, Earth Rotation Parameters (coordinates of celestial and terrestrial pole, and dUT1) are continuously provided by the IERS with sub-mas-accuracy (cf. IERS 2002) on a daily, weekly and monthly basis. However, ERP data accurate to sub-mas is merely available when post-processed by the IERS. This is the reason why the full accuracy potential of astrogeodetic observations can not be completely exploited in real-time.

- **Image coordinates x,y:** Digital image data acquired with CCD-technique implicitly contains the direction measurements to stars near the zenith. In contrast to analogue methods, the astrogeodetic observation procedure is considerably accelerated by using digital imaging and applying digital image processing algorithms (image moment analysis and point spread function, cf. Hirt 2001, 2004). During a relatively short time-window (half a minute to 20 minutes) star image data is redundantly collected with the result that some thousand stars are evaluated at a single station. The accuracy of a single star measurement amounts to 0.2"-0.4", the one of the station solution is significantly higher due to the redundancy of the observations (cf. Table 1).

- **Transformation model:** Other than processing of photographic plates, for DZCS-observations a simple 4-parameter-model (shifts in x, y, rotation and scale factor) is completely sufficient for relating image coordinates to equatorial coordinates. This is mainly due to the extremely stable and precisely manufactured geometry of the CCD-sensor. As usual in astrometry, the tangential projection is applied in order to convert (spherical) equatorial coordinates into plane coordinates (cf. Seeber 1972, 2003).

- **Refraction:** Basically, observations in zenith direction minimize the impact of atmospheric refraction since refraction is assumed to disappear in this direction. However, changing weather situations or atmospheric conditions near the observation site may occur which cause slightly tilted atmospheric layers with respect to the plumb line. In this case, light rays are also refracted in zenithal direction. The resulting effect is called *anomalous refraction* or *zenithal refraction.* This effect which is currently not well-known is considered to be an essential error source. A reasonable estimate for mean amplitudes of anomalous refraction is on the order of some 0.01" (Sugawa 1956, Nakjima 1979, Sugawa and Kikuchi 1979). However, even larger amplitudes up to 0.1" or more may basically be possible, e.g. in mountainous regions, as shown by Ramsayer (1967, 1970) and Bretterbauer (1965). As long as anomalous refraction can not be sufficiently eliminated or mitigated (e.g. by tailored observation strategies or modeling), this effect limits the accuracy of astrogeodetic techniques to the order of some 0.01".

- **Timing:** Due to its highly-precise basic observable *(signal travel) time*, GPS has become the standard tool for numerous timing tasks and applications – one is timing in geodetic astronomy. After initialization, the GPS-receiver's internal oscillator is synchronized to the GPS-time scale, and herewith it easily provides access to UTC which can be converted to time scales UT1, GMST and GAST required as measure for Earth orientation (cf. Equation 2). Depending on the type of receiver and chosen timing approach, GPS-timing procedures are accurate to microseconds up to nanoseconds using sophisticated time transfer techniques (see Seeber 2003).

For DZCS, the electromechanical shutter which is needed for exposure control is linked to a GPS-receiver in order to time-tag the epoch of the exposure. A thorough calibration of

the temperature-depending delay of the shutter's motion characteristics is necessary. The accuracy of the calibration has been found to be on the order of 1 millisecond (cf. Hirt 2004). Hence, the effectively obtained external accuracy for GPS-based timing for DZCS is limited to 1 ms (= 0.015") being adequate for the determination of astronomical longitude Λ. A completely different and sophisticated timing approach was developed by Schildknecht (1994) called Zimmerwald shuttering technique. Here, the precisely timed charge transfer on the CCD is utilized for time-tagging yielding the microsecond accuracy level.

- **Tilt measurements:** They are of prime importance for vertical deflection measurements as astrogeodetic observations basically refer to the direction of the plumb line. Up to now, tilt measurements incorporated one of the limiting parts in zenith camera systems. Recently developed high-resolution tilt sensors are used for the alignment of the zenith camera in the direction of the plumb line. A second task is to monitor inevitable small deviations between instrument and vertical direction occurring and varying during observation. Extremely sensitive tilt sensors (electronic levels) are used for this purpose; the resulting tilt angles are accurate to 0.04-0.05" (Hirt and Kahlmann 2004). In order to access this accuracy level, precise calibration of the scale factors, the use of an appropriate transformation model (mostly affine), and rigorous elimination of zero offsets is required. The latter is achieved by observing in two camera directions. The scale factors of the electronic levels are derived in-situ by means of a specially developed astrometric observation strategy which is based on the determination of angular differences as measured with the *tilt sensors and ICRS-stars*. This new calibration approach called *celestial calibration* provides scale factors consistent with the ICRS angular scale on a relative accuracy level of 0.1-0.2 % (see Hirt 2004).

4 Accuracy of Astrogeodetic DZCS-Observations

The astrogeodetic determination of vertical deflections may be characterized as *absolute* observation technique. Contrary to differential geodetic methods (e.g. Differential GPS) systematic errors (e.g. instrumental drifts or improperly modeled effects in the observation data) are not canceled out. Therefore *repeatedly performed observations* in different nights (under changing atmospheric conditions) and *comparative measurements* with different types of data are necessary in order to obtain reasonable accuracy estimates and to monitor the instrumental stability. *Anomalous refraction* is believed to be the dominant error source limiting the accuracy of the deflection data.

In order to study accuracy, atmospheric influences and instrumental stability, a comprehensive series of vertical deflection observations using the system TZK2-D has been acquired at a dedicated station located near the IfE in Hannover. The data observed within 70 different nights between February 2003 and January 2006 comprises more than 18.000 single observations and covers a wide spectrum of environmental conditions (e.g. season, temperature, air pressure) and resulting refractivity. The analysis of single and mean values computed from this new data set – and double observations at field stations in different nights – provides well-founded empirical accuracy estimates.

Table 1: Accuracy of vertical deflection measurements.

Type of mean values (observation class)	Observation duration	Single observations	Processed stars	Level of accuracy [']
Single observation [a]	30 sec	1	40-100	0.2-0.3
Field observation	20 min [b]	50	2000-5000	0.08-0.1
Extended observation	2 h	200	10000-20000	0.05
High-precision reference observation	10-20 h [c]	> 1000	>50000	0.02-0.03

[a] A single observation consists of two images of zenithal stars, exposed in two opposite directions. Each of the images typically contains between 20 and 50 (or even more) imaged stars.
[b] Typical observation time for ordinary field stations.
[c] For high-precision reference stations, the observation time of 10-20 h should be split up to different nights in order to observe under different atmospheric conditions thus randomizing anomalous refraction.

Table 1 summarizes the characteristics of the different types of mean values. The observation classes are single-, field-, extended- and high-precision reference observations:

- The accuracy of *single values* (single observations) of the deflection of the vertical is simply obtained as standard deviation of the observation series performed during one night. Typical values vary between 0.2" and 0.3" (cf. Hirt 2004 and Figure 11).
- In order to suppress high-frequent observation noise, the observation is typically repeated 50 times at field stations. The resulting mean values called *field observations* are usually accurate to 0.08-0.1" (see Hirt and Seeber 2005). Hence, field observations show an excellent degree of repeatability even under changing environmental conditions implicitly contained in the data.
- A series of *extended observations* (each consisting of 200 single observations) has been performed during 40 different nights between March and December 2005. The standard deviation computed over 40 extended observations is below 0.05" for both deflection components as such revealing the extremely low noise-level of vertical deflection measurements with DZCS (cf. Figure 8). However, the current limitation of accuracy due to anomalous refraction is already indicated in the data.
- In a last stage, five or more of the extended observations performed in different nights are averaged. The resulting vertical deflection values, called *high-precision reference observation*, are reproducible up to a few 0.01" thus effectively mitigating refraction influences to a large extent.

The listed figures in Table 1 are believed to be representative for field stations with similar refraction characteristics as for Hannover station (*not* located where large tilts of atmospheric layers are likely to occur, at land-sea transitions or in strongly sloped terrain). However, the individually obtainable accuracy certainly depends on the presence of refraction anomalies during observation, which e.g. also may occur during passing weather fronts.

As encouraging as these results of repeated observations are, *systematic errors* possibly contained in the data are not detectable. Therefore, vertical deflection measurements have been extensively performed synchronously with the camera systems DIADEM and TZK2-D and, additionally, at selected stations with different types of comparative data available.
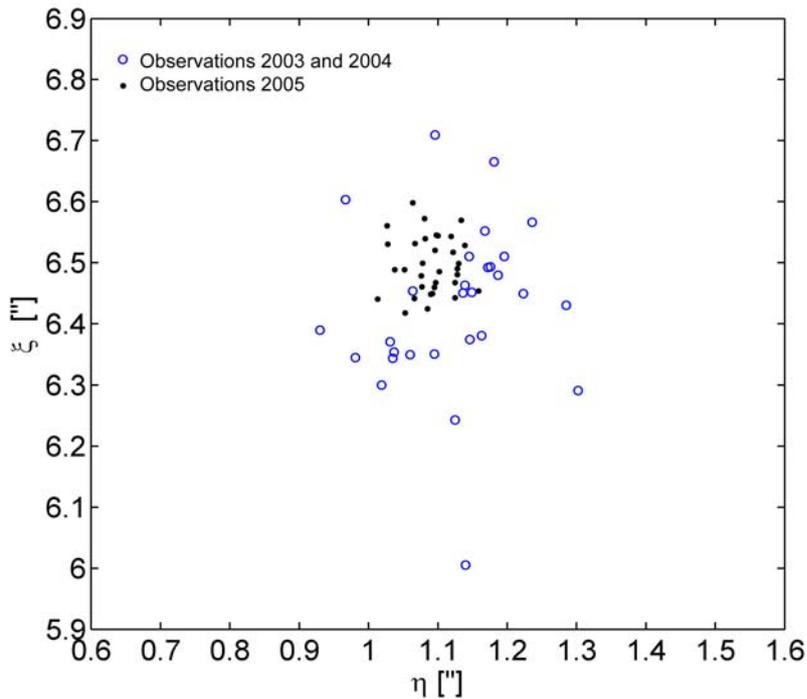
Figure 8: Repeated observations of the vertical deflection at a selected station near the IfE in Hannover. The figure shows the observations performed between 2003 and 2004 (circles) and 2005 (dots). Each dot or circle represents the nightly mean value of about 200 single observations, referred to as extended observation.

In 2003-2004, the accuracy of the deflection data has been found to be about 0.10-0.15". Since 2005, the accuracy is significantly improved (standard deviations of 0.045" and 0.039" for ξ and η due to a refined observation technique.

Parallel observations using both cameras have been carried out at different sites in Switzerland (Geostation Zimmerwald in 2003, Pradella (Lower Engadine) and Zurich in 2005, currently unpublished). The correspondence of the data sets acquired is on the order of 0.1"-0.15" (cf. Müller et al. 2004). At the site of the former Hamburg Photographic Zenith Tube (PZT), the TZK2-D has been used from 2003-2004 for comparison with the high-precision PZT-observations. The agreement of both data sets is within 0.1" (see Hirt et al. 2004).

In spring 2005, the observation technique has been further refined with the result that the impact of instrumental zero offset variations on the deflection data is reduced to a large extent (cf. Figure 8). In the sequel, additional comparison measurements have been carried out at a number of stations in the Netherlands where vertical deflections were already determined with high-precision by using optical instruments (Schreutelkamp 2000). The correspondence of TZK2-D and visually performed observations is on the order of some 0.01", showing the excellent quality of both data sets (Hirt and Schreutelkamp 2006). The general conclusion of this comparison campaign is that the deflection data do not contain significant systematic errors.

The analysis of repeated and comparative measurements has demonstrated the extremely high precision of the observation systems TZK2-D and DIADEM for the determination of vertical deflection data. The noise level for mean values formed by 50 single observations has been found to be about 0.08-0.1", the one of 200 observations is on the order of 0.05". If compared to the accuracy of formerly used analogue zenith cameras (order of 0.5", cf. Seeber and Torge 1985, Wissel 1982, Bürki 1989), the accuracy of DZCSs is considerably enhanced by about one order of magnitude. Besides the new star catalogues and high-precision imaging and tilt sensors, the redundancy of observations – several 1000 stars are measured at each station – is certainly responsible for achieving the unprecedented 0.05-0.1" accuracy level.

5 Current and Future Astrogeodetic Applications

Numerous research areas such as e.g. geodesy, geophysics, marine sciences, hydrology, and GIS-applications depend on precise knowledge of point positions both in terms of lateral coordinates and particularly on heights. The use of the space based and hence purely geometrically defined coordinates as obtained with GPS often requires an adequate link to coordinates and heights obtained with classical geodetic methods referring to the Earth gravity field. This holds true especially for GPS-based determination of physical heights (GPS-leveling). As shown in Figure 7, the geoid plays an important connecting role in this context. With respect to usually applied gravimetric techniques for geoid computation (e.g. Torge and Denker 1999), astrogeodetic observations represent an independent complementary data set which can be used for *validation purposes* and *combined computations*. Astrogeodetically determined vertical deflection data contribute to a considerable reinforcement in the determination of the geoid and its fine structures, particularly in mountainous areas. Vertical deflections are also important in order to precisely *reduce terrestrial observations* (horizontal and vertical angles) to a reference ellipsoid (e.g. Featherstone and Rüeger 2000, Wolf 1981). Due to the progress in geodetic astronomy, the classical technique of *astronomical leveling* (Figure 7) is of increasing relevance for applications requiring precise information on the local gravity field either *along profiles* or *between points*. Application examples are, e.g., engineering, geophysical exploration, validation of other gravity field observables (gravimetry, satellite data, INS/GPS), or hydraulic engineering projects in geodetically less developed regions. Compared with gravimetric techniques, a major advantage of astronomic leveling is that no data is needed outside the working area. In the following, some examples of recent astrogeodetic applications are given and future applications are briefly outlined.

- **Local Geodetic Networks – example AlpTransit**

The Swiss construction project "AlpTransit" is part of the European high speed train project that connects the major European towns. The most challenging part of this project consists of a railway tunnel of 57 km length crossing the St. Gotthard massiv in the Swiss Alps. The accuracy required for a secure and reliable underground survey of the tunnel axis require an excellent knowledge of the geoid and the corresponding deflections of the vertical. In order to provide additional observations for the validation and refinement of the geoid in the project area, some selected stations have been observed in late summer 2005. The measurements near 5 important tunnel portal stations have been performed simultaneously with the two systems TZK2-D and DIADEM (Figure 9). The comparison of the individual results revealed an accuracy of about 0.1". These indispensable deflection values helped to improve the geoid and reduction of geodetic data thus enabling an adequate combination of the geodetic data and the GPS measurements including orthometric heights (Bürki et al. 2005).

Moreover the realization of underground direction alignments for the tunnel axis require special reference azimuth-lines which provide calibration values for the instruments used for the tunnel survey, especially high-precision geodetic gyroscopes. In order to accomplish this demand, astronomical azimuths have been observed at five specially selected calibration lines using the measurement system ICARUS (see section 2 and Figure 10). Repeated azimuth measurements revealed a precision about 0.5". In order to validate these values, an independent check has been performed by processing the corresponding azimuths from GPS measurements. Since the differences obtained showed no outliers, the precision values are believed to be a realistic and reliable accuracy measure.
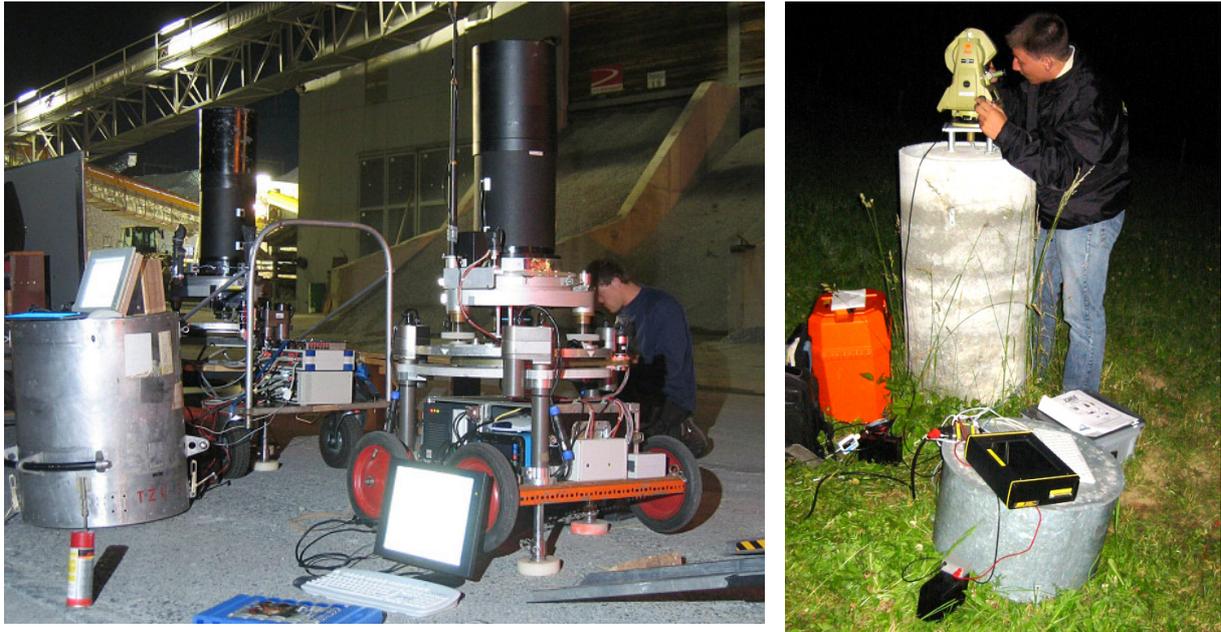
Figure 9, 10: Deployment of the two systems DIADEM (left) and TZK2-D on the AlpTransit construction site Bodio, summer 2005. Right picture: Measurement of an astronomical azimuth at the portal pillar Faido by means of the on-line measuring system ICARUS of ETH Zurich.

- **Combined gravity field determination**

The determination of the geoid with an accuracy of a few centimeters in countries with "normal" or smooth topography is relatively easy, provided that there is sufficient gravimetric data available. While this holds true for most regions, the gravimetric solution suffers from reduced accuracy in mountainous areas where it is extremely difficult to reach the cm-accuracy-level without vertical deflection data (Marti 1997, Schödlbauer 2000). In such cases, astrogeodetic vertical deflections improve the geoid solution substantially. Therefore the zenith camera systems from IfE and ETH Zurich have been deployed in several dedicated projects in Europe (e.g. 2003 in Switzerland, see Müller et al. 2004 and Brockmann et al. 2004, or in Portugal 2004, results currently unpublished).

- **Geophysics and fine structure determination of Earth's gravity field**

In exploration, usually gravimetric, magnetic and seismic techniques are utilized. Due to their sensitivity for variations of mass and density distribution, also vertical deflection data is applicable for geophysical prospecting and exploration purposes. Since the local mass distribution affects the direction of the local plumb line, intracrustal or subsurface density anomalies may be localized by means of astrogeodetic profile measurements. The possibility of using astrogeodetic data in geophysics for the localization of subterranean structures (salt domes, intracrustal mass anomalies) has already been demonstrated in the analogue era of geodetic astronomy (e.g. Tugluoglo 1971, Seeber and Torge 1985, Bürki 1989). Due to the advances in astrogeodetic technique, the potential geophysical use of deflection data is currently under re-evaluation by means of extensive observations above salt domes (Hirt et al. 2004, Hirt and Seeber 2005), in cooperation with German Mining Company K+S GmbH. Only by combing gravity anomalies and vertical deflection data, the local gravity vector (cf. Equation 1) yields its complete information content. Particularly, geophysical inversion and forward modeling techniques could benefit from combined gravimetric and astrogeodetic input data sets.

A related aspect is the investigation of the less-studied fine-structure of Earth's gravity field by means of astronomical leveling with DZCS. By arranging the vertical deflection stations very densely (e.g. 50 m distances) the geometry of the local gravity field may be determined with highest spatial resolution (see Hirt and Seeber 2005). This way extended knowledge on the high-frequency spectral domain of the gravity field (e.g. wavelengths in the km-range and smaller) is obtained.

- **Validation of gravity field models**

Being independent from gravity anomalies and other gravity field observables, vertical deflections may be used for the validation of gravimetric gravity field models, either at selected points or along profiles. Due to their low noise level of about 0.05"-0.1", vertical deflections observed with DZCSs rather serve as check on gravimetric gravity field models than the other way round:

– During summer 2005, a field campaign took place in the Northern Aegean (Greece) in the frame of a collaboration of the Aristotle University of Thessaloniki and GGL at ETH Zurich. The main task consists of the validation of the gravimetric geoid solution in the area of the North Aegean geoid trough between Chalkidiki and the chain of the Northern Sporades islands with DIADEM-vertical deflection data on land and with new data sets obtained with GPS-equipped buoys and ships at sea (results are currently unpublished).

– In order to verify the gravity field models NLGeo2004 and EGG97, additional high-precision observations of vertical deflections using the TZK2-D have been carried out at a number of stations in the Netherlands in autumn 2005 (Hirt and Schreutelkamp 2006).

– In cooperation with the US National Geospatial Intelligence Agency, the complete vertical deflection data observed with the TZK2-D (~300 stations) will serve as spot-check on the new Earth Geopotential Model EGM06 to be published in 2006.

– Further astrogeodetic research at IfE focuses on the validation of gravity field models (e.g. EGG97) in regions where the related accuracy is rather weak (e.g. mountainous regions). For this purpose, recently a new astrogeodetic gravity field profile consisting of 100 vertical deflection stations has been observed in the German Alps in cooperation with TU Munich in autumn 2005 (results to be published).

- **Monitoring of anomalous refraction**

In section 4, anomalous refraction has been turned out to be the major source of error for precise astrogeodetic observations. Up to now, the characteristics of refraction anomalies are less-known. The new generation of astrogeodetic instrumentation is capable of monitoring the fluctuations of the zenithal refraction field. For the first time, 2 observations per minute may be carried out by employing a DZCS. Time series covering several hours of night-time allow to enhance the knowledge on the typical behavior of anomalous refraction with respect to mean amplitudes and frequencies. Recently, the zenith camera TZK2-D has been used for continuous observation of fluctuations of zenithal refraction during 60 hours within 5 nights. A preliminary result is exemplarily shown in Figure 11.
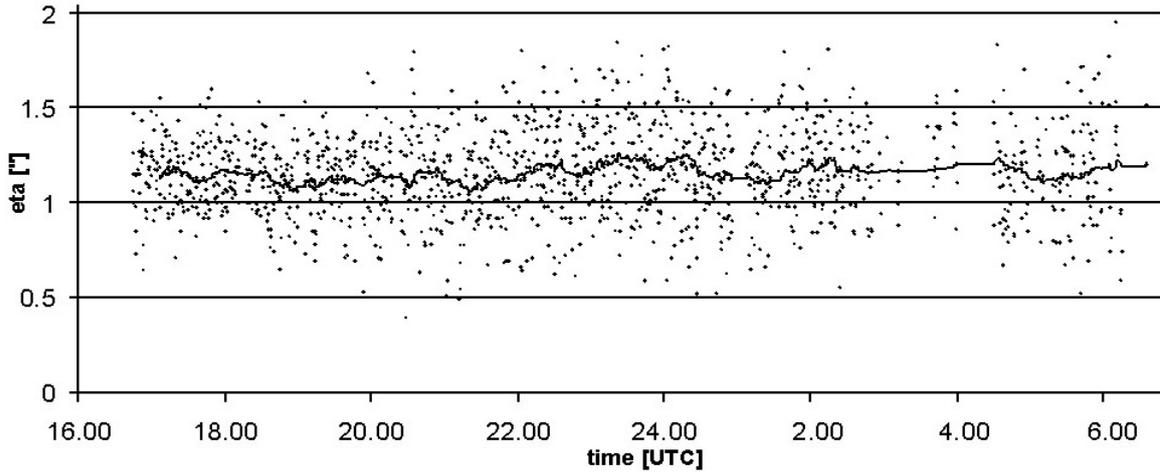
Figure 11: Continuously observed vertical deflection component η (single values and smoothed data with moving average technique) at station Hannover on 09. January 2006. The data set consists of 1420 single solutions based on a total of about 97.500 measured stars. The time series covers about 13.7 hours night time. The standard deviation of the single values is 0.23". Mean amplitudes of the smoothed deflection component are on the order of 0.05" which are most likely due to the time varying fluctuation of zenithal refraction.

- **Geometric-astronomical leveling**

In the age of satellite-based positioning, the technique of geometric-astronomical leveling for the determination of ellipsoidal height differences is fallen into oblivion. The main idea of this technique is to combine traditional astronomical leveling (Figure 7) with geometric (spirit) leveling. While the first one provides geoid height differences ΔN, orthometric height differences ΔH are determined from spirit leveling (giving height increments dn). Combined, ellipsoidal height differences Δh are obtained (e.g. Torge 2001):

$$\Delta h_{12} = h_2 - h_1 \ = \ \Delta H + \Delta N \ = \ \int_1^2 dn \ - \int_1^2 \ (\xi \cos\alpha \ + \ \eta \sin\alpha) \, ds. \qquad (6)$$

The main conceptual advantage is related to the fact that second order corrections, accounting for the plumb line's curvature E_{12}, are canceled out. Due to the recent advances made in geodetic astronomy, geometric-astronomical leveling could be reactivated as interesting alternative or supplementary method for satellite-based height determination. Astronomical leveling with a station spacing ds of 50 m is capable of providing geoid height differences ΔN accurate to an order of about 0.1 mm/km (Hirt and Seeber 2005). The related accuracy of leveled (orthometric) height differences ΔH is typically in the range of 0.2-0.3 mm/km. Hence, the resulting accuracy for ellipsoidal height differences Δh is about 0.3 mm/km. Over very short distances (km range or less), corresponding ellipsoidal height information determined with geometric-astronomical leveling is obtained with sub-mm-accuracy thus usable as valuable *external check* on GPS-based observations of ellipsoidal height differences. A variant of this approach is to enlarge distances thus allowing to cross-validate GPS-heights, leveling data and vertical deflections as described by Soler et al. (1989).

The method of geometric-astronomical leveling with DZCSs can also be applied in engineering projects, e.g. for the alignment of new linear accelerators which requires extraordinarily precise knowledge on the geometry of the gravity field (Schlösser and Herty 2002, Becker et al. 2002). Here the astronomical method is combinable – instead of spirit leveling – with the much more accurate hydrostatic leveling (giving accuracies in the micrometer range when using ultrasonic techniques). Such a combination allows to derive

ellipsoidal height differences at an accuracy level of about 0.1 mm/km as such meeting even highest accuracy requirements (Hirt and Seeber 2005).

- **Validation of the gravity field satellite mission GOCE**

ESA's challenging satellite mission GOCE to be launched in 2007 is expected to improve the knowledge of the global gravity field to an accuracy level of 1 cm for a spatial resolution down to 100 km. For validation purposes of upcoming GOCE gravity field models, terrestrial gravity field observables may be applied as important external check. In the context of the recently approved German "GOCE-GRAND II" joint research project, a new vertical deflection data set will be collected using the Hannover digital zenith camera TZK2-D (cf. GOCE-GRAND 2005). The vertical deflection stations to be observed in 2006 and 2007 shall be arranged in two profiles running in East-West and North-South direction in Germany (about 4 km station spacing, target length of each profile is 400 km).

- **Validation and calibration of INS/GPS vector gravimetry**

Today, combined INS/GPS systems are widely used for kinematic determinations of gravity on land, at sea and in the air (e.g. Jekeli 2001). However, currently no or only minor use is made of the horizontal components of the measured gravity vector. This is related to the fact that at present merely the vertical component, the intensity of gravity, can be obtained with sufficient accuracy (Schwarz 2006). At least for ground-based land applications, using a set of highly-precise vertical deflections may help to overcome these limitations. Assumed to provide true information, vertical deflections could serve as reference along INS/GPS profile measurements thus allowing to determine systematic error sources of the INS much more accurate and to obtain a proper assessment of the capability of INS/GPS for vector gravimetry (cf. Jekeli and Li 2006). The *combined* use of DZCS and INS/GPS vector gravimetry opens up encouraging prospects for the continuous acquisition of 3D-gravimetry data, both intensity of gravity and vertical deflections, along profiles. For instance, a DZCS may provide deflection data at equally spaced base stations, e.g. 2 km, whereas the INS/GPS data densify the base stations continuously – once being calibrated to the highly-precise DZCS-deflection data.

- **Celestial positioning and navigation at sea**

Nowadays automated astrogeodetic methods for positioning and navigation at sea are of great military interest. Due to its independence of GPS, astrogeodetic positioning may serve as backup in case of jamming or failures due to electromagnetic distortions. At the United States Naval Observatory, a new technique called SPACEI (System for Positioning and Attitude from Celestial Electronic Imaging) is currently under development as modern variant of the classical sextant (USNO 2005). Similar to the currently used DZCS technique used for land applications, SPACEI is expected to provide astronomical positions fully automatically, however also on ships and aircrafts. Additionally, both *daylight* and night use shall be possible. The target accuracy for positions is on the order of about 1". Conceptually, the described approach could also be of great interest for marine and physical geodesy. In future, a civil version of this new technique could possibly be used for vertical deflection measurements arranged in profiles at sea as complement for shipborne gravimetry.

6 Conclusions

The status of current astrogeodetic research has been outlined with emphasis on the new high-precision Digital Zenith Camera Systems for the automatic determination of vertical deflections. Due to their efficiency and accuracy, astrogeodetic techniques have been reactivated for highly-precise local and regional gravity field determination. The combination of present and future astrogeodetic, gravimetric and GPS leveling data will allow to compute the geoid to centimeter or even millimeter accuracy.

Despite the remarkable enhancement of precision by about one order of magnitude into the unprecedented range of currently about 0.05-0.1", the accuracy level of astrogeodetic observations and those of geodetic space techniques still differs by at least two orders of magnitude. This will remain the case as long as the influence of anomalous refraction can not be minimized at the required accuracy level. Future approaches for mitigating refraction influences could base on observation strategies (differential astrogeodetic observation concepts) or modeling (e.g. digital weather models).

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Frequently used abbreviations: ZfV = Zeitschrift für Vermessungswesen. DGK = Deutsche Geodätische Kommission. SGK = Schweizerische Geodätische Kommission.

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