FAST AND ACCURATE DETERMINATION OF ASTRONOMICAL COORDINATES Φ, Λ AND AZIMUTH, USING A TOTAL STATION AND GPS RECEIVER.

D. D. Balodimos, R. Korakitis, E. Lambrou and G. Pantazis

National Technical University of Athens

ABSTRACT

This work reports the development of a system for fast and accurate determination of astronomical latitude (Φ), longitude (Λ) and azimuth (A). The system consists of a high-precision total station, with the appropriate software for automatic registration of the measured elements, connected to a GPS receiver through which accurate UTC timing is provided. This system allows the acquisition of a large amount of data during the tracking of selected stars around their meridian transit. After the appropriate processing of the data, an accuracy of $\sigma_\Phi = \sigma_\Lambda = \pm 0''.01$, $\sigma_A = \pm 0''.2$ may be achieved for the determination of the astronomical coordinates and azimuth.The developed system compares favourably to older classical ones, due to its compactness and the accuracy obtained within a short period of time. Thus, combined with GPS receivers for the geodetic coordinates determination, it can easily be used for the determination of the deviation of the vertical and eventually of the geoid separation N.

INTRODUCTION

The determination of the astronomical coordinates latitude Φ and longitude Λ at several points on the Earth's surface permits the determination of the shape of the geoid and its geometric relation with the reference ellipsoid. Even today the accurate determination of the shape of the geoid remains a major challenge and the single obstacle in getting the orthometric heights H through the ubiquitous Global Positioning System (GPS) measurements.

The orthometric height H, measured along the plumb line, is used in all geodetic works because it is immediately perceptible and its variation is directly measured by levelling. On the other hand, the GPS gives the geometric height h (measured along the normal to the reference ellipsoid) quite easily. In order to compute the orthometric height H, one needs to know the position of the geoid with respect to the reference ellipsoid i.e. the geoid separation N: H = N + h.

The determination of the geoid separation is based either on the variations of the deviation of the vertical or on the gravity anomalies Δg [**4**]. The components ξ, η of the deviation of the vertical can be computed easily and with satisfactory accuracy by [**4**]

$$\xi = \Phi - \phi \tag{1}$$

$$\eta = (\Lambda - \lambda) \cdot \cos \Phi \tag{2}$$

where φ, λ are the geodetic coordinates obtained directly through the GPS measurements. Therefore, the decisive factor in determining the shape of the geoid is the ease and accuracy of getting the astronomical coordinates Φ, Λ (Figure 1).

The astronomical coordinates are determined by combining measurements of angles (horizontal and vertical) to several stars with corresponding measurements of time. Several methods have been developed for such a determination, using classical time and angle measuring instruments [**12**]. However, the procedure is time-consuming and quite demanding in measurement and computational effort, so large-scale applications were very difficult. The technological evolution of the last decade and, particularly, the availability of precise timing information through GPS receivers and the digital registration of measured angles by the improved geodetic instruments (total stations) allow for more accurate measurements to stars.

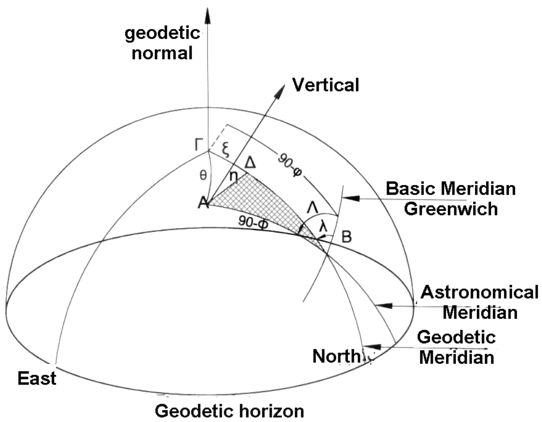

Fig.1. The components ξ, η of the deviation of the vertical.

In addition, the enormous capabilities of today's computers allow for a comprehensive and fast data processing that lead to an accurate determination of the coordinates Φ, Λ and the astronomical azimuth A.

In this work a methodology is presented for the accurate determination of astronomical coordinates, based on the principles mentioned above, which takes advantage of:

- The use of modern, high accuracy instruments
- The capability to time the observations, on the UTC scale, through GPS.
- The ability to make and register many observations to stars around their meridian transit, which is a preferable position since it allows the elimination or accurate determination of several systematic errors.
- The thorough use of modern, high-precision digital data for stars and the solar system.
- The use of rigorous algorithms for data reduction.

These improvements lead to a compact and lightweight system, which is easily set up in the field and in a few hours, can collect enough data for the determination of the astronomical coordinates to an accuracy of ±0″.01 and the astronomical azimuth to an accuracy of ±0″.2 or better.

THE SYSTEM - OBSERVATIONS

The necessary observations are obtained through a system consisting of a high – accuracy digital total station (TDM 5000 – Leica), a GPS receiver (4000 DL – Trimble), a portable data logger for the registration of meteorological data (atmospheric pressure and temperature) and optionally, a portable computer (Figure 2).[**9**]

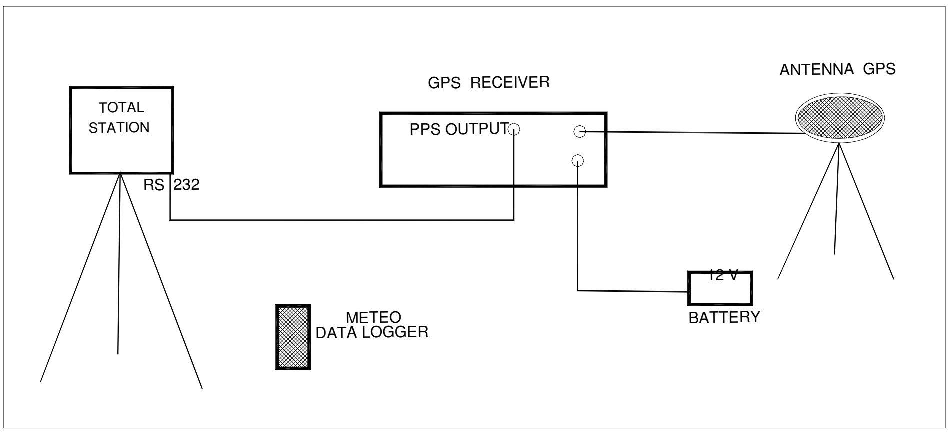

Fig.2. System for astronomical observations

The digital total station offers the possibility of registering horizontal and vertical angles, to an accuracy of 1^{cc} or 0".3 [**10**], after a suitable trigger by the observer, up to a rate of 30 observations per minute. It can also register the time of its observation (using internal clock) to an accuracy of 1msec. In addition, it constantly checks the levelling of itself and automatically makes appropriate corrections to the measured angles when necessary [**10**]

The GPS receiver provides accurate time information in the form of 1pps (pulse per second) output, which is synchronised with the UTC time to an accuracy of a few microseconds [**14**]. Of course it can also provide the geodetic coordinates of the observing station, which may serve as approximate values of the astronomical coordinates of the station. The timing pulse of the GPS is fed to the total station, through a suitable cable and converter, and is used by the software loaded to the total station for the registration of the UTC time to an accuracy of 1msec.

The portable data logger is used to register the atmospheric temperature (accurate to 0.05°C, using a digital sensor) and pressure (accurate to 0.1mbar, using a digital sensor) during the observations. [**1**]

Optionally, one can also include a portable computer, which may be used on-site for the preparation of the observations, the transfer and storage of data and the reduction of the observations. If the computer is not available in the field, these operations can be performed at another convenient place and time.

The determination of the coordinates is based on observations of stars around their meridian transit. The transit zenith distances of several pairs of stars are used for the determination of latitude (Sterneck method), while the transit times of the same stars are used for the determination of longitude (Mayer method) [**12**]. Since observations at transit are needed, a preliminary orientation of the instrument is necessary and this can be achieved easily and accurately through several pointings to the Polaris (α UMi) at the beginning of the observing session.

Selection of the appropriate stars and planning of the observations are very important, in order to obtain suitable measurements. This can be done in advance or on-site, by appropriate software on the portable computer, using the geodetic coordinates φ, λ (from the GPS) as approximations to the astronomical coordinates. The planning of the observations is greatly facilitated by the use of a digital planetarium run on the computer, as the SkyMap Pro software does [**11**], which accurately depicts the celestial sphere as seen at any time and from any place on Earth. This procedure allows the selection of 12 star pairs, which correspond to about four hours of observations, and the collection of necessary data in less than two hours. The data include the designation of each star, approximate time and vertical angle at transit, accurate celestial coordinates, magnitude etc. It should be noted that the celestial coordinates, right ascension and declination as well as other astrometric data for each star, are taken from the Tycho2 catalogue [**5**] which provides positions (ICRS, epoch J2000) of 2.5 million stars to a mean accuracy of 7 milliarcseconds (for stars brighter than magnitude 9) and proper motions to an mean accuracy of 2.5 mas/year.

The programme stars are selected in pairs, culminating North and South of the zenith at about equal distances (within 1°), and having magnitudes around 5 to 6. The range of allowable zenith distances is from 5° to 30°, approximately. Each star is observed for several minutes around the meridian transit, corresponding to an arc of 5 to 6 degrees. During this interval, 80 to 120 pointings to the star are made in rapid succession and the total station registers the measured angles and the time instant of each observation.

Allowing for a time interval of about 10 minutes between successive star transits, this procedure permits the observation of 12 star pairs, in about 4 hours, collecting 2000 to 3000 individual time and angle measurements.

DATA REDUCTION

The first step of the reduction is the accurate determination of the orientation of the total station (astronomical azimuth of the zero point of horizontal readings). This is done from the measurements of Polaris to an accuracy better than 0″.2.

The data collected from all stars are then corrected for the following effects:

- The horizontal angles are corrected for the value of the astronomical azimuth of the zero point of horizontal readings.
- The vertical angles are corrected for the effect of astronomical refraction, using the meteorological data collected during the observations.
  The equation R = z_1 – z gives the correction of the measured value of the vertical angle to its real value. This correction is calculated by the equation **[8]**:

$$R = R_0 \frac{P}{1013.25} \cdot \frac{273}{273+\theta} \tag{3}$$

where $R_0 = 60''.34 \cdot \tan z - 0''.0669 \cdot \tan^3 z$, is the standard refraction

P = the atmospheric pressure at the observation point in mbar
θ = the temperature at the same point in °C

- The registered time of each observation is corrected for the drift and delay of the internal clock of the total station, as well as for the average response time of the observer, which is experimentally determined in the field.

The corrected data are then used for the determination of the transit time (UTC) and the true zenith angle at transit of each star, as follows:

The zenith distance at upper transit for each star is determined by fitting a 4th degree polynomial to all (horizontal angle, vertical angle) pairs of measurements to each star. In a similar manner, the UTC time of transit for each star is determined by fitting a 3rd degree polynomial to all (horizontal angle, time) pairs of measurements to each star (Figure 3) [**9**] .

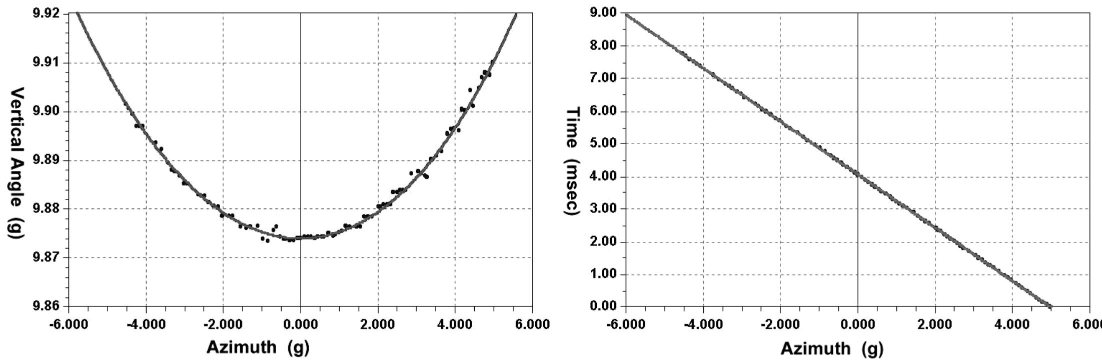

Fig.3. Illustration of the polynomial regression to the measurements

The combination of all observations of each star in these polynomial regressions greatly reduces the random (pointing) errors and permits the determination of the zenith angle at transit to an accuracy of 0″.3 and the UTC transit time to an accuracy of 0.03 sec as demonstrated by the application.

The next step of the reduction is the computation of the apparent place of each star at the instant of meridian transit. This is done following the standard procedure [**6**] and is based on:

-The Tycho2 positions and motions of the stars and
-The numerical ephemeris of the solar system DE200 of Jet Propulsion Laboratory [**13**]

This procedure ensures that the values for the apparent coordinates of each star are accurate to ±1msec for right ascension (α) and ±0″.01 for declination (δ).

From this point onwards, the well-known methods of Sterneck (for latitude) and Mayer (for longitude) are used [**12**].

A value for the latitude Φ_i is computed from each pair of stars by:

$$\Phi_i = \frac{\delta_N + \delta_S}{2} + \frac{z_S - z_N}{2} \tag{4}$$

where z_S, z_N are the zenith distances at transit for the south and the north star, respectively. The final value of the latitude Φ is given by the mean value of Φ_i for all pairs of measured stars, properly weighted by their respective errors. Using 12 pairs, the rms error of the mean value of Φ is of the order of 0.01″.

Since the Total Station used has the capability of automatically maintaining its levelling during the measurements, a simplified form of Mayer's formula [**12**] is used for the determination of longitude:

$$\Lambda = \alpha_i - \theta_i = \Lambda + \mathrm{A}_i \cdot \delta\mathrm{A} \quad (5)$$

where θ_i is the (true) Greenwich sidereal time at the instant of transit of each star (corrected for the effect of diurnal aberration), A_i the Mayer parameter :

$$\mathrm{A}_i = \pm \frac{\sin z_i}{\cos \delta_i} \quad (6)$$

(+ for South and – for North stars) and δA the residual error of orientation of the instrument, which is determined by least-squares fitting along with the best estimate of longitude Λ. Using 24 stars, the rms error of the mean value of Λ is of the order 0″.01. The value of δA is comparable to the azimuth error, of the order of 0.″2.

RESULTS

An experimental application of the proposed system and the method was carried out at the Astro B pillar of the N.T.U.A check field. Eleven star pairs were observed on a single night in May 2002 (about 4 hours of field work in total) and the astronomical coordinates were found to be [**9**] :

Φ = xx° xx′ 44″.548 ± 0″.011, Λ = yy° yy′ 02″.552 ± 0″.016

The above values have been corrected for Polar motion and for curvature of the plumb line [**12**].

For comparison, the values determined in 1970 using classical equipment are reproduced **[3]**:

Φ = xx° xx′ 44″.705 ± 0″.159, Λ = yy° yy′ 02″.762 ± 0″.183

These values, again corrected for Polar motion and for curvature of the plumb line, were derived using 19 pairs of stars for Φ and 81 stars for Λ, observed on three nights, with a total observing time about 24 hours.

DISCUSSION

The combination of modern, high-precision instruments with appropriate measurement and data reduction procedures, as presented here, provides several important advantages for a fast and accurate determination of astronomical coordinates:

1. The automatic registration of angles (horizontal and vertical) by the total station, with a resolution of 0.1^{cc} or 0".03 and an accuracy of 1^{cc} or 0".3 [**10**]. This represents an important improvement over classical theodolites, having readings of the order of 1^{cc} at best.
2. The simultaneous automatic registration of the instant of observation, to accuracy of 10^{-3} sec of UTC time, is provided by the GPS receiver. This is a major improvement over classical synchronisation methods, both in terms of accuracy and ease of use.
3. The capability to register more than 100 accurate measurements to each star leads to a remarkable suppression of random observational errors. The classical methods allow for a single observation at transit or a few (5-10) before and after transit [**3**].
4. The use of appropriate software (digital almanacs, virtual planetariums etc) on modern computers permit a fast and efficient planning of the observations, which is mandatory for reliable measurements and results, as well as a rigorous data processing.
5. The total system weight (about 15Kgr) and set-up time (less than 10 minutes) compares very favourably to classical equipment, weighting from 100 to 150 Kg [**15**] and needing about two hours' effort of experienced staff to set-up.

6. Finally, the proposed method needs a field time of around 4 hours to obtain excellent first-order results, whereas the classical procedures demand at least 3 nights of 8 hours each to achieve similar results [**3**], at much greater cost and effort.

CONCLUSIONS

The combined use of a modern, digital total station and a GPS receiver, with the appropriate hardware and software, leads to a fast and accurate determination of astronomical coordinates (Φ, Λ) and azimuth A. This is achieved by:

a) Eliminating many systematic errors and taking into account the effects of the remaining errors.
b) Reducing the random errors by combining a large number of measurements.
c) Registering digitally all measured quantities (angles and time), thus greatly reducing the time needed for observations and eliminating reading errors.
d) Registering the UTC in real time, using the connected GPS receiver.

The above improvements, combined with the ease of set-up, measurement and data reduction, make the proposed method quite attractive and efficient for the accurate determination of the deviation of the vertical and the geoid separation N.

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