Further development and geodetic applications of the QDaedalus system (Professional final report of OTKA)

The earlier classical method of determining deflection of vertical (DOV) was related to astronomical position determination. Due to the rather lengthy and costly method, such measurements were made only at a very small number of points. At present, in Hungary there are only 138 points with 0.3-0.5 arc-second accuracy of DOV values, which are the most important input data for geoid determination. In recent times, significant progress has been made with the GGMplus model calculation and especially with the possibility of applying the QDaedalus measurement system.

The QDaedalus system was developed by experts of the Technical University of Zurich, and the Department of Geodesy and Surveying of the Budapest University of Technology and Economics was also involved in the use and development of the system. QDaedalus is an automatic measuring system supplemented with GNSS technology, whose basic geodetic instrument is a suitably modified Leica TCA1800 total station. The system is capable of determining DOV values with an accuracy of 0.1-0.3 arcseconds in just 20-30 minutes measuring periods, depending on the measurement conditions.

The precise time signal required for astronomical measurements is provided by the GNSS receiver integrated into the system, which also provides the WGS84 ellipsoidal coordinates. The conceptual design of the complete system is shown in Figure 1.

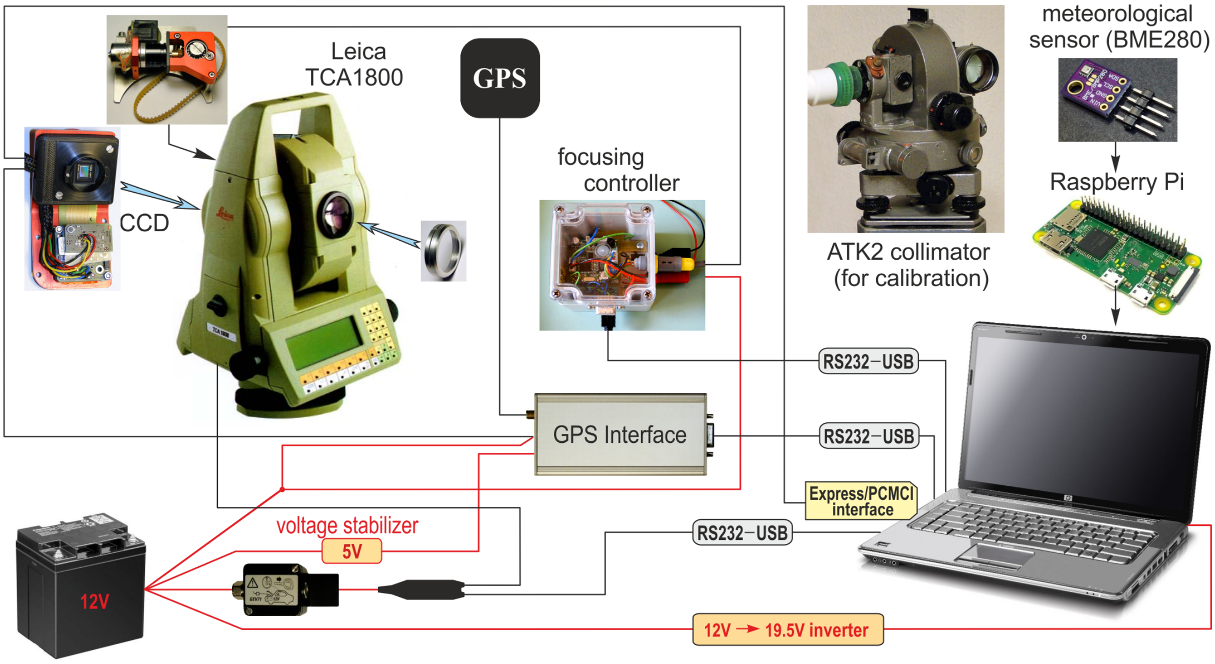

Figure 1. Schematic structure of the QDaedalus system

The GNSS system provides data in two directions: it supplies the CCD sensor and the control computer with an accurate time signal for astronomical imaging, and it also transmits WGS84 coordinates to the computer via an RS232 to USB converter. The large data stream of images captured by the CCD sensor is transferred to the control/processing computer via a high-speed connection using PCMCIA or EXPRESS CARD. The automatic search and measurement of the stars is also controlled by the external computer via another RS232-USB channel and an interface of the total station.

The whole system is controlled and processed the data by the QDaedalus software. This controls the movement of the total station, controls the focusing of the telescope, searches for the measured stars in sequence, receives and processes the CCD sensor images, manages the GNSS data, sorts the initial and measured data into a database, determines the astronomical and geodetical latitudes and longitudes by adjustment, and determines the DOV values on the spot.

Calibration is the most important initial step in the measurement process, linking the readings taken on the horizontal and vertical circles of the total station with the data recorded in the CCD sensor's coordinate system. This operation is followed by the actual measurements on the stars. The measuring system searches for a series of stars around on the zenith axis within a zenith-axes cone angle range 30º±2º takes a series of images of them, then automatically evaluates the images and determines the celestial equatorial coordinates of the zenith point. From this, after a series of corrections and coordinate transformations, the DOV values are obtained.

Our research results have been published in 6 national and 2 international conference presentations and 10 publications so far during the research grant period. Studies on our latest research results have not yet been published, but we are currently preparing a paper for publication in Geophysical Journal International (Q1). The topic of QDaedalus is already presented at the Department of Geodesy and Surveying in the Geophysics and Physical Geodesy and Gravimetry subjects. So far, 3 diploma plans have been completed and a PhD research has been started on this topic.

Our most significant research results are the following.

1. Development of a new calibration method for CCD sensors

The first step in our astronomical measurements is the calibration of the CCD sensor, which establishes a link between the readings at the total station and the measurement data in the CCD sensor's coordinate system. For calibration, we initially used fixed LED diodes placed at a distance of several hundred meters, but in night field conditions their proper use and handling was difficult and dangerous, and even the light sources placed at a distance of several hundred meters did not produce a perfectly sharp image on the CCD sensor. We also tried to use the α Ursa Min. (Pole Star) for the calibration, but due to its movement, it was also not suitable for accurate calibration. After that, we were looking for a solution that is suitable for simple and accurate calibration even at night in field conditions. We managed to solve the problem by using a collimator. Our collimator is an auxiliary telescope that produces parallel beams of light from an object placed at the focal point on the side of the eyepiece, just as parallel beams of light from infinitely distant objects (stars) enter our instrument. Our collimator for calibration measurements is a suitably modified ATK-2 astronomical instrument with its parallax fixed at infinity. The calibration object in the ATK-2 instrument is a crosshair placed at the focal point, and we created special LED lighting to illuminate it.

In our measurements and tests, we have addressed the optimal number of calibration measurements, the determination of the optimal calibration matrix size and the effect of temperature variation. We have found that a minimum of 10 calibration measurements is recommended when using the QDaedalus system, however, more than 15 measurements will not significantly improve the measurement results. The area of the CCD sensor included in the calibration measurement can be varied depending on the size of the calibration matrix and the grid spacing. We found that increasing the size of the calibration matrix does not result in a significant increase in the accuracy of the principal point position with a significant increase in the measurement duration. Matrix sizes of 2×2 and 3×3 are most suitable, and the optimal solution is to increase the number of measurements with a smaller matrix size. We have investigated how much error is caused by temperature variation in the system operation. We found that the temperature change between the start of calibration and the end of the astronomical measurement should not be more than 2 degrees Celsius. In the case of intensive cooling at night (decrease in temperature), calibration measurements should be taken before and after the astronomical measurement and the average value should be used to calculate the position of the principal point and the transformation parameters (Völgyesi-Tóth 2018, 2019, 2020).

2. Calibration measurements of the QDaedalus system

In order to check the correct operation of the measuring system, it is necessary to periodically perform comparative measurements at a suitable calibration point where the value of the DOV components is known with high accuracy. For calibration measurements, we have established the *Pistahegy* point, where from 2013 to now we have made a total of 266 astronomical measurements with different instruments in different seasons between −14 and +32 degrees Celsius, under extreme atmospheric pressure, humidity and a wide range of meteorological conditions. To the best of our knowledge, such a large number and the very long term of our measurements have never been made at the same point anywhere in the world, and so the $\xi = -2.33''$, $\eta = 5.14''$ DOV is probably one of the most accurate values in the world (Tóth-Völgyesi 2017, 2019; Völgyesi-Tóth 2021).

3. Investigation of the effect of atmospheric refraction

The most significant source of error in all astronomical measurements is the phenomenon of atmospheric refraction, which is a function of the physical state of the atmosphere and meteorological conditions. The *Pistahegy* point is not only well suited for calibration measurements, but also for the study of atmospheric refraction, since the deviation of individual DOV measurements from the very accurate mean value is due to the atmospheric refraction. For these analyses, we processed a significant part of the measurements (averaged over 30 minutes time-period) at *Pistahegy* point using two different methods (resistant adjustment with the Danish method and robust adjustment with Cauchy-Steiner weights). In each case, we determined the DOV components based on the standard refraction model found in the literature. We then examined the relationship between the DOV components and the in situ temperature and barometric pressure data. Our hypothesis is that if the measured values are mainly affected by some kind of unaccounted refraction effect, then we should find a clear relationship between our measurements and the temperature, humidity and barometric pressure at the time of measurement. We found the strongest positive correlation between the measured temperature and the results of the N-S direction of the DOV component processed with Cauchy-Steiner weights. Although the temperature and barometric pressure data are correlated, our measurements correlate less well with the barometric pressure data (the relationship is negative), so it is highly plausible that the maximum ±0.5" DOV variations are mainly caused by local refraction effects (Tóth-Völgyesi 2017, 2019).

We have also performed some post-processing of the GNSS measurements for meteorological purposes and compared the results with the errors of DOV determined by the QDaedalus measurements with the aim of reducing the effect of atmospheric refraction. Unfortunately, no correlation was found.

4. Software and hardware developments

Since the original QDaedalus software does not provide the opportunity to reprocess the measurements or try out different processing versions after the measurement is completed, we developed our own new processing software. With this software, called QDBME, it is possible to post-process the measurement results stored in the original database and to apply own processing algorithms. The own software is able to calculate astronomical coordinates and DOV values, and also to apply different calibration processing procedures using the instrument calibration files. By examining the measurement corrections obtained by processing the QDaedalus measurements using the traditional resistant Gaussian least squares (Danish method), we find that the corrections to the horizontal direction values measured by the total station are always significantly smaller within each series of stars than the corrections between series of stars. We suspect that this is because the measuring station is misadjusting the telescope with an unknown value of around 0-15 arcseconds for the first measurements of the series. Therefore, we extended the processing algorithm to include these adjustment errors in the estimated parameters. We also implemented the modified algorithm in the processing software. In addition, we have developed a new robust processing algorithm based on Cauchy-Steiner weights that results in near-optimal parameter estimation for measurement corrections (residuals) that differ significantly from the Gaussian distribution. This algorithm has also been incorporated into the QDaedalus measurement processing software. We have had positive experience with both methods.

By estimating the adjustment errors, the results of processing with the Danish method improved by 25% in terms of the variance of DOV components. On the other hand, the results of processing with Cauchy-Steiner weights were even better by 19% on average based on the measurements of DOV at the *Pistahegy* point (Tóth-Völgyesi 2017). The research results of related mathematical methods are summarized in Awange-Paláncz-Lewis-Völgyesi (2018, 2023).

We have also made significant hardware and software developements by continuously monitoring environmental parameters (temperature, barometric pressure, relative humidity) with high accuracy during the measurement, and we have also significantly improved our measurement processing software in this direction. On the one hand, the software interpolates the continuously measured environmental data to the measurement times and continuously calculates the atmospheric refraction value taking these into account. Compared to calculations with average ambient parameters, the improvement is significant and can exceed ±0.1" over a 30-minute measurement. On the other hand, a new idea has been developed to further improve the accuracy of our astronomical measurements, as the original software did not take into account that the atmospheric refraction value depends on the spectra of the measured stars. Thus, as a result of a significant further software improvement, our software is able to calculate the spectrally dependent refraction. The refraction due to spectra of the stars is also quite significant, reaching ±0.1" for stars of different spectral classes (Völgyesi-Tóth 2021)

5. Azimuth measurements

During the azimuth test measurements performed with the QDaedalus system, we found that the original software is extremely limited to use for daytime measurements. This made it necessary to evaluate the image of the target objects recorded with a CCD sensor using a completely different concept than before. We have carried out extensive research in this area, some of the results of which are reported in our book published by Springer Publishers (Awange-Paláncz-Völgyesi 2020). The post-processing software has been revised and tested. Since computing ephemerides is time-consuming, we developed a 17000-line C program that is called as an external module from the main program. During night measurements, planets can be measured too, so their ephemeris can be calculated with the improved program. The calculation of ephemeris was done using NASA JPL Development Ephemeris for the period 2013-2031. The calculated positions generally agreed within ±0.3", but the solar ephemeris was better, within ±0.05". Unfortunately, professional daytime azimuth determination was not possible due to various hardware problems, the system in this hardware configuration is not suitable for high precision measurements, and a new remote-controlled focus adjustment system based on a different concept has to be designed and built too.

6. DOV measurements with the QDaedalus system

Partly due to the COVID epidemic and partly due to the failure of the measuring system, our field measurements were suspended for almost two years. After replacing the failed components in 2022, we were able to make the QDaedalus system fully suitable for field operations, allowing us to make enough night-time field measurements and to determine enough DOV values to perform astronomical levelling along the selected test section. As a result of the measurements and calculations, we have had very positive experiences with the field applicability of our QDaedalus system. On the one hand, it has been proven that we are able to reliably determine DOV values with an accuracy of a few tenths of a second, even under very unfavourable field conditions. Depending on the distance of the measurement points (depending on the transportation time), DOV values can be measured comfortably and with high accuracy at least 2-4 points per night. Compared with the several months of determination time required for previous astronomical position determinations and taking into account the increased measurement accuracy this is an extremely large advance (Tóth-Völgyesi 2018, Völgyesi-Tóth 2021).

7. Determination of the fine structure of the geoid

The numerical values of DOV depend on the choice of geodetic datum. The current astrogeodetic data are in the HD72 geodetic datum and can be reduced to the geoid from the surface of the Earth using the normal curvature of the vertical line. The quasi-geoid definition, however, requires values on the surface of the Earth, so it is necessary to take into account the datum transformation and the normal curvature of the vertical line. We have developed software that is capable of calculating both effects, so that these data can be used together with the QDaedalus measurements for geoid determination. We have had very positive experience with our studies to determine the fine structure of the geoid. Using the measured and calculated DOV values along our test section, we have determined the section of the geoid by astronomical levelling, which, compared to the Hirt model, is in very good agreement. Our calculations also show that the QDaedalus measurements can be used to determine a very accurate geoid undulation (with a relative accuracy of less than one cm) from DOV values.

8. A new possible method of geophysical researches

Comparing the DOV values determined from our measurements with the values calculated from Hirt's GGMplus global model we find that the difference in the two values offers a new important opportunity for the study of subsurface masses. The reason is that, the QDaedalus measurements determine the true vertical direction, whereas the Hirt model is a theoretical model defined from geopotential data, topographic masses, and *g* measurements, which does not include the gravity effect of subsurface density inhomogeneities. Therefore, the difference between the values we measured with high accuracy and the values calculated with the Hirt model shows the effect of the mass anomalies that are hidden below the surface. This unexpected research result has great practical significance and benefits, since in previous gravity research only the magnitude of the gravity force could be measured and used in geophysical structure research. Now, however, a new opportunity has arisen: with QDaedalus measurements we can determine not the magnitude of the gravity force, but its direction with very high accuracy and with high point density. This, however, is new information on the structure of the gravity. (Papers on this topic are in preparation for publication in prestigious journals.)

Short comment

An accurate knowledge of the local vertical direction – the deflection of the vertical (DOV) – is essential in geodesy. The slow, complicated and insufficiently accurate measurement methods available so far have not allowed the determination of sufficient quantity and quali-ty of data. Therefore, the possibility of its application in geophysics, for example, was not even considered. Now there has been a major turnaround, with the QDaedalus system open-ing up a great potential not only for geodetic but also for geophysical applications. It is expected that the method will be more widely used around the world, and we are among the first in the development and use of this system.

Publications published so far with the support of the OTKA project No.124286

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