On the Accuracy of Vertical Deflection Measurements Using the High-Precision Digital Zenith Camera System TZK2-D

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Abstract. In this paper the accuracy of vertical deflections (ξ, η) provided by the Digital Zenith Camera System TZK2-D is comprehensively analysed. During 2003 and 2004 various vertical deflections have been measured repeatedly at particular sites with different types of comparative data available. Emphasis is placed on the presentation of comparative measurements with highly accurate reference data at the Hamburg PZT station. As main result, the external accuracy level of the deflection data has been found to be about $0''.10$ - $0''.15$ as such exceeding considerably the accuracy of the formerly used photographic zenith cameras. The high accuracy level makes the Digital Zenith Camera System TZK2-D a very powerful system for highly accurate geoid determination in local areas.

Keywords. Digital Zenith Camera System, Photographic Zenith Tube (PZT), vertical deflection, accuracy

1 Introduction

At the University of Hannover, the Digital Zenith Camera System TZK2-D (Transportable Zenitkamera 2 - Digitalsystem, Figure 1 and 5) has been constructed for the automated determination of vertical deflections (ξ, η) and is described in Hirt (2004, 2003); Hirt and Bürki (2002); Hirt and Seeber (2002); Hirt (2001). In the course of instrumental implementation attention has been laid on the development of appropriate calibration methods. After completing the development and calibration phase, various vertical deflection measurements have been carried out at about 100 stations in Northern Germany and Switzerland (cf. Brockmann et al. 2004; Hirt 2004; Hirt and Reese 2004; Müller et al. 2004; Reese 2004). An important issue is the estimation of the accuracy level of the observed deflections. Therefore, comparative and repeated measurements have been extensively performed at selected stations in Hamburg, Hannover and Benthe. In this contribution some exemplary results are presented, demonstrating the accuracy level reached for the deflection data (ξ, η). The deflection data listed in this paper is on the reference system ETRS89. For precise ellipsoidal position data of the measurement stations presented in this contribution the reader is referred to Hirt (2004).

2 Comparative Measurements at the Hamburg PZT station

The site of the Photographic Zenith Tube (PZT) in Hamburg is considered as one of the most precise astronomical reference stations in Germany. The Hamburg PZT (see Figure 2) has been operated within the framework of the international services for monitoring Earth rotation, the Bureau International de l'Heure and the International Polar Motion Service, over a period of almost three decades. (e.g. Enslin 1964, 1972; BIH 1984; IPMS 1984). In 1986, the operational use of the PZT signed off. Due to the high-precision of astronomical PZT-observations being in the order of $0''.1$, the site of the former PZT is well-suited for comparisons with modern astrogeodetic instrumentations like the Digital Zenith Camera TZK2-D. On the one hand comparative measurements are used to estimate the external accuracy of the deflection data. On the other hand larger remaining systematic errors may be revealed.

At the Hamburg PZT station, the system TZK2-D has been extensively used for comparative measurements over five nights during winter 2003 and spring 2004. The internal accuracy (precision) is obtained

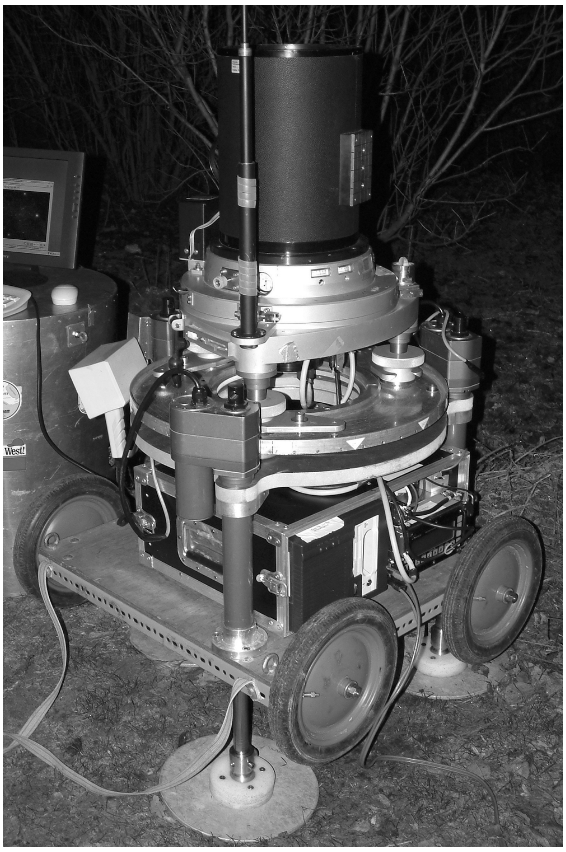

Figure 1. The Digital Zenith Camera System TZK2-D (during observation at the former PZT site in Hamburg). The depiction shows the complete system including electronic components for data acquisition and processing. All parts of the system are compactly mounted on a vehicle simplifying the astrogeodetic field work.

by repeated measurements during the same night. Table 1 exemplarily shows results obtained on 9th December 2003. Considering the spreading of single solutions, the internal accuracy is found to be about $0''.08$. Vertical deflection measurements carried out during other nights show comparable internal accuracy estimates for the mean values (Hirt 2004).

Table 1. TZK2-D measurements at Hamburg PZT station on 20031209

Data set	ξ $['']$	η $['']$	r_ξ $['']$	r_η $['']$
20031209_2000	1.88	-0.94	-0.08	0.01
20031209_3000	1.72	-0.88	0.08	-0.05
20031209_4000	1.87	-1.07	-0.07	0.14
20031209_5000	1.78	-0.87	0.02	-0.06
20031209_6000	1.76	-0.91	0.04	-0.02
Mean	1.80	-0.93		
Std.dev.			**0.07**	**0.08**

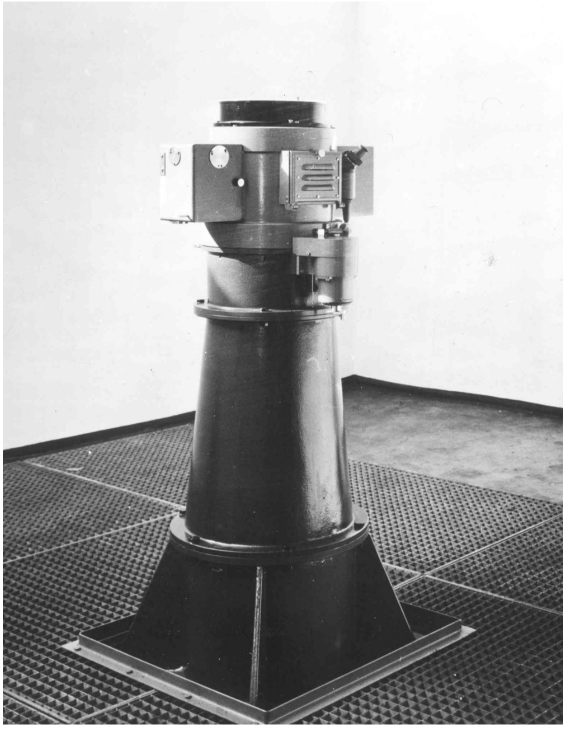

Figure 2. The formerly used Hamburg Photographic Zenith Tube (photo courtesy of Bundesamt für Seeschifffahrt und Hydrographie, H. Besser)

The mean (ξ, η) values obtained in five different nights are listed in Table 2, the nominal (reference) values provided by PZT observations are given by Table 3. Assuming that the PZT numbers correspond to the true values, the external accuracy of both components is $0''.14$. The remaining, non-significant differences of $0''.11$ in ξ and $0''.06$ in η underline the high degree of correspondence between both types of deflection data.

Table 2. TZK2-D measurements at Hamburg PZT station in Winter 2003 and Spring 2004. The last columns contain the differences $(\varepsilon_\xi, \varepsilon_\eta)$ between the TZK2-D observations and the PZT reference values.

Date	ξ $['']$	η $['']$	ε_ξ $['']$	ε_η $['']$
20031209	1.80	-0.93	-0.01	0.17
20040325	2.01	-0.99	0.20	0.11
20040413	2.04	-1.10	0.23	0.00
20040415	1.89	-1.26	0.08	-0.16
20040424	1.87	-0.93	0.06	0.17
Mean	1.92	-1.04		
Std.dev.			**0.14**	**0.14**

Table 3. Comparison at PZT station Hamburg. The last columns contain the differences $\Delta\xi$, $\Delta\eta$ with respect to the TZK2-D mean values.

Data set	ξ [$''$]	η [$''$]	$\Delta\xi$ [$''$]	$\Delta\eta$ [$''$]
TZK2-D Mean	1.92	-1.04		
PZT Values	1.81	-1.10	**0.11**	**0.06**
EGG97	2.15	-1.12	**-0.23**	**0.08**

At the same site computed deflections based on the European Gravimetric Geoid EGG97 (Torge and Denker 1999) could also be used for a comparison (Table 3). The mean accuracy of the computed deflections is specified to be in the order of $0\overset{\prime\prime}{.}2$ (Denker 2004, 1988). The comparison shows non-significant differences of -$0\overset{\prime\prime}{.}23$ (ξ) and $0\overset{\prime\prime}{.}08$ (η) between observed and computed vertical deflections.

A remarkable, larger difference of $0\overset{\prime\prime}{.}34$ in the ξ-component between the PZT and EGG97 values reveals a discrepancy of the comparison data sets. Due to their accuracy specification, the difference is believed to come for the most part from the computed deflections based on EGG97. It should be positively noticed that the vertical deflection values provided by the TZK2-D are located within the range formed by the comparison data (component ξ). Although the reference data is not of higher-level accuracy in comparison to those of the TZK2-D, the results clearly indicate an external accuracy level of at least $0\overset{\prime\prime}{.}15$.

3 Comparative Measurements in Hannover

In order to determine the repeatability and to obtain very precise reference coordinates, repeated measurements over 14 nights over a period of 13 months have been carried out at a reference station at the University of Hannover between February 2003 and March 2004. As reference station, a stable pillar located on the roof of the geodetic institute has been selected.

The deflection data acquired covers a wide spectrum of environmental conditions. Besides daytime and season-dependent residual effects, most different weather situations (temperature, air pressure) and resulting refraction anomalies are implicitly contained in the deflection data as well as the impact of various star fields taken from star catalogues Tycho-2 (Høg et al. 2000) and UCAC (Zacharias et al. 2004) used for astrometric data reduction.

Table 4. Comparison at station Hannover

Data Set	ξ [$''$]	η [$''$]	$\Delta\xi$ [$''$]	$\Delta\eta$ [$''$]
TZK2-D Mean	6.47	1.15		
EGG97	6.60	1.15	**-0.13**	**0.00**

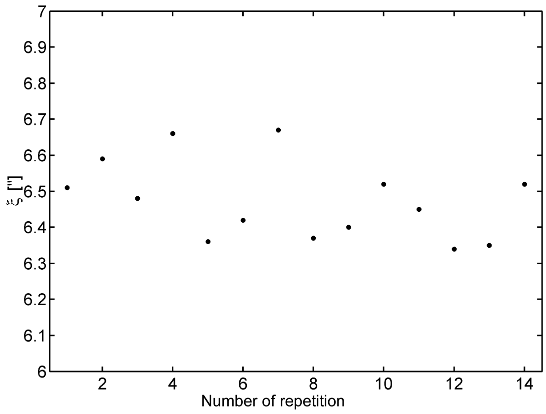

Figure 3. TZK2-D observations of ξ at station Hannover

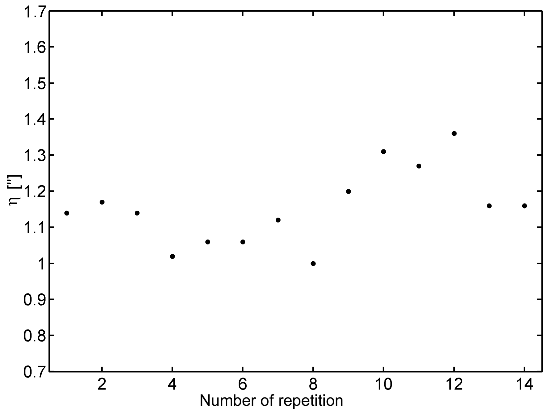

Figure 4. TZK2-D observations of η at station Hannover

Figures 3 and 4 show the observation results for the Hannover station. The standard deviation of the (ξ, η) mean values obtained at different nights is $0\overset{\prime\prime}{.}11$ for both components; the scattering interval obtained as max-min values of the observation series is less than $0\overset{\prime\prime}{.}35$. In conclusion, the observation of vertical deflections using the system TZK2-D reveals a high repeatability under changing environmental conditions. A comparison between measured and computed deflections (from EGG97) shows an excellent consistency with non-significant differences of $0\overset{\prime\prime}{.}13$ in ξ and $0\overset{\prime\prime}{.}00$ in η (Table 4).

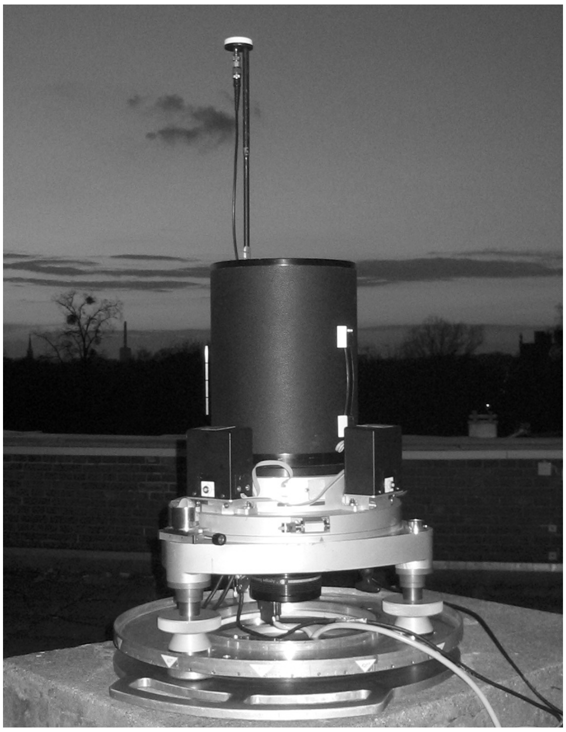

Figure 5. The Digital Zenith Camera System TZK2-D at station Hannover

4 Comparative Measurements in Benthe

At Benthe near Hannover, 10 different stations have been occupied twice in various nights. Regarding the residuals of the double measurements, standard deviations below $0''.10$ are obtained (cf. Hirt and Reese 2004; Hirt 2004). At one station, measured and computed deflections were compared (Table 5). In both components, the discrepancies are less than $0''.10$ as such being non-significant.

Table 5. Comparison at station Benthe

Data Set	ξ [$''$]	η [$''$]	$\Delta\xi$ [$''$]	$\Delta\eta$ [$''$]
TZK2-D Mean	7.07	2.71		
EGG97	7.01	2.80	**0.06**	**-0.09**

5 Discussion

The accuracy of vertical deflection measurements using the Digital Zenith Camera TZK2-D has been comprehensively investigated at different sites in Northern Germany. Based on the results obtained both by means of numerous repeated and comparative measurements, a reasonable external accuracy estimate is $0''.10$ to $0''.15$.

Compared to the accuracy level of the Digital Zenith Camera System TZK2-D, the accuracy of formerly used analogue (photographic) zenith cameras has been found to be in the order of $0''.5$ (cf. Seeber and Torge 1985; Wissel 1982; Bürki 1989). Hence, the accuracy level of the Digital Zenith Camera TZK2-D exceeds those of the analogue zenith cameras considerably by a factor of 3 to 5.

Some application fields significantly benefit by the accuracy improvement achieved. Highly precise deflection data provided by the system TZK2-D opens a new level of accuracy for local astrogeodetic geoid determinations. Even the millimeter-range can be attained economically in local areas by means of astronomical levelling. Typical applications are, for example, the validation of geoid models, the analysis of the fine structure of the gravity field and the localization of density anomalies below the surface (cf. Hirt and Reese 2004). In mountainous regions such as the European Alps highly precise determined vertical deflections serve as valuable observation of the Earth's gravity field for geoid computations (cf. Brockmann et al. 2004; Müller et al. 2004; Marti 2004).

A couple of reasons in combination are responsible for this significant accuracy improvement compared to analogue zenith cameras. Above all, the high-precision star catalogues Tycho-2 and UCAC enable the highly accurate determination of vertical deflections. They provide access to the celestial reference system with external accuracies for star positions of a few $0''.01$ (cf. Zacharias et al. 2000). Furthermore, a high number of repeated observations (usually at least 60 single solutions per station) reduces residual error sources significantly. But also the application of state-of-the-art digital technology for data acquisition and a refined modelling of instrumental systematics contribute to the increased accuracy level.

The difference between the internal accuracy, found to be about $0''.08$, and external accuracy level ($0''.10$ to $0''.15$) most likely comes from zenithal refraction anomalies resulting in tilt of atmospheric layers (cf. Dimopoulos 1982, Ramsayer 1967). Such anomalies can falsify the measured direction of the plumb line and thus the vertical deflection data. This effect is considered to limit the accuracy of the vertical deflection measurements. In order to overcome these restrictions future research should deal with the analysis of atmospheric data sets (e.g. digital weather models) to correct for zenith refraction.

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