Automatic Determination of Vertical Deflections in Real-Time by Combining GPS and Digital Zenith Camera for Solving the “GPS-Height-Problem”

Christian Hirt
Institut für Erdmessung, Universität Hannover, Germany

BIOGRAPHY

Christian Hirt studied from 1995 to 2000 and received his Dipl.-Ing. in Geodesy from the Universität Hannover. He is currently working as Ph.D. student in satellite geodesy and geodetic astronomy under the supervision of Prof. Günter Seeber at the Institut für Erdmessung, Universität Hannover, Germany.

ABSTRACT

The availability of automatic astronomical observation methods like a digital zenith camera in combination with highly developed satellite methods like GPS allows a real-time determination of vertical deflections. They can be utilized for astrogeodetic geoid surveys in geodesy. Physically defined height information is obtained by using geoid information in conjunction with GPS heights. Consequently the “GPS-height-problem” can be solved.

As a state-of-the-art instrument for modern astronomical position determination, a digital zenith camera developed at the Institut für Erdmessung is introduced. The data flow starting from data registration with suitable sensors, data transfer to a computer and data processing by appropriate methods up to astronomical coordinates longitude and latitude and vertical deflections is presented. Emphasis is laid on algorithms for processing digital zenith images in combination with digital star catalogues.

The performance of a real-time software-package for a fully automatical calculation of the astronomical latitude and longitude is described.

Practical results obtained from field tests which verify the system’s accuracy of approximately 0.2 arcseconds for vertical deflections are given. In conclusion, the paper demonstrates possible applications of the automatic determination of vertical deflections in geodesy and geophysics. Current research activities for further improvements of the digital zenith camera’s accuracy and performance are outlined.

1 INTRODUCTION

1.1 ZENITH CAMERA, GPS AND THE “GPS-HEIGHT-PROBLEM”

Before the age of satellite-based positioning systems global position determination have only been conducted by astronomical positioning methods. Main application fields have been (a) navigation at sea, (b) the determination of ellipsoid dimensions as an earth model and the (c) orientation of geodetic networks in geodesy.

During the last decades, the need for very precise, reliable and “easy obtainable” position information has been led to modern satellite-based positioning systems like GPS (Global Positioning System). These systems can be considered not as competitive but supplementary to conventional astronomical positioning methods.

With astronomical methods one yields global position information by using stars as control points. On the other hand, satellite-based methods like GPS utilize satellites (“artificial stars”) as control points. Table 1.1 shows the basic differences between both methods.

	Astronomical methods	Satellite-based methods
Observable	directions	distances (derived from time-differences)
Results	latitude Φ longitude Λ	latitude φ longitude λ height h
Dimension of results	2D	3D
Reference of results	earth’s gravity field	rotational ellipsoid

Table 1.1: Comparison of astronomical and satellite-based methods

A zenith camera can be used to determine the astronomical latitude Φ and longitude Λ by processing zenithal star images. Astronomical coordinates are directly refered to the earth's gravity field and define the direction of the plumb line within the global coordinate system.

Highly developed satellite methods provide three dimensional positions (φ,λ,h) refered to a rotational ellipsoid. The ellipsoidal latitude φ, longitude λ and height h are geometrically defined without any conjunction to the earth's gravity field. Therefore an ellipsoidal height difference Δh between two points does not imply any information about the gravity-field depending phenomenon where water flows. This problem is known as the "GPS-height-problem".

However, many disciplines using GPS like surveying, geodesy and hydraulic engineering need information about the water flow which is only given by physically defined heights like orthometric and normal heights H. The geoid undulation (geoid height) N concatenates the physically defined height H and the geometrically defined height h. Therefore, the combination of GPS and geoid undulation solves the "GPS-height-problem" (equation 1.1 and figure 1.1).

$$H = h - N \tag{1.1}$$

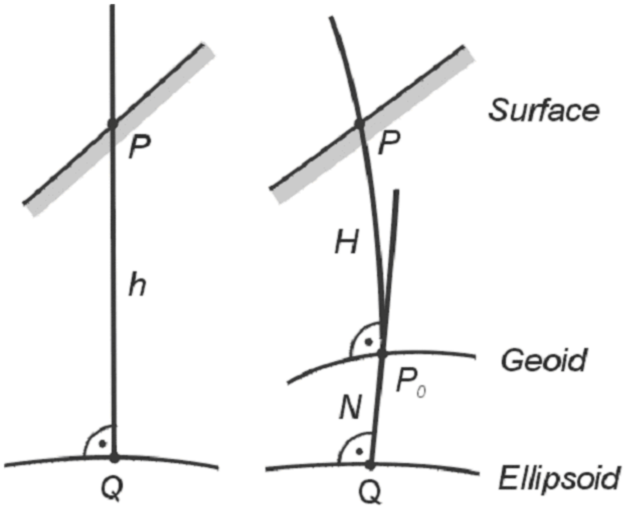


Figure 1.1: Ellipsoidal height h, orthometric height H and geoid undulation N (*Torge*, 2001)

Usually, the geoid undulation N is determined via Stokes' formula from gravity anomalies. In areas with scarce gravity data, however, the accuracy of geoid models is rather weak. There, or at least for limited areas or profiles, N can be obtained by combining satellite-based and astronomical observation methods.

Vertical deflections (η,ξ) can be computed by comparing ellipsoidal coordinates (φ,λ) with astronomical coordinates (Φ,Λ) (*Torge,* 2001):

$$\xi = \Phi - \varphi \tag{1.2}$$
$$\eta = (\Lambda - \lambda) \cos \varphi \tag{1.3}$$

The element ε

$$\varepsilon = \xi \cos \alpha + \eta \sin \alpha \tag{1.4}$$

is the component in azimuth α. Vertical deflections can be interpreted as inclination of geoid W against the ellipsoid surface. The integration of vertical deflections ε along the path ds yields to geoid height differences ΔN.

$$\Delta N = \int \varepsilon \cdot ds \tag{1.5}$$

This classic method of geoid determination is known as astronomical leveling. Figure 1.2 shows its basic principle.

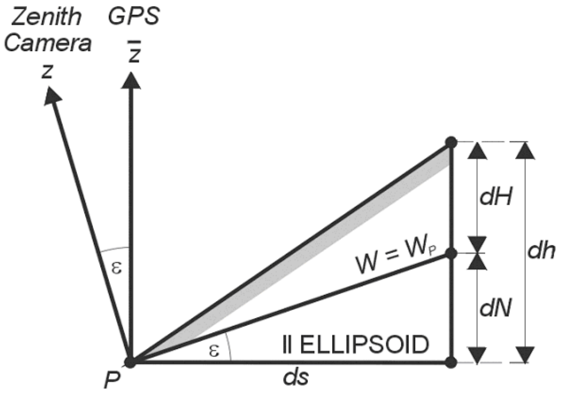


Figure 1.2: Basic principle of astronomical leveling (*Torge*, 2001)

The orthometric (or normal) height difference ΔH can be determined easily by combining ellipsoidal height differences Δh and geoid height differences ΔN between two points:

$$\Delta H = \Delta h - \Delta N \tag{1.6}$$

In order to determine absolute orthometric heights H, the geoid height N for at least one point has to be determined by comparing ellipsoidal height h and orthometric height H got by nivellement. As now geoid heights N - and not only differences ΔN - are known, orthometric heights H are obtained directly from ellipsoidal heights h by applying equation 1.1.

Since the methods of position determination with GPS are known, and the required accuracy for the ellipsoidal coordinates (φ,λ) is not very high, main emphasis in this paper is given to the astronomical part of the problem, i.e., the real-time determination of the astronomical coordinates (Φ, Λ) with a digital zenith camera.

1.2 BASIC PRINCIPLE OF ASTRONOMICAL POSITION DETERMINATION

Methods of geodetic astronomy take advantage of the equivalence between astronomical coordinates latitude Φ and longitude Λ, describing positions on the earth's surface, and equatorial coordinates declination δ_Z and right ascension α_Z, defining star positions on the celestial sphere. As illustrated by figure 1.3, the astronomical latitude Φ of a position on the earth is obviously equal to the declination δ_Z of a star being located in zenith. The astronomical longitude Λ is identical with the star's hour angle t_{GR} refered to Mean Greenwich Meridian, which is equal to the difference of Greenwich Apparent Sidereal Time *GAST* and the star's right ascension α_Z (*Seeber*, 1978):

$$\Phi = \delta_Z \tag{1.7}$$

$$\Lambda = t_{GR} = GAST - \alpha_Z \tag{1.8}$$

Consequently, a star (δ_Z, α_Z) located in the zenith directly gives the astronomical coordinates (Φ, Λ). Usually stars are not located exactly in zenith which is why the zenith direction has to be interpolated into the zenithal star field.

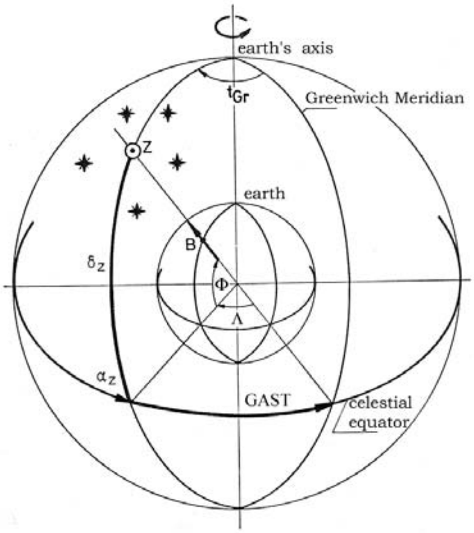


Figure 1.3: Identity between astronomical and equatorial coordinates (*Seeber*, 1978)

2 ZENITH CAMERA

2.1 FORMERLY AND TODAY

The photographic zenith cameras TZK1 and TZK2 have been developed at the Institut für Erdmessung, Universität Hannover between 1974 and 1981 (*Gessler*, 1975), (*Wissel*, 1982). As economic and precise transportable instruments, they have been successfully used for astrogeodetic determination of vertical deflections and geoid undulations in Germany, Denmark, Brazil, Venezuela and other countries. Data processing of photographic zenith camera measurements has been performed analytically: Direction information to stars has been registered with a photo-plate as analogue sensor and measured out at a rectangular two-coordinate comparator by an operator. Further processing steps leading to the astronomical coordinates and vertical deflections have been performed by a computer program (figure 2.1).

Since about 1985 the significance of astrogeodetic geoid determination by using photographic zenith cameras decreases because of time-intensity of the initial data processing steps like film development and manual measurement of image coordinates. Furthermore, the availability of gravimetric measurements and satellite data for economic geoid determination increases considerably.

The development of the so-called charge coupled device (CCD) was initiated by the progress in semiconductor-technology during the past years. A revolution in astronomical observation methods followed. Conventional photographic sensors were replaced by CCD-sensors. Serving both as digital sensor and storage device, a CCD-sensor provides digital image data immediately. Consequently, direct image data processing is feasible. In addition, the light-sensitivity assigned to CCD-sensors outperforms conventional photographic sensors clearly by a factor of 20 to 30. This dramatic development in the area of sensor technology opens new capabilities for astrogeodetic observation methods. An approach comparable to the one described in this paper has already been tested with different instrumentation and software by another research group (*Fosu* et al., 1998).

By the combination of zenith camera and CCD, zenithal star images can be stored digitally and transfered to a computer instantaneously. Suitable methods of digital image processing allow to compute the observer's astronomical position automatically.

The developments make – quite similar to the evolution of GPS – astronomical coordinates in terms of efficiency, real-time capability and reliability available. The *combination* of GPS and digital zenith camera allows the determination of vertical deflections for the calculation of geoid information to a high degree of automation.

2.2 SPECIFICATION AND PERFORMANCE OF THE DIGITAL ZENITH CAMERA

The digital zenith camera TZK2 (figure 2.2) is composed of a lens, a CCD sensor, electronic levels and a time unit for data acquisition. A laptop for device control, data flow control and data processing completes the system.

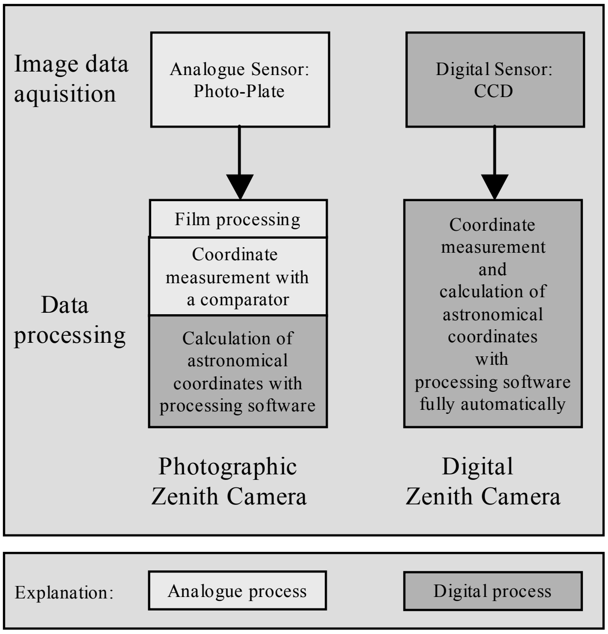


Figure 2.1: Comparison of data acquisition and processing for photographic and digital zenith camera

Focal length	1000 mm
Relative aperture	1:5.6
Field of view	3.5 x 3.5 degrees
Effective field of view	47.4 x 31.6 arcminutes
Size of CCD-sensor	1530 x 1020 pixel
Pixel size	9 x 9 µm

Table 2.1: Specifications of the digital zenith camera

The camera is directed towards zenith point as counterpart of direction of the plumb line. It is turnable around its rotation axis in any azimuth. The zenith direction to be interpolated into the zenithal star field is realized by the rotation axis.

Integral part of the digital zenith camera is a CCD-sensor ST8 by the Santa Barbara Instrument Group (SBIG) consisting of an array of 1530 x 1020 pixel. The array is shown in figure 2.3. Each pixel (size 9 x 9 µm) corresponds to a celestial area of 1.8 x 1.8 arcseconds.

Since only a fraction of the field of view is utilized by the CCD, the digital zenith camera can image a celestial area sized 47.4 x 31.6 arcminutes – this effective field of view corresponds to double the area the sun appears from earth.

Figure 2.2: Digital zenith camera

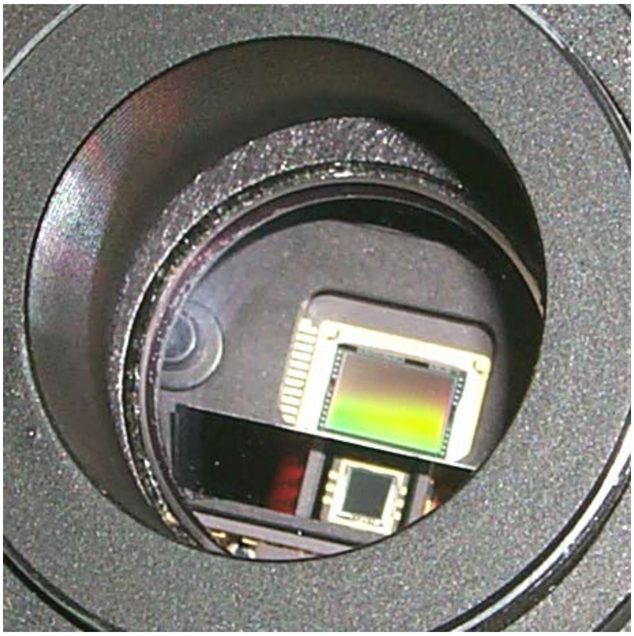


Figure 2.3: CCD-sensor as integral part of the digital zenith camera

Sensor	Magnitude	Number of Stars
Eye	6	4,850
Photographic Zenith Camera	10	324,000
Digital Zenith Camera	14	13,800,140

Table 2.2: Magnitudes and numbers of stars depending on the sensor (*Paech* and *Baader,* 1995)

The digital zenith camera can image stars up to a magnitude of 14.0 mag without compensating earth rotation. If it was possible to image the whole sky, not only a small field of view, the digital zenith camera would image about 13,800,000 stars (table 2.2).

Two electronic levels Talyvel-2 by Taylor-Hobson indicate inclination of the rotation axis against the plumb line to an accuracy of 0.2 arcseconds (*Wissel*, 1982).

With the current equipment, the time measurement is realized by a quartz clock being synchronized with the radio time signal DCF 77. Time is read at the beginning of the exposing interval in order to link equatorial coordinates of stars with the observer's astronomical coordinates (section 1.2). Exact exposure time will be taken from the GPS-receiver in a later version of the system.

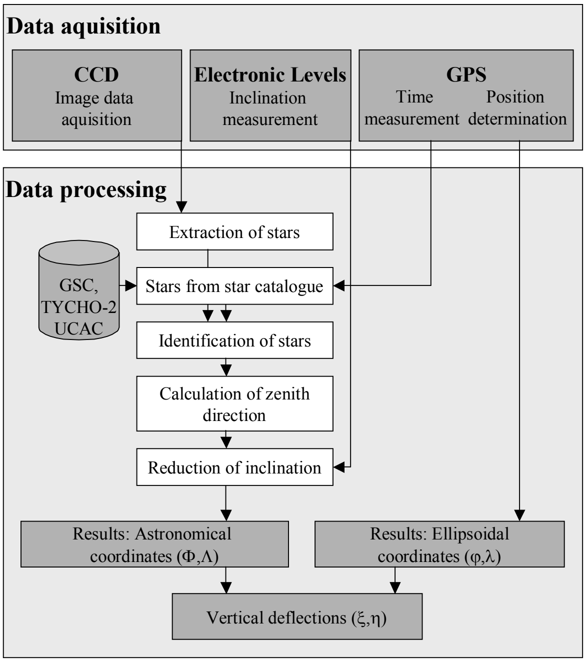


Figure 2.4: Concept of the digital zenith camera

The CCD-sensor is connected to a computer that controls exposure process, exposure time and image data transfer. After transfering digital image data, time measurements, inclination measurements and GPS measurements to the laptop, the astronomical coordinates and vertical deflections are calculated immediately with the algorithms described in section 3.1 to 3.6. They are implemented in the software package AURIGA-ZC for data processing presented in section 4. An overview of the concept of the digital zenith camera is shown in figure 2.4.

2.3 EXAMPLES OF IMAGE DATA

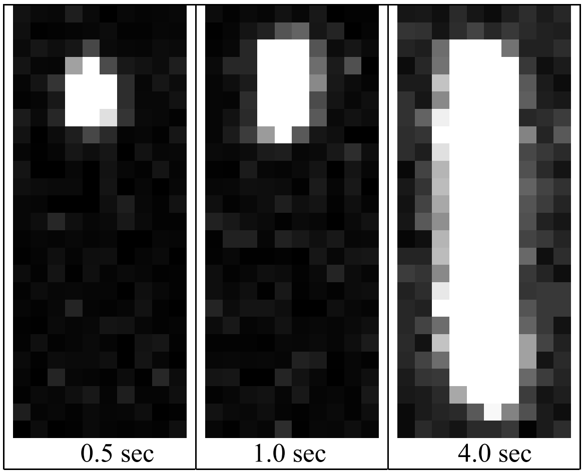


Figure 2.5: Enlarged images of stars depending on the exposure time

Enlarged images of stars are depicted in figure 2.5. A short exposure time (0.5 sec) leads to nearly circular images of the stars. The influence of the earth rotation on the images can be clearly seen in images with exposure times of 1.0 sec and longer. The circularity of star images decreases, they form longish pixel regions.

3 ALGORITHMS AND METHODS FOR DATA PROCESSING

The fundamental algorithms for processing digital zenith images and calculating the direction of the vertical are presented in the following sections.

3.1 EXTRACTION OF STARS

The overwhelming progress in information technology and the increased interest in automatic processing and analyzing of digital images make different image processing algorithms available. Some algorithms are very well suited for the automatic extraction of stars from digital zenith images. The extraction of stars can be formulated as a sequence of two processes:

(1) Detecting stars within the digital image
(2) Measuring the position (image coordinates) of detected stars

The sequence of both processes converts raster graphic into a vector-representation. Hence implicit direction information to stars contained within the image is transformed into an explicit data representation, suitable for further processing steps.

An appropriate method for the star extraction is the so-called region-growing-technique (*Haralick* and *Shapiro*, 1993). As segmentation-based method, the region-growing-technique groups all pixels with similar gray values to autonomous regions called segments. Mainly two groups of segments can be found within a digital zenith image: (a) star images as bright segments in front of (b) darker background regions. We can interpret gray values of those pixels belonging to star images as *signal* with high contrast in comparison to the background. Equations (3.1) and (3.2) allow to compute the average value μ and standard deviation σ of a digital image (*Heipke*, 1999).

$$\mu = \frac{1}{RC} \sum_{r=0}^{R-1} \sum_{c=0}^{C-1} g(r,c) \tag{3.1}$$

$$\sigma^2 = \frac{1}{RC-1} \sum_{r=0}^{R-1} \sum_{c=0}^{C-1} (g(r,c)-\mu)^2 \tag{3.2}$$

where

R,C : size of digital image
$g(r,c)$: gray value at position (r,c)

For the identification of an arbitrary pixel as signal, we can postulate that the corresponding gray value g must differ significantly from the average value μ. In other words, the difference $(g - \mu)$ has to contrast clearly with the standard deviation σ. This is achieved by following expression (*Hirt* 2000):

$$\frac{g-\mu}{\sigma} > 3 \tag{3.3}$$

This expression yields to the threshold value g_S.

$$g > g_S = 3\sigma + \mu \tag{3.4}$$

Every pixel of a star has to exceed the threshold value to belong to a star image formally. The region-growing-technique extracts stars by applying equation 3.4 systematically to every pixel of the digital image. Once a pixel is detected as signal, the gray values of its 4 neighbor pixels have to be checked recursively to form a linked pixel region. Depending on the gray values, all pixel of the digital zenith image are classified either as signal or background. The region-growing-technique yields to linked pixel regions (segments) for each star.

For every segment the position (x,y) of its center has to be measured. A simple and accurate method can be found by weighting the image coordinates (r,c) with the gray value g for each pixel a segment consists of (*Hirt*, 2000):

$$x = \frac{1}{\sum g_i} \sum_{i=1}^{n} r_i g_i \tag{3.5}$$

$$y = \frac{1}{\sum g_i} \sum_{i=1}^{n} c_i g_i \tag{3.6}$$

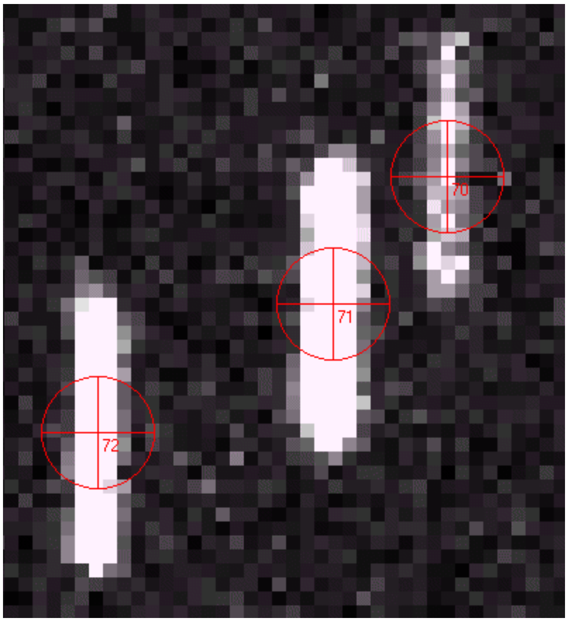


Figure 3.1: The vector graphic shows the results of the star extraction process and measuring process of image coordinates (x,y).

The presented region-growing-technique extracts stars with a sub-pixel-accuracy of about 0.2 pixels – which corresponds to an accuracy of 0.4 arcseconds.

3.2 STAR CATALOGUES

Star catalogues play an important role in geodetic astronomy. As mentioned in section 1.2, the zenith direction has to be interpolated into the zenithal star field. For this purpose equatorial coordinates of zenithal stars are required. They serve as control points and can be taken from a star catalogue.

According to the camera's capability to detect approximately 14,000,000 stars up to 14th magnitude on the celestial sphere, a star catalogue with a high density of stars is necessary. Special attention has to be put on the availability of proper motion for stars. Stars are moving objects in space, so their equatorial coordinates change with time. Only if proper motion is known, its influence on the equatorial coordinates can be taken into account. Otherwise, accuracy of equatorial coordinates decreases with time, which directly has an effect on the accuracy of astronomical latitude and longitude (*Hirt*, 2000).

At the present time, three star catalogues are applicable to astronomical position determination. They can be described briefly as follows:

Catalogue	Stars [Mio]	Mean Accuracy [arcsecs]	Remarks
Tycho-2	2.5	0.06	Low density, Proper motion available
GSC (Guide Star Catalogue)	19.0	0.50-1.00	Proper motion not available, low accuracy
UCAC (U.S.Naval Observatory CCD Astrograph Catalogue)	80.0	0.02-0.07	Proper motion available, catalogue currently only available for southern hemisphere

Table 3.1: Comparison of Tycho-2, GSC and UCAC catalogues

The Tycho-2 catalogue is characterized by the availability of proper motions and very precise positions. Still, the identification of stars (section 3.4) is not satisfactory because of the small number of stars.

On the one hand the Guide Star Catalogue has a high star density, but on the other hand its position accuracy of about 1 arcseconds or less – caused mainly by neglected proper motion – is low. This is why its use for astronomical position determination is limited.

The U.S. Naval Observatory CCD Astrograph Catalogue UCAC is currently only available for the southern hemisphere. Its release for the northern hemisphere is intended for Summer 2003. Obviously the UCAC will be very suitable as reference for astronomical position determination, because it integrates the high accuracy of Tycho-2 and surpasses the density of GSC four times.

Further information on Tycho-2 can be found in (*Hog* et al., 2000a) and (*Hog* et al., 2000b). Information about the GSC is published in (*McLean,* 1996). The performance of the UCAC is described in (*Zacharias* and *Rafferty,* 2000a) and (*Zacharias* and *Rafferty,* 2000b).

Star catalogues provide mean places of stars for a given date. They vary with time because of the influence of different time-depending phenomena. For astronomical observations apparent places of stars are needed, which can be calculated by taking the influence of proper motion, precession, nutation, parallax and aberration on star coordinates into account. Applicable formulas can be found in (*Seidelmann,* 1992).

The star catalogue has to be accessed with minimal and maximal right ascension and declination of the imaged section of the celestial sphere in order to extract a star field corresponding to the stars of a digital zenith image. These coordinates are computed depending on (a) approximate astronomical latitude and longitude of the digital zenith camera, (b) the observing time GAST and (c) the camera's field of view (*Hirt*, 2000).

3. 3 TANGENTIAL COORDINATES

The image of the zenithal star field is nothing else but the projection of the celestial sphere into a plane (figure 3.2). The equatorial coordinates (δ, α), defined on the celestial sphere, have to be transformed into plane coordinates being appropriate for further data processing.

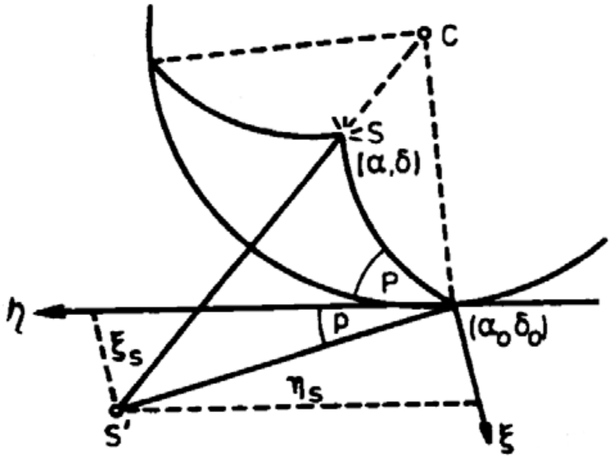


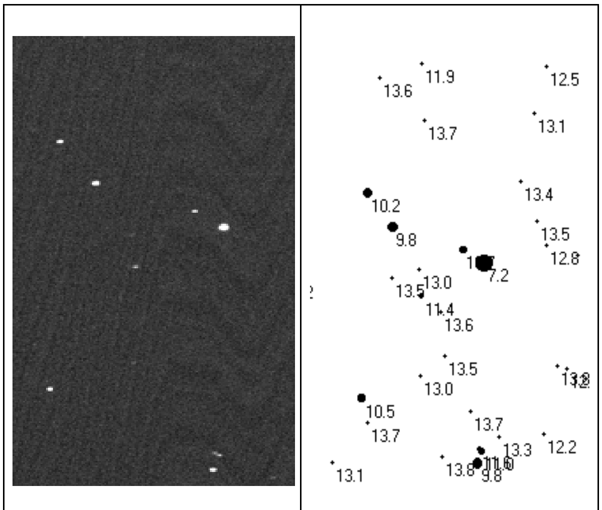
Figure 3.2: Relationship between equatorial and tangential coordinates (*Seeber*, 1993)

For this purpose tangential coordinates (ξ, η) are introduced. Tangential coordinates are equivalent to equatorial coordinates and can be rigorously determined with the formulas of the gnomonic projection. Using approximate values for the camera orientation (δ_0, α_0) and introducing an auxiliary quantity q, the tangential coordinates (ξ, η) can be computed by (*Seeber*, 1993):

$$\begin{aligned} \cot q &= \cot\delta\cos(\alpha-\alpha_0) \\ \xi &= \frac{\tan(\alpha-\alpha_0)\cos q}{\cos(q-\delta_0)} \qquad (3.7) \\ \eta &= \tan(q-\delta_0) \end{aligned}$$

3.4 IDENTIFICATION OF STARS

Instantaneously, stars extracted out of digital zenith images are nothing else but measured segments. They do not have any connection to those stars taken from a star catalogue. In order to calculate the astronomical coordinates, the image coordinates of the extracted stars have to be assigned to their corresponding equatorial coordinates from a star catalogue. This process is called the *identification of stars*.



1. Section of a zenith image.

2. Corresponding stars from a star catalogue.

Figure 3.3: Comparison between star images (1) and reference stars taken from a star catalogue (2). Beneath the reference stars their magnitudes are shown.

A suitable algorithm for the identification of stars has to cope with following problems: (a) Not all star images have a corresponding star in the catalogue because of the incompleteness of some star catalogues (for instance Tycho-2). (b) Not all stars taken from a catalogue have a corresponding star imaged by the CCD sensor (as shown in figure 3.3). Those stars (a) and (b) have to be excluded from further processing. The basic idea of the implemented algorithm is as follows.

In preprocessing, the equatorial coordinates (δ, α), taken from a star catalogue, are transformed into tangential coordinates (ξ, η) with equation (3.7).

At the beginning of the algorithm, image coordinates (x,y) of stars extracted out of the zenith image and tangential coordinates (ξ, η) are introduced. An arbitrary pair of image coordinates and an arbitrary pair of tangential coordinates (ξ, η) are supposed to be *identical points*. Both points form the basis for calculating parameters of a linear transformation (four parameters: scaling, rotation, displacement in x and displacement in y). These parameters are used to transform the stars (x,y) into corresponding tangential coordinates (ξ', η'). If the points supposed to be identical are *identical* indeed, the distance between at least n stars (ξ, η) and (ξ', η') will fall below a lower bound ε (*Hirt*, 2000):

$$\sqrt{(\eta-\eta')^2+(\xi-\zeta')^2} < \varepsilon \qquad (3.8)$$

$\varepsilon = 2$ arcseconds $\qquad n \geq 4$ stars

The identification has been performed successfully, if and only if equation (3.8) is complied by at least 4 different stars. Then, stars (ξ, η) taken from a star catalogue are assigned to those stars (x,y) extracted out of digital images whose equatorial coordinates (ξ, η) and transformed coordinates (ξ', η') can be applied to equation (3.8). All other stars not complying equation (3.8) have to be excluded from further processing.

If the identification has not been performed successfully, another pair of stars as basis is automatically chosen at the beginning of the algorithm. This procedure is repeated until successful identification of the image coordinates.

3.5 REDUCTION OF ZENITH IMAGES

After the successful identification, the zenith direction has to be interpolated into the field of zenithal stars. For this purpose we have to set up the functional model between measured image coordinates and equatorial coordinates. The functional model cannot be set up directly because measured image coordinates are cartesian and equatorial coordinates are spherical ones. Hence, we have to use tangential coordinates being introduced in section 3.3.

Tangential coordinates (ξ, η) are related to image coordinates (x,y) through formulas of the projective transformation with eight parameters:

$$\xi = \frac{a_1 + b_1 x + c_1 y}{1 + dx + ey}$$

$$\eta = \frac{a_2 + b_2 x + c_2 y}{1 + dx + ey} \qquad (3.9)$$

Usually, this model sufficiently approximates physical reality of the imaging process (*Wissel,* 1982). The transformation parameters are determined within a least squares adjustment.

3.6 DETERMINATION OF ASTRONOMICAL COORDINATES

The digital zenith camera images the zenithal star field in two camera positions with an azimuthal difference of 180 degrees. Since the zenith point is not marked on the CCD, the reduction process starts with approximate values, which can be found in the origin of the image coordinate system. These coordinates are transformed for both camera positions into the system of equatorial coordinates with formula (3.9) and inverse formula (3.7) sequentially.

Each camera position yields different equatorial coordinates of the zenith direction after the reduction process because of the approximate character of the initial values. Due to the symmetry conditions the mean of both results provides a better approximation of the zenith direction. These values are reintroduced at the beginning of the reduction process. These calculations are repeated and converge to final result for the “true” zenith direction after 2 or 3 iterations (*Seeber* and *Gessler*, 1975).

Taking the observation time *GAST* as described in section 1.2 into account, the equatorial coordinates of the zenith point can be transformed into astronomical coordinates by using equations (1.7) and (1.8).

Finally, vertical deflections are derived from the comparison of ellipsoidal coordinates and astronomical coordinates with equations (1.2) and (1.3).

4 SOFTWARE PACKAGE FOR DATA PROCESSING

All introduced algorithms are implemented within the real-time software package AURIGA-ZC (Automatic Real-time Image Processing System for Geodetic Astronomy - Zenith Camera) described detailed in *Hirt* (2000). It has been developed modularly in C, C++ and the scripting language Tcl/Tk. The software package consists of executable programs (C,C++) for data calculation and graphical user interfaces (Tcl/Tk) for data input, data flow control and data visualization. In the current state of development, the software package is featured by following capability characteristics:

- Real-time capability
- Fully automatic or optional interactive processing
- Automatic extraction of stars
- Automatic access to star catalogues GSC, Tycho-2 and UCAC
- Automatic identification of stars
- Capacious project data management
- User-friendly graphical interfaces
- Various ways of data visualization
- Logging of all results and provisional results calculated by the different processing steps

After transferring measuring data to the laptop, the software package allows the computation of vertical deflections in a fully automatical process. Since the data processing for a single station lasts less than 3 seconds using a 1 GHz-processor, a quasi real-time capability is guaranteed. The advantages of data processing in real-time are obvious. Besides of a considerable enhancement of efficiency, the immediate computation on a field station provides information about data quality and achieved inner accuracy estimated from repeated observations (*Hirt*, 2000).

The software package allows automatic and interactive data processing (figure 4.1). In the interactive mode, the user can make use of data analyzing tools like visualization of star extraction and image coordinate measurement. Furthermore, it is possible to display the zenithal star field from a catalogue, the procedure of star identification and the process of reduction. The visualization of residual errors (figure 4.2) gives information about how the functional model approximates physical reality. For instance, systematic errors caused by atmospheric scintillation or neglected proper motion (GSC stars) can be recognized as well as random errors of star positions taken from image and star catalogue effectively.

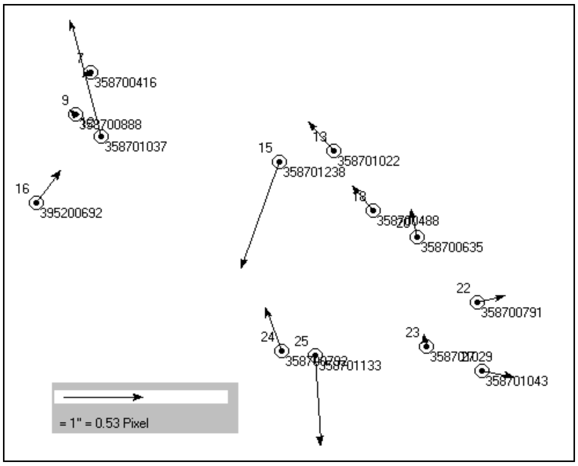
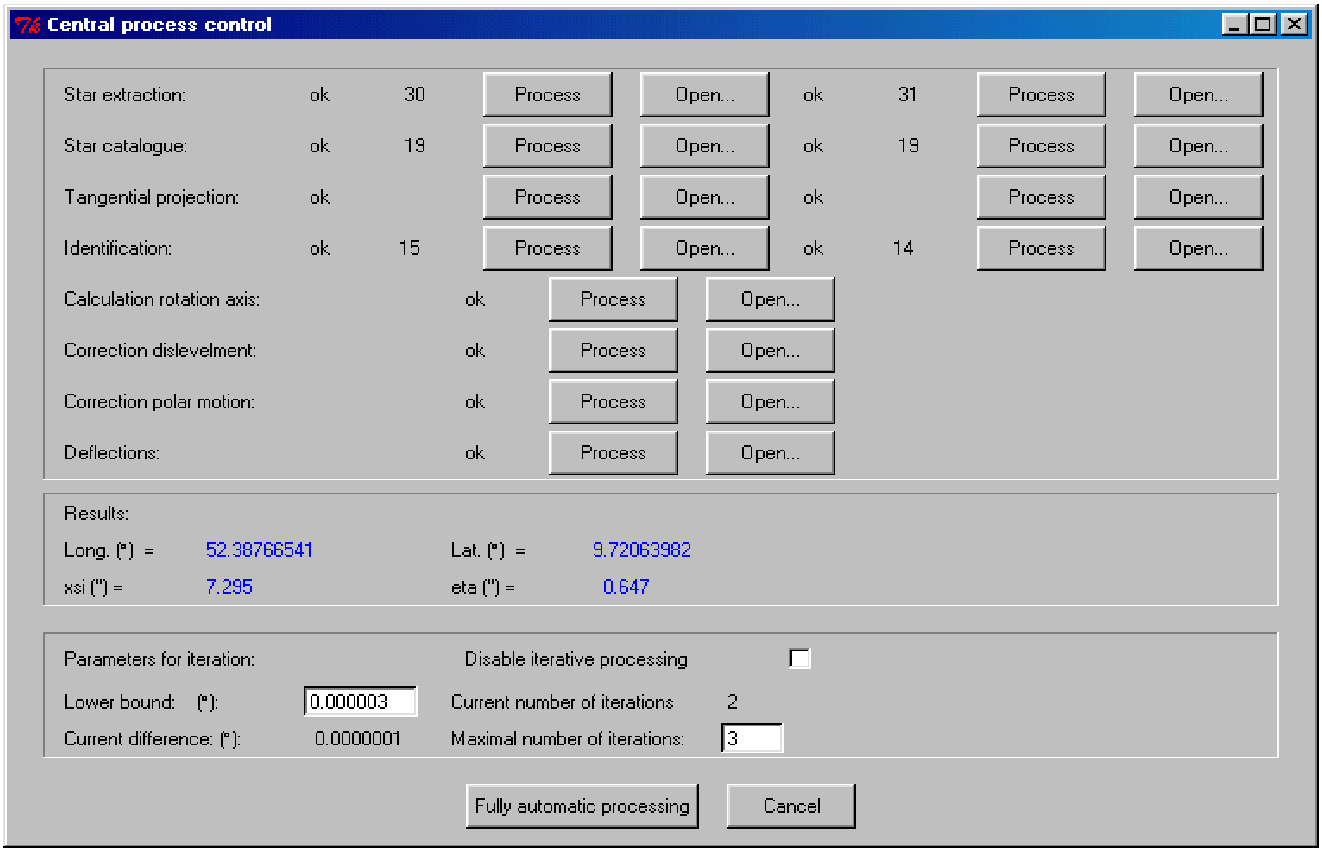


Figure 4.2: The software package allows the visualization of residual errors after the reduction of zenith images.

5 RESULTS OF FIELD TESTS

The digital zenith camera system was tested in September 2000 at the Universität Hannover. The astronomical coordinates of a control point were determined by 12 repeated measurements. Ellipsoidal coordinates of the observation point were measured with GPS. The system’s internal accuracy of about 0.2 arcseconds is shown in the standard deviation of the vertical deflections (*Hirt,* 2000). The difference of less than 0.5 arcseconds between known vertical deflections for the control point and the observed vertical deflections underlines the high external accuracy.



Star extraction: ok 30 ok 31
Star catalogue: ok 19 ok 19
Tangential projection: ok ok
Identification: ok 15 ok 14
Calculation rotation axis: ok
Correction dislevelment: ok
Correction polar motion: ok
Deflections: ok

Results:
Long. (°) = 52.38766541 Lat. (°) = 9.72063982
xsi (") = 7.295 eta (") = 0.647

Parameters for iteration:
Disable iterative processing ☐
Lower bound: (°): 0.000003
Current number of iterations 2
Current difference: (°): 0.0000001
Maximal number of iterations: 3

Figure 4.1: Central process control window of the processing software. The complete processing of digital zenith images will be performed by the successive execution of eight single processes. The star extraction has been discussed in section 3.1 and the role of star catalogues has been presented in 3.2. In section 3.3, tangential coordinates have been introduced. The identification process of stars has been outlined in section 3.4. Both the status of every single process and the number of used stars is depicted in the upper part of the window. In the middle section of the graphical user interface the results (astronomical latitude and longitude and the vertical deflections xsi, eta) of the calculation can be found. Only one click (button "Fully automatic processing") is necessary to compute the astronomical coordinates and vertical deflections.

However, it should be stated, that the external accuracy of the astronomical observations is limited by the influence of refraction (*Seeber*, 1978). Depending on the inclination of zenithal air layers astronomical coordinates can be falsified up to 0.5 arcseconds. One simple solution to decrease the influence is provided by the observation in different nights and the calculation of mean positions. As a result, the systematic character of the influence becomes stochastically. But this solution is contradictory to the advantages of a real-time approach described in section 4.

6 SUMMARY OF WORK UP TO DATE

Astronomical coordinates and vertical deflections can be determined in a fully automatical process in real-time with the combination of GPS and a digital zenith camera. The accuracy of results is about 0.2 arcseconds.

Due to the capabilities of light-sensitive CCD, which revolutionized astronomical observing methods, a digital zenith camera as state-of-the-art instrument for astronomical position determination has been developed. The system is based on an existing traditional photographic zenith camera.

A software package with capabilities for data processing in real-time has been developed in order to obtain the astronomical coordinates immediately on a field station. Special emphasis has been laid on a suitable algorithm to extract coordinates of star images from digital zenith images. As reference, the digital star catalogues Tycho-2 (2,5 million stars) and Guide Star Catalogue (19,0 million stars) provide equatorial coordinates. They are related to image coordinates of extracted stars by a projective transformation with eight parameters.

Since the software package enables the observer to process the data in real-time, astronomical coordinates are obtained almost immediately (less then 3 seconds) after the measurement process. Besides the aspect of high efficiency (figure 6.1) information about data quality and achieved internal accuracy is directly available.

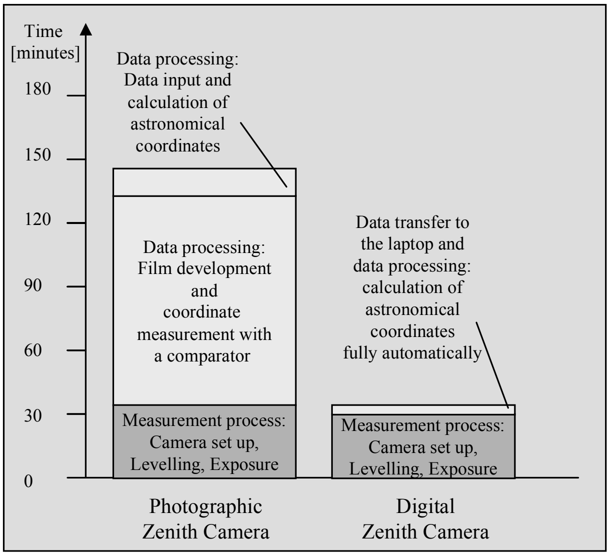


Figure 6.1: Time-intensity of measurement and data processing for the conventional photographic zenith camera and the digital zenith camera. With respect to efficiency the digital zenith camera outperforms the photographic zenith camera clearly.

7 APPLICATIONS

The combination of GPS and digital zenith camera provides a solution for the "GPS-height-problem" by using vertical deflections for astrogeodetic geoid and quasigeoid determination. Once a geoid is determined and digitally available, GPS users can determine physically defined heights in real-time.

The main field of application can be seen in the economic and precise geoid determination in local and regional networks and the geoid determination in geodetically low-developed countries. In mountainous regions, the fine structure of the existing gravimetric geoid models is improved appreciably by assimilating astronomical measurements. In geophysics, vertical deflections can be utilized for the identification of density anomalies below the earth's surface. Further information on the field of application of astronomical geoid determination can be found in (*Wissel*, 1982) and (*Bretterbauer*, 1997).

8 FUTURE WORK

There remain some open questions for an improvement of the zenith camera system's accuracy and performance. The procedure of time measurement as integral part of the method (equation 1.8) will be improved by assimilating highly precise time information provided by GPS. An accuracy for the time measurement better then 1 μsecond is possible.

As mentioned in section 5, a factor limiting the external accuracy of the astronomical observations is the influence of refraction. Investigations of atmospheric models in order to better correct the influence of refraction are necessary.

In the near future, the method's performance will be tested at several field stations in northern Germany. In some European regions featured by intense geoid variations - for instance the Alps - the determination of the geoid's fine structure is intended in cooperation with the Swiss Federal Institute of Technology, Zürich. Furthermore, field-tests aimed at the precise determination of regional geoid information are intended in cooperation with the Universities of Recife and Curitiba (Brazil) and Maracaibo (Venezuela) in South America.

ACKNOWLEDGEMENTS

I like to thank Professor Dr.-Ing. G. Seeber for supporting my work continuously and Dipl.-Ing. W. Paech for making his private CCD-Camera ST8 during my Diploma Thesis available. Without this support the work would not have been possible.

REFERENCES

Bretterbauer, K. (1997). *Eine Renaissance der Astrometrie in der Geodäsie*. Österreichische Zeitschrift für Vermessung und Geoinformation 1/97, Wien.

Fosu, C., Eissfeller, B., Hein, G. (1998). *CCD to Marry GPS*. Proceedings of the 11th. International Technical Meeting of the Satellite Division of the Institute of Navigation, Nashville, Tennesee.

Gessler, J. (1975). *Entwicklung und Erprobung einer transportablen Zenitkamera für astronomisch-geodätische Ortsbestimmungen*. Wissenschaftliche Arbeiten der Lehrstühle Geodäsie, Photogrammetrie und Kartographie an der Technischen Universität Hannover, Nr. 60.

Haralick, R. and Shapiro, L. (1993). *Computer and Robot Vision Vol.2.* Addision Wesley, Reading, Massachusetts.

Heipke, C. (1999). *Skriptum Photogrammetrie I/ Digitale Bildverarbeitung*. Institut für Photogrammetrie und Ingenieurvermessungen, Universität Hannover, unpublished.

Hirt, C. (2000). *Theorie und Realisierung eines echtzeitfähigen Auswertesystems zur astronomischen Ortsbestimmung mit einer digitalen Zenitkamera*. Diploma Thesis at the Institut für Erdmessung, Universität Hannover, unpublished.

Hog, E., Fabricius, C., Makarov, V., Urban, S., Corbin, T., Wycoff,G., Bastian, U., Schwekendiek, P. and Wicenec, A. (2000a). *Guide to the Tycho-2 Catalogue*. Published in WWW: **http://www.astro.ku.dk/~cf/CD/dosc/guide.pdf.**

Hog, E., Fabricius, C., Makarov, V., Urban, S., Corbin, T., Wycoff,G., Bastian, U., Schwekendiek, P. and Wicenec, A. (2000b). *The Tycho-2 Catalogue of the 2.5 Million Brightest Stars*, Published in WWW: **http://www.astro.ku.dk/~cf/CD/dosc/guide.pdf.**

McLean, B. (1996). STScI Catalogs and Surveys Branch – *The Guide Star Catalogue Information*. Space Telescope Science Institute/NASA. Published in WWW: **http://www-gsss.stsci.edu/gsc/gsc.html.**

Paech, W. and Baader,T. (1995). *Tipps und Tricks für Sternenfreunde*, dritte Auflage. Verlag Baader Planetarium, Mammendorf.

Seeber, G. and Gessler, J. (1975). *Latitude and Longitude Determinations with a Transportable Zenith Camera*. Deutsche Geodätische Kommision (DGK), B 213, München.

Seeber, G. (1978). *Die transportable Zenitkamera, ein modernes Instrument zur geographischen Ortsbestimmung*. Sterne und Weltraum, Issue 2/1978. Verlag Sterne und Weltraum, Heidelberg.

Seeber, G. (1993). *Satellite Geodesy, Foundations, Methods and Applications*. De Gruyter, Berlin, New York.

Seidelmann, P.K. (1992). *Explanatory Supplement to the Astronomical Almanach*. University Science Books, Mill Valley, California.

Torge, W. (2001). *Geodesy*, Third Edition. De Gruyter, Berlin, New York.

Wissel, H. (1982). *Zur Leistungsfähigkeit von Transportablen Zenitkameras bei der Lotabweichungsbestimmung*. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 107.

Zacharias, N. and Rafferty, T. (2000a). *First Light for UCAC-S*. United States Naval Observatory. Published in WWW: **http://www-aries.usno.navy.mil/ad/ucac/firstlite.html.**

Zacharias, N. and Rafferty, T. (2000b) *Overview of UCAC project*. Unites States Naval Observatory. Published in WWW: **http://www-aries.usno.navy.mil/ad/ucac/overview.html.**