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# Experiences with the QDaedalus system for astrogeodetic determination of deflections of the vertical

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**Abstract**: This paper explores the astrogeodetic deflection of the vertical (VD) determination with a light-weight tachymeter-based measurement system called "QDaedalus" developed at ETH Zurich. A description of the relevant components of the system is given to show the set up and operation. The measuring process including CCD-tachymeter calibration and the astronomical data processing are summarized. The paper then analyses the achievable accuracy of VDs based on new measurement data acquired in Bavaria over several nights. Our measurements were executed atop a pillar on the roof of the TUM and at six stations in the Bavarian Alps (Estergebirge) with highly-accurate VDs from previous digital zenith camera measurements available. Our comparisons indicate an accuracy level of 0.15-0.20 arc-seconds for VDs measured with QDaedalus. As a conclusion, our results show that the QDaedalus measurement system is a promising sensor for accurate local astronomical gravity field surveys when a zenith camera is not available or deployable, e.g., away from road infrastructure.

## 1 Introduction

Until the 1990s the astrogeodetic determination of deflections of the vertical was often based on analogue zenith cameras (e.g. Wildermann 1988, Bürki 1989). At the beginning of the 21$^{st}$ century they were replaced by digital zenith cameras which were developed, e.g., in Germany and in Switzerland (Hirt and Bürki 2002, Hirt 2004, Bürki et al. 2004, Müller et al. 2004, Hirt et al. 2010), in Poland (e.g., Kudrys 2009), and more recently in Turkey (Halicioglu et al. 2012), China and Japan (Hanada et al. 2012, Wang et al. 2014, Tian et al. 2014), Latvia (Abele et al. 2012) and Hungary (Hirt et al. 2014). Digital zenith cameras use CCD-technology to enable recordings as well as evaluation in a fully automatic way (Hirt and Bürki 2002). The systems are capable of achieving accuracies of up to 0.05-0.1" for the determination of VDs (Hirt and Seeber 2008). While being very accurate, some of the cameras and required equipment are expensive and, importantly, rather cumbersome, making operation away from road infrastructure difficult. However, VDs may also be required in less accessible terrain too, e.g. for accurate local geoid determination in mountainous regions or developing countries, or as a check of regional or global gravity field models. Here the operation of zenith cameras may be restricted, requiring alternative instrumentation.

Over the past years ETH Zürich developed an alternative measurement system called QDaedalus (Guillaume et al. 2010, 2012, Guilllaume and Bürki 2014, Charalampous et al. 2015) which is considerably lighter than some of the existing zenith cameras (e.g. TZK2-D by University of Hannover, Germany or DIADEM by ETH Zurich, Switzerland) and thus better to operate in less accessible terrain. QDaedalus combines a precision tachymeter and CCD-imaging for astronomical positioning, which follows a concept that has been investigated by Schirmer (1994). A QDaedalus system was acquired by the Institut für Astronomische und Physikalische Geodäsie (IAPG, TU Munich) in 2014. Given the QDaedalus system is relatively new, there are only few experiences with the QDaedalus system reported in the literature. To our knowledge, the achievable accuracy for VDs measured with QDaedalus has not yet been studied in detail with the help of high-quality external comparison data.

The present paper reports first experiences made with the QDaedalus system - and its measurement accuracy - at TU Munich. This includes a description of the hardware components (Section 2), the instrumental handling (set-up and measurement process, Section 3) as well as the data reduction (Section 4). Attention is placed on the accuracy analysis of QDaedalus VD data based on new measurements carried out in Munich and in the Bavarian Alps at selected field stations with high-quality independent comparison data available (Section 5). Our findings are discussed and summarized in Section 6.

It should be noted that QDaedalus is a measurement system for a number of tasks in geodesy and surveying. Besides VD determination, astronomical azimuths can be measured, even during day time through observation of Sun, Moon or Planets (Völgyesi et al. 2014). In engineering geodesy, QDaedalus has been shown to be suited for measurement of structural displacements (Guillaume et al. 2012b, Charalampous et al. 2015). In this paper we solely focus on the astrogeodetic application of QDaedalus for VD measurements.

The basic principle applied in QDaedalus to determine the instrument's position in terms of astronomic coordinates (astronomical latitude and longitude $\Phi,\ \Lambda$) is based on the base line method (Torge and Müller 2012). This involves direction measurements to known stars using a CCD-tachymeter (Guillaume et al. 2012). To calculate VDs, geodetic coordinates (latitude and longitude $\varphi, \lambda$) are required which are determined by GPS observations. The two components of the VD ($\xi =$ north-south, $\eta =$ east-west) are obtained via (Heiskanen and Moritz 1967, p. 186):

$$\xi = \Phi - \varphi, \quad (1)$$
$$\eta = (\Lambda - \lambda) \cos \varphi. \quad (2)$$

VDs from Eq. (1) and (2) are defined at the Earth's surface and follow the Helmert definition (Jekeli 1999). Second- and higher-order terms, which are neglected here, are provided in (Pick et al. 1973, p. 432) and Jekeli (1999). Generally, VDs describe the angular deviation of the true vertical – defined by the direction of the Earth's gravity vector – with respect to some reference direction (Jekeli 1999) In case of QDaedalus we use the geometric definition of the reference direction identifying it as ellipsoidal normal. VDs can be used to determine the local geoid or quasigeoid following the principles of astronomical levelling, astronomical-topographic and GPS-levelling (e.g., Torge and Müller 2012). VDs are also important for reduction of precision surveys to the geodetic ellipsoid (e.g., Featherstone and Rüeger 2000) and for testing of high-resolution geopotential models.

## 2 Components of the QDaedalus system

Key components of the QDaeadalus system are a Leica tachymeter (Leica 2006), a CCD camera AVT Guppy F-080C (AVT 2008), a GPS-antenna ANN-MS-0 (u-blox 2013), and a standard laptop computer. Further, there is a dedicated QDaedalus interface box (where an u-blox LEA 6T GPS-only receiver (u-blox 2015) is embedded) which is responsible for the communication between all components and for tagging of the acquired images with GPS time. The power supply for all units of the system is provided by an external 12 V battery. All components are shown in Fig. 1.

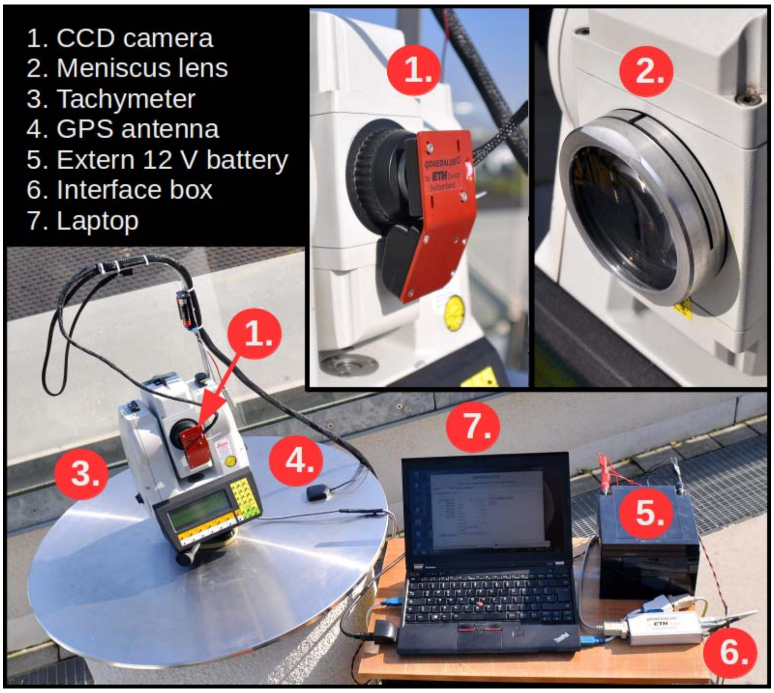


**Fig. 1** QDaedalus system on the roof of the TUM. Note that the tachymeter shown is the Leica TDA5005, while the results in this study are based on measurements with a Leica TCA2003.

Importantly, a tachymeter with a Leica GeoCom-interface is a prerequisite for use together with the QDaedalus software. At TUM, a Leica TCA2003 tachymeter was used for all measurements reported in this paper. The TCA2003 is capable of measuring (single) directions to 0.5" accuracy, facilitating sufficiently accurate direction measurements to reference stars. For the digital imaging of reference stars the AVT Guppy F-080C CCD sensor is applied. It replaces the ocular of the tachymeter to enable automatic star observation. The chip size of the CCD sensor is 1024x768 pixel with a respective size of 4.65x4.65 microns. Using a FireWire port, it is capable of transmitting up to 30 frames per second. The shutter time can be freely selected, depending on the brightness of the measuring environment. As a guide, a shutter time of 300 ms is suitable for well-defined star images on the CCD. The operation of the CCD-tachymeter combination requires an additional lens (meniscus lens) placed in front of the tachymeter's objective (telescope). The meniscus lens shifts the focal point into the CCD imaging plane.

The sensors (tachymeter, CCD, and GPS) are controlled by dedicated QDaedalus software (Guillaume et al. 2010) that runs on the laptop computer. The software is responsible for the automatic steering of the tachymeter, particularly the motorized pointing of the telescope towards the reference stars, and the data acquisition. The data acquisition involves (i) circle readings of the tachymeter, (ii) acquisition of CCD star images, and (iii) recording of the associated GPS epochs.

## 3 Measuring process

At field stations, operation of the QDaedalus system requires some preparatory steps. These include setting up and levelling the tachymeter at the observation site. Furthermore, the cable clamp including the camera must be mounted on the total station. The camera is connected with the computer via FireWire and with the interface box. The GPS antenna is positioned and connected to the interface box as well. The interface box itself is linked to the computer via USB and the connection between tachymeter and computer is established by the GeoCom cable. It is convenient to have a small table to allow for room for the hardware. Fig. 1 shows the complete installation of the QDaedalus system on the roof of the TUM.

An important prerequisite for accurate QDaedalus VD measurements is the calibration of the camera. The main goal of the calibration is the determination of calibration parameters to enable the transformation between CCD (plane) and tachymeter (spherical) coordinate frames. As a terrestrial target object for the calibration, a small, illuminated, punctual and immobile target is chosen with a high contrast to the environment. In our studies a small flashlight was used as target, which we dimmed such that the illumination characteristics of the target (during calibration) and stars (during measurement) are largely similar. The calibration method used here is the grid (spatial point array) overlay of the CCD sensor (cf. Guillaume et al. 2010, 2012). The observations are done at various locations covering the whole of the CCD sensor. This is accomplished by slightly changing the orientation of the telescope after each measurement. The calibration measurements are executed fully automatically in two camera faces to reduce the impact of the standard systematic errors of the tachymeter on the calibration.

After completion of the calibration, geodetic coordinates (latitude and longitude) of the observation site are determined using the inbuilt GPS equipment. The last step preceding the actual star observation is the orientation of the telescope. For this task Polaris is used because it has almost no apparent movement over the celestial sphere. The sighting on Polaris involves manual star pointing and manual telescope focussing, changing the focus from the terrestrial target to infinity such that a well-defined and sharp star image is obtained. For observation sites located in the Southern Hemisphere, one would use, e.g., Sigma Octantis as the star brighter than 6th magnitude that is closest to the Southern Celestial Pole.

The process of direction measurements to stars with QDaedalus is as follows. First, suitable stars are selected from a star catalogue (details in Section 4) such that (i) their zenith distance is in the range of 29° to 31° at the observation site, and (ii) they are evenly distributed in four azimuth classes ranging from 0° … 90° to 270° … 360°. This follows classical observation strategies in geodetic astronomy, e.g., Torge and Müller (2012), p. 166ff. Only stars with a magnitude of 6 and brighter are sighted. The QDaedalus software determines the sequence of observable stars depending on their relevance for an even distribution in the four azimuth classes (observation programme).

Next, the tachymeter is approximately oriented towards a selected star. Subsequently CCD camera and GPS receiver are set into trigger mode and both are triggered simultaneously, followed by synchronizing the camera shutter with GPS time via the interface box. Simultaneously, the direction of the telescope (horizontal and vertical) are read and transferred to the laptop, along with the CCD image. Once the star has been sighted and successfully matched by the software against the star catalogue (Section 4), it is measured at least 4 times in succession before moving to the next star. This is done in order to reduce random errors associated with atmospheric scintillation and instrumental circle readings.

The described measurement process is applied for any star of the observation programme. During the programme there is no need for further interaction by the observer, apart from occasionally guiding the camera cable. The total number of observations depends on the total observation time per session, i.e., an observation programme that usually lasts about 10-15 minutes. It comprises several repeated measurements to about 20 different stars. As a rule, for a 15 minute session the total number of star measurements is about 250-300. From our experience, it is advisable to execute 3 or 4 sessions at one point with a total observation time of 10-15 minutes for each session.

## 4 Data processing

This section briefly introduces the basic ideas of the processing of QDaedalus measurement data, from star observations to vertical deflections. The mathematical models are summarized rather than described in every detail to avoid duplication of textbook knowledge. In a first step, the CCD image coordinates of the star are determined using a centre-of-mass-algorithm, where (i) all pixels of a star image are identified based on the grey value (brightness) and (ii) followed by a weighting of image coordinates of identified pixels with their grey value (e.g., Stone 1989). The measured, plane star coordinates (in the CCD frame) are then converted to spherical increments using the calibration parameters (Guillaume et al. 2010, 2012) which are added to the tachymeter circle readings. This procedure yields the direction to the star, measured in terms of horizontal directions and zenith angles. Because of the polar alignment of the system (Section 4), the horizontal direction approximately corresponds to the astronomical azimuth of the star.

The QDaedalus system thus measures approximate azimuths and precise zenith angles to known stars in a local topocentric system. The stars position, in terms of right ascension $\alpha$ and declination $\delta$, is taken from the star catalogue FK6 (Sixth Catalogue of Fundamental Stars), (Wielen et al. 1999) as a realisation of the International Celestial Reference System (ICRS). The accuracy of FK6 star positions is well below the 0.01"-level, so more than adequate for VD determination with QDaedalus.

For every star observed, a space vector $X_{topo}$ is computed as a function of azimuth and zenith angle (see Torge and Müller 2012, p 48). The space vector $X_{ITRS}$ represents the spatial direction of the star $S\ (\alpha, \delta)$ at the time $t$ in the International Terrestrial Reference System (ITRS). The QDaedalus software computes $X_{ITRS}$ as a function of $X_{ICRS}$ , which is the star's space vector in the ICRS, using the NOVAS-C routines (Kaplan et al. 2009). The computation of $X_{ICRS}$ from right ascension $\alpha$ and declination $\delta$ involves corrections for proper motion, parallax and aberration. The corrections are detailed in Kaplan et al. (1989) and Kaplan et al. (2009), so not repeated here. Astronomical latitude and longitude $(\Phi,\ \Lambda)$ are then the unknown parameters that establish the mathematical relation of $X_{topo}$ and $X_{ITRS}$. Fig. 2 shows the relations between the three space vectors $X_{ITRS}, X_{ICRS}$ , $X_{topo}$ involved in the determination of $(\Phi,\ \Lambda)$.

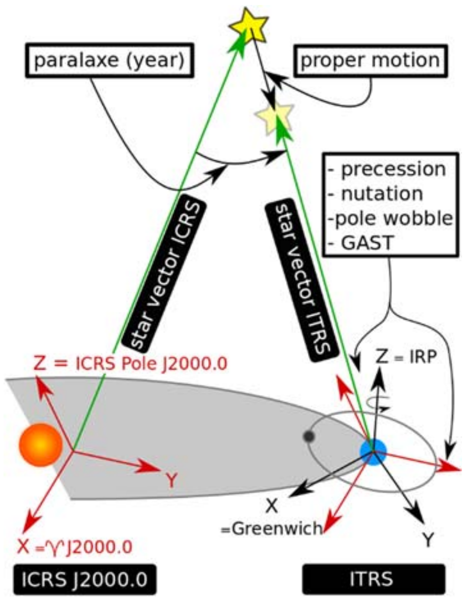


**Fig. 2** Mathematical Model for QDaedalus (after Guillaume et al. 2012).

The transformation from the celestial reference system ICRS into the terrestrial reference system ITRS requires spatial rotations, which depend on Earth Rotation Parameters (ERP) and nutation/precession matrices (Eq. 4). The QDaedalus software uses the IAU (1980) nutation and precession theory and numerical ERP values, which are sufficiently accurate for the purpose of astronomical VD determination (e.g., Hirt 2004). To compute precise astronomic coordinates $(\Phi,\ \Lambda)$, ERPs are provided for observation session.

Equations 3 and 4 describe the fundamental relation between the transformations as mathematical model used in the QDaedalus software (Guillaume et al. 2012):

$$X_{topo}(t) = T(\Phi, \Lambda) X_{ITRS}(t) \quad (3)$$

$$X_{ITRS}(t) = R_2(-x_p) R_1(-y_p) R_3(\mathrm{GAST}) N(t) P(t) X_{ICRS*}(t). \quad (4)$$

where $T(\Phi, \Lambda)$ is the transformation matrix from ITRS to the local topocentric system, $\Phi, \Lambda$ are the (unknown) astronomic latitude and longitude, $R_2(-x_p)R_1(-y_p)$ are polar motion matrices, $R_3(\mathrm{GAST})$ is the Earth rotation matrix, $N(t)$ is the nutation matrix, $P(t)$ the precession matrix and $t$ = time of the observation (in terms of Julian Date). For definition of the rotation matrices see e.g., Torge and Müller (2012), p 42ff.

The functional models for the observed horizontal directions in the topocentric system are (Guillaume et al. 2012):

$$\hat{r}^* = -\omega_0 + \arctan\left(\frac{y_{topo}}{x_{topo}}\right) - \frac{c}{\sin z^*} - i \cot z^* \quad (5)$$

with $\hat{r}^*$ the adjusted observed horizontal direction of the star, $z^*$ the observed zenith angle of the star, $\omega_0$ the orientation unknown w.r.t. astronomical North, $x_{topo}, y_{topo}$ the topocentric horizontal coordinates of the star (normalized), $c$ the collimation error of the tachymeter and $i$ the horizontal axis error of the tachymeter. For the observed zenith angles, the functional model reads

$$\hat{z}^* = \arctan\left(\frac{\sqrt{x_{topo}^2 + y_{topo}^2}}{z_{topo}}\right) - i_z - \delta \quad (6)$$

with $\hat{z}^*$ the adjusted observed zenith angle of the star, $i_z$ the index error of the tachymeter and $\delta$ the atmospheric refraction angle. The observations in Eqs. 5 and 6 are pairs of azimuths $r^*$ and zenith angles $z^*$ for any measured star. As unknown parameters, $\Phi, \Lambda$ (see Eq. 3), $\omega_0$, $i_z$ and $\delta$ are usually introduced. In our experiments and practical measurements, the instrumental axis errors $(c, i)$ were determined through a standard tachymeter calibration before the star observation and applied as corrections. The influence of the atmospheric refraction depends on the zenith angle and is considered by assuming a normal atmosphere, relative to which the (residual) atmospheric refraction angle $\delta$ is determined. The unknowns are iteratively estimated during a robust least squares adjustment (Niemeier 2008), p 202ff. As a last step, the VDs are calculated on the basis of the estimated astronomical coordinates and ellipsoidal coordinates, determined by GPS, through Eq. (1) and Eq. (2).

## 5 Measurements and results

### 5.1 Measurements in Munich

To become familiar with the system, VDs were initially determined atop a pillar on the roof of the TUM over several nights (see Fig. 1). Our main motivation was to investigate the system's precision for VDs as a function of observation time, and, hence, the amount of star observations. For the pillar precise geodetic coordinates ($\sigma_{\varphi,\lambda} \leq 0.001''$) from the TUM precision geodetic network are available which refer to ETRS89. Therefore, the geodetic coordinates, derived from GPS u-blox antenna ($\sim 0.04'' \leq \sigma_{\varphi,\lambda} \leq \sim 0.07''$), were replaced by the more accurate coordinates from the TUM precision geodetic network in our tests.

Measurements were executed with a total observation time between 4 and 9 min, which is equivalent to a session comprising 50 to 150 star observations. In total, VD data from 40 sessions over 3 days were collected. Fig. 3 shows the estimated VD solutions (blue) in a scatter plot together with a preliminary VD reference value from GGMplus (Global Gravity Model plus) that has an accuracy of about 1" over Europe (Hirt et al. 2013). The differences between VDs from QDaedalus and GGMplus are always less than 1" (Fig. 3). Given the GGMplus accuracy, the differences between the model and observations are non-significant and satisfactory.

The computed standard deviations of the 40 VD solutions (4-9 min sessions) are 0.22" for $\xi$ and 0.33" for $\eta$, Table 1. This indicates good measurement precision, considering the fairly short observation times of less than 10 minutes per session. To increase the measurement precision, we extended the total observation time per session to 15 min (equivalent to 250-300 star observations per VD-solution). In this way, 30 sessions each of 15 min duration were completed over four nights. The results of this experiment are reported in Fig. 3 (red) and in Table 1. In comparison to solutions with a shorter total observation time, the scatter of the VD-solutions with a longer total observation time is reduced. The standard deviations for the VDs are 0.20" (for $\xi$) and 0.15" (for $\eta$), showing improved measurement precision especially for the East-West component. Furthermore, there is a difference of approximately 0.2" in the mean values of $\eta$ while the change in the $\xi$ mean values is below 0.1". The experiments show that increasing the total number of observations per session to ~250-300 stars leads to a decreased standard deviation in the estimated VDs.

Based on this results four additional sessions of 30 min duration were executed. The solutions (black) in Fig. 3 show a slight change in the values in the direction of the GGMplus value and decreased standard deviations (Table 1) in comparison to solutions with a shorter total observation time. However, due to the small sample size the statistical power of the VD values and standard deviations is reduced. From an economic point of view the total observation time per session must be balanced appropriately.

Based on the collected VD data described in Table 1, a new astrogeodetic reference solution was formed for the TUM pillar (Table 2). The reference values were computed as weighted average of the VD solutions from all sessions using the session duration as weight. The new reference values may be used for future comparisons with astrogeodetic instrumentation at the same site.

In summary the initial testing of QDaedalus on the roof of the TUM was successful. It has been found that the determination of deflections of the vertical with a high precision (level of 0.15-0.2") is possible within 15 min. Nevertheless, in the absence of a reference value of higher-order accuracy (e.g., better than 0.1”), our experiments at the TUM pillar are not capable of detecting systematic deviations possibly contained in the QDaedalus VD measurements. As such, our experiment gives good indication of the measurement precision, but does not allow conclusions regarding the external accuracy of the VDs.

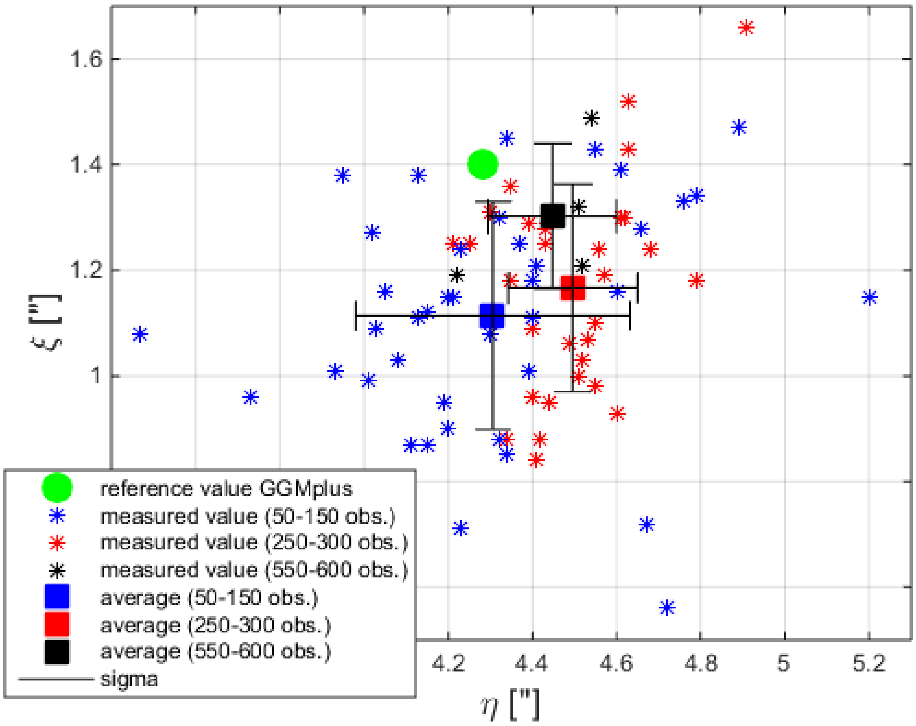


**Fig. 3** Scatter plot of VDs measured at the TUM roof, estimated by 74 sessions with a total observation time of 4-9 min. (blue), 15 min. (red) and 30 min. (black) each together with the GGMplus reference value.

**Table 1** Descriptive statistics of the QDaeadalus VD observations on the TUM roof for (a) short sessions (4-9 min), (b) normal sessions (15 min) and (c) long sessions (30 min). For short sessions, 50-150 star observations were used to compute the VD. For normal sessions, the VDs are based on 250-300 observations each and for long sessions, they are based on 550-600 observations each.

| Session type | Number of sessions | North-South component $\xi$ | | | | East-West component $\eta$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Mean | STD | Min | Max | Mean | STD |
| Short (4-9 min) | 40 | 0.56 | 1.47 | 1.11 | 0.22 | 3.47 | 5.20 | 4.31 | 0.33 |
| Normal (15 min) | 30 | 0.84 | 1.66 | 1.17 | 0.20 | 4.21 | 4.91 | 4.50 | 0.15 |
| Long (30 min) | 4 | 1.19 | 1.49 | 1.30 | 0.14 | 4.22 | 4.54 | 4.45 | 0.15 |

**Table 2** Reference solution for the measuring point on the TUM roof (ellipsoidal height: 587.199 m).

| Reference solution | $\varphi$ [dms] | $\lambda$ [dms] | $\Phi$ [dms] | $\Lambda$ [dms] | $\bar{\xi}$ ["] | $\bar{\eta}$ ["] |
|---|---|---|---|---|---|---|
| Measuring point | 48 08 57.61 | 11 34 06.70 | 48 08 58.77 | 11 34 13.34 | 1.17 | 4.38 |

## 5.2 Measurements in the Bavarian Alps

In order to investigate the external accuracy, we carried out dedicated QDaedalus VD observations in the Bavarian Alps (Estergebirge) where VD comparison data with an accuracy of about 0.08" is available from previous measurements with a digital zenith camera (TZK2-D), cf. Hirt and Flury (2008). Our VD comparison data set comprises six stations (sites) which are part of a data set of 103 stations arranged along a 23 km long profile located in the Isar valley near the Estergebirge mountains. The VD comparison data was collected with the TZK2-D instrument in 2005.

VD measurements with QDaedalus were carried out by a measurement team of two persons in 2 nights at 6 stations of the existing VD profile, with one station occupied in both nights (station 153). At each station, between 2 and 4 sessions (each comprising 15 minutes) were completed. The observed VDs and comparisons with the reference values from the digital zenith camera are reported in Table 3 and Table 4 for the six stations. The residuals are mostly at the level of 0.2" and always smaller than 0.6". The standard deviation of VDs from 15 min sessions were calculated from the residuals between the session results and TZK2-D reference VDs, yielding values of 0.24" for $\xi$ and 0.20" for $\eta$ (Table 5).

Next, we formed mean values of all consecutive sessions at each station, effectively increasing the observation time to ~30-60 minutes. For these VD mean values from QDaedalus, the residuals are at the level of 0.15", with the maximum not exceeding 0.4". The standard deviations computed from these residuals are 0.18" for $\xi$ and 0.16" for $\eta$ (see Table 5). These values are a good indication of the (external) accuracy of QDaedalus VD measurements. However, given the rather small sample size (seven 30-60 min measurements at six stations), further measurements are required for a more comprehensive accuracy assessment. We also note that the residuals between QDaedalus and TZK2-D VD observations reflect uncertainties from both measurement systems, bearing in mind that the TZK2-D data is not error-free. As such it is reasonable to conclude that some (albeit small) portion of the residuals is the result of TZK2-D measurement errors too, cautiously suggesting that the computed standard deviations for QDaedalus are somewhat too pessimistic.

From a visualisation of the residuals for each session (Fig. 4 left) and for the mean value of all sessions at each site (Fig 4 right), there are virtually no notable significant residual errors with systematic character included in the measurements. From the good agreement in $\eta$-direction, implicit evidence is obtained that systematic timing errors, which would be associated with the shutter and GPS-based time tagging procedure, play a negligible role for QDaedalus measurements. Altogether, the solutions determined with QDaedalus at six different locations in the Bavarian Alps show very good agreement with the solutions of the digital zenith camera. In turn, we surmise that the VD observations atop the roof of the TUM are of similarly high quality as the results obtained in the Bavarian Alps.

Our field tests have shown that the field use of the system requires a bit of flair and experience such as wiring the system during set-up and guiding the camera cable manually during measurement. This somewhat reduces speed of VD production and the degree of observation automation. It can therefore be said that the QDaedalus system is not yet perfectly matured.

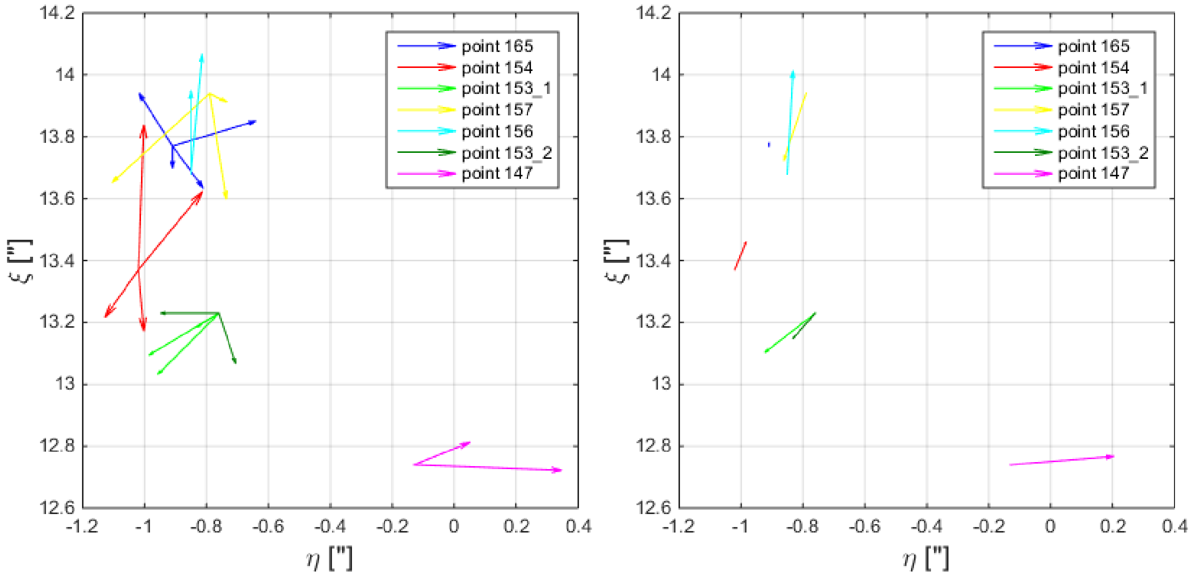


**Fig. 4** Residuals (differences between VDs from QDaedalus and TZK2-D) for all 15 min sessions in the Bavarian Alps centred to the reference value (**left**) and residuals for 30-60 min sessions (**right**). The panel show no systematic behaviour that would be associated with residual instrumental errors.

**Table 3** VDs measured with QDaedalus in the Bavarian Alps in 2014 and comparison with reference values measured with the digital zenith camera TZK2-D in 2005. Results are reported for observations at stations 165,154 and 153 (night 1). For each station, the first line reports the TZK2-D reference VDs, followed by the VDs from the individual QDaedalus sessions. The last line for each station gives the average VDs over all QDaedalus sessions and average residual.

| Solution | $\xi$[''] | $\eta$[''] | $v_{\xi ref}$[''] | $v_{\eta ref}$[''] |
|---|---|---|---|---|
| Point 165 ref. | 13.77 | -0.91 | | |
| No. 1 | 13.96 | -1.11 | 0.19 | -0.12 |
| No. 2 | 13.86 | -0.69 | 0.09 | 0.30 |
| No. 3 | 13.69 | -0.98 | -0.08 | 0.00 |
| No. 4 | 13.62 | -0.87 | -0.15 | 0.11 |
| Average | 13.78 | -0.91 | 0.01 | 0.00 |
| Point 154 ref. | 13.37 | -1.02 | | |
| No. 1 | 13.20 | -1.14 | -0.17 | -0.12 |
| No. 2 | 13.15 | -1.00 | -0.22 | 0.02 |
| No. 3 | 13.89 | -1.00 | 0.52 | 0.02 |
| No. 4 | 13.65 | -0.79 | 0.28 | 0.23 |
| Average | 13.47 | -0.98 | 0.10 | 0.04 |
| Point 153(1) ref. | 13.23 | -0.76 | | |
| No. 1 | 13.01 | -0.98 | -0.22 | -0.22 |
| No. 2 | 13.18 | -0.84 | -0.05 | -0.08 |
| No. 3 | 13.08 | -1.01 | -0.15 | -0.25 |
| Average | 13.09 | -0.94 | -0.14 | -0.18 |

**Table 4** VDs measured with QDaedalus in the Bavarian Alps and comparison with reference values measured with the digital zenith camera TZK2-D. Results are reported for observations at stations 157,156 and 153 (night 2) and 147.

| Solution | $\xi$["] | $\eta$["] | $v_{\xi ref}$["] | $v_{\eta ref}$["] |
|---|---|---|---|---|
| Point 157 ref. | 13.94 | -0.79 | | |
| No. 1 | 13.56 | -0.73 | -0.38 | 0.06 |
| No. 2 | 13.62 | -1.14 | -0.32 | -0.35 |
| No. 3 | 13.91 | -0.73 | -0.03 | 0.06 |
| Average | 13.70 | -0.87 | -0.24 | -0.08 |
| Point 156 ref. | 13.68 | -0.85 | | |
| No. 1 | 13.98 | -0.85 | 0.30 | 0.00 |
| No. 2 | 14.11 | -0.81 | 0.43 | 0.04 |
| Average | 14.05 | -0.83 | 0.37 | 0.02 |
| Point 153(2) ref. | 13.23 | -0.76 | | |
| No. 1 | 13.23 | -0.97 | 0.00 | -0.21 |
| No. 2 | 13.05 | -0.70 | -0.18 | 0.06 |
| Average | 13.14 | -0.84 | -0.09 | -0.08 |
| Point 147 ref. | 12.74 | -0.13 | | |
| No. 1 | 12.72 | 0.40 | -0.02 | 0.53 |
| No. 2 | 12.82 | 0.07 | 0.08 | 0.20 |
| Average | 12.77 | 0.24 | 0.03 | 0.37 |

**Table 5** Standard deviations of VDs computed from residuals between QDaedalus observations and TZK2-D reference values. Results are reported for (a) residuals from each sessions (b) residuals between the mean value of all QDaedalus sessions and the TZK2-D reference values. For numerical values of all residuals used to compute the standard deviations see Tables 3 and 4.

| Session duration | Number of sessions | Standard deviation for $\xi$ | Standard deviation for $\eta$ |
|---|---|---|---|
| Individual sessions (15 min observation time) | 20 | 0.24 | 0.20 |
| Mean of all sessions (30-60 min observation time) | 7 | 0.18 | 0.16 |

## 6 Conclusions

In this paper the structure, function, practical operation and data processing of the QDaedalus system were presented, followed by an investigation into the accuracy of QDaedalus deflection of the vertical data. Our measurements atop the roof of the TUM have shown that the system is capable of determining and reproducing deflections of the vertical with a high precision. Of particular value were the QDaedalus measurements in the Bavarian Alps allowing a comparison with highly-accurate VD observations from the digital zenith camera TZK2-D. These comparisons yielded evidence for the (external) accuracy of VD data from the QDaedalus system being in the range of 0.15" and 0.20" for ~30-60 minute observations. For shorter observation times of about 15 minutes, the VD accuracy was found to be at the level of 0.20" to 0.25". As such, VDs from QDaedalus are of high quality, but not quite as accurate as those from digital zenith cameras (better than 0.1"). Our results also show that the 0.3-0.4" accuracy specification of the developers (Guillaume and Bürki 2014) is rather conservative.

As a key conclusion of our paper, the QDaedalus system can be considered as an adequate means for astrogeodetic determination of VDs when a digital zenith camera is not available (such as at TU Munich) or deployable (e.g., when observations are needed in rugged terrain away from roads).

Future investigations should look at optimizing the zenith angle of target stars (currently 30° ± 2°), the role of observations of stars in two positions (now one position, relying on instrumental calibration). Of interest are comparative measurements deploying two or more QDaedalus systems simultaneously to separate instrument-specific from external error sources such as anomalous refraction (e.g. Hirt 2006).


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