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Digital zenith camera system for Astro-Geodetic applications in Turkey

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Abstract

There are several current investigations on gravity field of the earth in Geodesy and Geophysics. Earth sciences and space researches are also interested in gravity studies. Geoid, which approximately has an equal potential to the potential of mean sea level, is the main datum for height systems and is used for coordinate transformation, reduction of measurements, subsurface density variations and similar scientific studies. Current studies focus on the determination of cm level geoid, in order to use Global Navigation Satellite Systems (GNSS) such as Continuously Operating Reference Stations (CORS-TR/TUSAGA-Active) in Turkey effectively. This study introduces general information about recent astro-geodetic observations performed by different institutions all over Europe. Furthermore, it also gives some details about data acquisition, instrumentation and processing technique that focuses on observation principle and new technologies used in modern Geodetic Astronomy. Finally, this study introduces the system design and the first observations of a Digital Zenith Camera System (DZCS) used in Istanbul, Turkey.

Keywords
Geodetic astronomy, Digital zenith camera systems, Vertical deflections, Geoid.

Özet

Türkiye'deki Astro-Jeodezik uygulamalar için sayısal zenit kamera sistemi

Jeodezi ve Jeofizik alanlarında yerin gravite alanının belirlenmesi ile ilgili pek çok güncel çalışma bulunmaktadır. Potansiyeli, ortalama deniz yüzeyi potansiyeline yakın olan jeopotansiyel yüzey "geoit", bir düşey datum olarak yükseklik sistemlerinin temelini oluşturur ve bu nedenle, koordinat transformasyonu, ölçülerin indirgenmesi, yoğunluk araştırmaları ve benzeri çalışmalarda özel bir öneme sahiptir. Bir santimetre geoidininin belirlenmesi ile ilgili çalışmalar devam etmektedir. Bir cm-geoidi GNSS'den (Türkiye için TUSAGA-Aktif) rasyonel yararlanmanın temel koşuludur. Bu çalışmada güncel astro-jeodezik gözlemlere ilişkin Avrupa genelinde devam eden çalışmalara yer verilmiştir. Bu çalışma ayrıca veri elde etme, ölçme ekipmanları ve değerlendirme yöntemleri ile gözlem esasları ve Jeodezik Astronomide yeni teknolojiler ile ilgili gelişmeleri içermektedir. Bu çalışmanın son kısmında ise İstanbul'da tasarlanan ve ilk test gözlemleri gerçekleştirilen Sayısal Zenit Kamera Sistemi tanıtılmaktadır.

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1. Introduction

Geoid determination studies use different theoretical and observation methods such as gravimetric (using Stokes equation and gravity anomalies), astro-geodetic (deflection of the vertical measurements derived from astronomic and geodetic coordinates), GPS/Leveling (modeling geoid undulations [N = h – H], using orthometric heights [H] derived from leveling, and ellipsoidal heights [h] derived from GPS), and using global geopotential models (using terrestrial, satellite and space techniques based on determination of geopotential harmonic coefficients). The accuracy and reliability of geoid modeling results can be tested with comparing other geoid determination methods. Using the combination of different techniques as such can eliminate the restrictions and disadvantages of techniques.

GPS/Leveling is the most expensive geoid determination technique, where the gravimetric technique needs a high density of modeling points that characterize the topography. The gravimetric technique is not suitable for the coastlines and national boundaries. Furthermore there are accuracy restrictions near the seashores and lakes. It has been proved that astro-geodetic technique is 2-5 times more economical than gravimetry, especially along coastlines (Gerstbach 1996). The astro-geodetic vertical deflections mostly include the effects of local mass distribution; hence they form an important input in order to determine the intermediate wavelength part of the geoid (Gerstbach 1996; Hirt and Bürki 2006; Halicioglu et al. 2008).

The determination of deflections of the vertical using traditional optical-mechanical direction measuring systems and time recording devices has an accuracy of ±1". Digital Zenith Camera Systems (DZCS) have been developed last decade, which are equipped with CCD technology, GPS time and position information, and electronic inclinometers. Automated control and processing procedures increase the accuracy of deflection of the vertical measurements up to ±0.2" (2 mm/km). After the first studies on DZCS in Germany and Switzerland, the Astro-geodetic Technology Project has also been operated by Australian researchers (Hirt et al. 2010).

In order to establish the national triangulation network of Turkey, deflections of the vertical in 98 astro-geodetic points were used in 1976 (Figure 1). The Astro-geodetic Geoid of Turkey (TAG-94) was computed using deflections of the vertical in 200 astro-geodetic points in 1994 (Ayhan and Alp 1995). The studies are decelerated after TAG-94, because of the accuracy limitations in traditional astro-geodetic techniques. In order to determine a cm level geoid using astro-geodetic method, 5-10 points/1000 km^2 are needed (Gerstbach 1996).

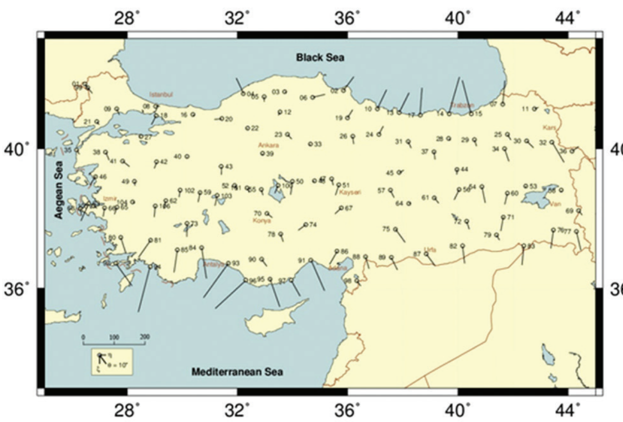

Figure 1: Astro-geodetic vertical deflections from (Ayan 1976)

2. Observation Principle

The objective of Geodetic Astronomy is the determination of the astronomic latitude Φ and longitude Λ as well as the astronomic azimuth A from observations of preliminary stars (Figure 2).

The astronomic latitude Φ and longitude Λ determine the direction of the tangent to the plumb line, and the geodetic coordinates (ϕ, λ) define the direction of the ellipsoid normal. The difference between these two directions at a point is known as the deflection of the vertical (Figure 3).

Another objective of Geodetic Astronomy is to determine astronomical azimuths A. The astronomic azimuth is the angle in the astronomic horizon (the plane perpendicular to the tangent of the plumb line) from the northern half of the astronomic meridian, easterly, to the plane containing both the plumb line tangent and the target point (Jekeli 2012).

2.1. CCD technology and Zenith Cameras

The invention of Charged Coupled Devices (CCDs) in the 1970s made a dramatic development in astronomy and astrometry. Applications in Geodetic Astronomy were also effected by this development through modernizing the optical and analogue equipment. There are several advantages of CCDs over traditional photographic and visual methods. CCDs are highly sensitive and accurate devices, which shorten the observation time. They also produce data in digital form, which allows a fully automatic data flow.

A digital image is composed of pixels that are arranged in a matrix form with rows and columns. The position of a pixel is defined by two dimensional coordinates, which indicates particular row and column. A CCD camera uses a CCD sensor that makes use of the photoelectric effect in silicon to convert photons into charges that can store image information. The sensor contains a certain number of rows and columns forming an array of pixels. The system that is designed in this study uses Apogee U32 CCD camera with the sensor of Kodak KAF-3200ME, which has 2184x1472 pixels and measures 14.8x10.0 mm. The pixel size of the camera is 6.8x6.8 µm. The field of view of our system with an 8" telescope is 17.2x25.5 arc minutes. In order to obtain the image coordinates, the images have to be recognized, and coordinates of the image center have to be determined. This process is called image extraction. The stars in the images are considered to be a group of pixels with similar properties, and they differ from the background through their high gray level values. There are several image extraction algorithms, which may lead an accuracy of 0.1 to 0.2 pixel accuracies for determination of star centroids.

The stars have to be identified and related to the International Celestial Coordinate System (ICCS) given by star catalogs after the star extraction process. Recent observations require dense star catalogs because of the high sensitivity and small field of view of CCD sensors. Today very accurate and dense star catalogs are available such as Guide Star Catalog (GSC), TYCHO-2, and USNO CCD

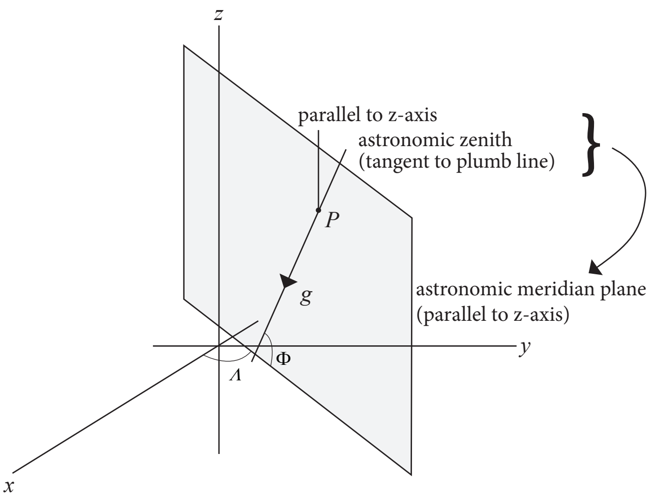

Figure 2: Astronomic coordinates (Jekeli 2012)

Astrograph Catalog (UCAC) catalogs. In this study, UCAC2, and UCAC4 in order to determine the coordinates of registered stars on the images are used. The United States Naval Observatory (USNO) produced UCAC4 star catalog by 2011 and completed version of this catalog was published on June 2012 with the whole sky coverage of 113 million stars. Reference star positions in UCAC4 are accurate at about 0.02" for brighter stars (10^{mag} to 14^{mag}), and a precision better than 0.1" is expected at the limiting magnitude of 16^{mag}.

As a result, the astrometric applications that are used today benefit from CCD technology for both ground and space based observations. The basic aim of CCD observations is to determine the camera orientation with respect to inertial frame.

The principle remains the same whether the camera mounted on a ground based observatory or to a space vehicle. In order to define the orientation of camera the orientation angles, declination δ_0, right ascension α_0, and swing angle κ_0 around the camera axis have to be determined (Figure 4). This process generally follows the procedure for the classical photogrammetric technique (Seeber 2003).

2.2. Astrometric plate reduction

The image of the star field is the projection of the astronomical sphere into a plane (Figure 5). Under the assumption of ideal conditions without distortions and refractions, plane tangential coordinates (ξ,η) can be computed from the equatorial star coordinates (α,δ) with respect to a known camera orientation α_0,δ_0 (Sebeer 2003).

Within the Astrometric plate reduction model, the tangential coordinates (ξ,η) and the plate coordinates x, y are related through polynomials.

2.3. Observation method and instrumentation

Star catalogs include the equatorial coordinates declination δ and right ascension α of stars in celestial reference system (ICRS). In order to extract the information from star catalogs the approximate astronomical coordinates $(\Phi,\Lambda)_0$ of the camera are needed. Zenith Camera Observations use the geodetic positions of camera (φ,λ) as approximate astronomical coordinates, which are observed by GPS.

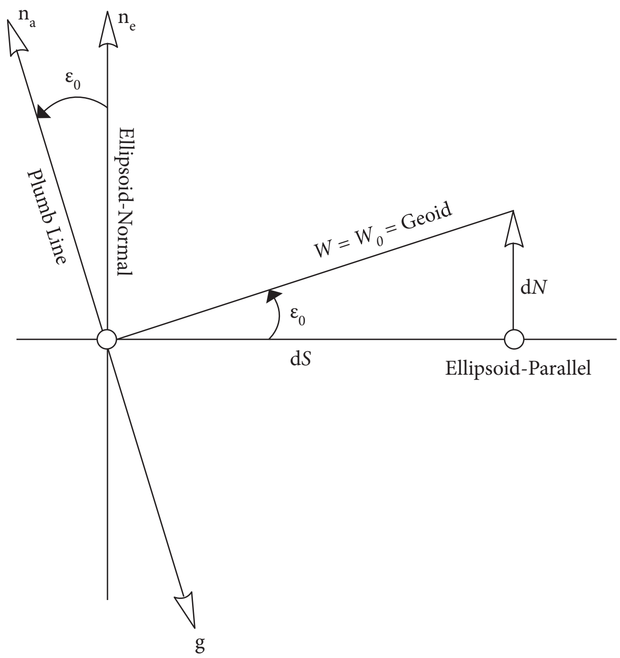

Figure 3: The relationship between geoid undulation and deflections of the vertical

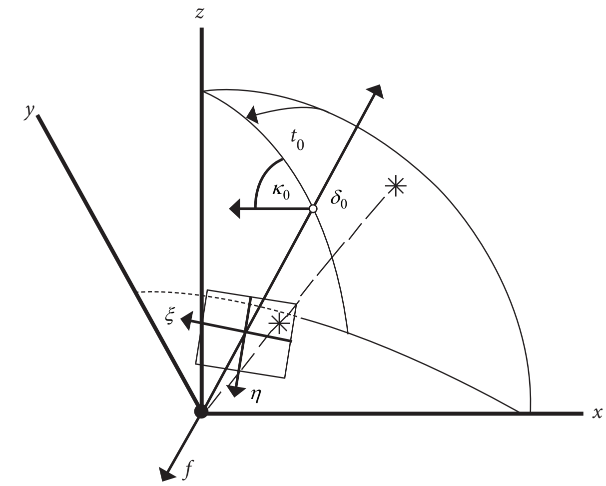

Figure 4: Camera Orientation parameters (Seeber 2003)

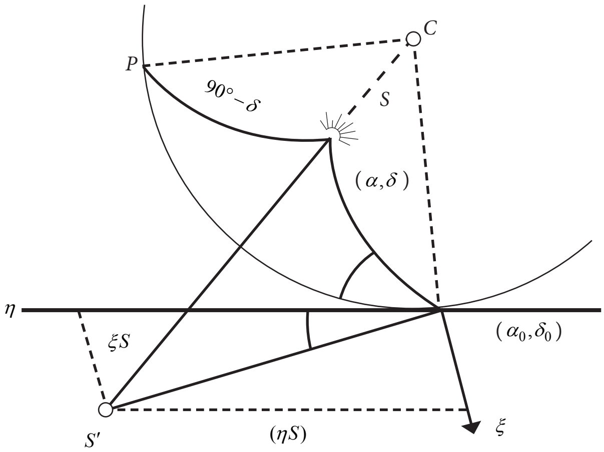

Figure 5: Tangential Coordinates (Smart 1971)

Astronomical coordinates (Φ, Λ) define positions of the observation points on the earth surface, and equatorial coordinates describes the positions of the stars in celestial sphere. Astronomic coordinates and equatorial coordinates can be linked with Greenwich Apparent Sidereal Time (*GAST*) for a star located at zenith (Figure 6).

$$\Phi = \delta,\ \Lambda = \alpha - GAST \tag{1}$$

However, a star usually cannot be observed at zenith and that's why zenithal direction has to be interpolated using the reference stars imaged near zenith with a CCD camera. The stars on the zenithal star field have to be identified using appropriate star catalogs.

Image coordinates of the stars (x, y) which are defined in image coordinate system cannot be linked directly with equatorial coordinates (α, δ). Tangential coordinates of stars have to be defined by projecting spherical equatorial coordinates (α, δ) onto a plane, which is tangent to the celestial plane in a common point (α_0, δ_0). Therefore, the tangential coordinates (ξ, η) are determined with the formulas of gnomic projection.

$$\cot q = \cot\delta \cos(\alpha - \alpha_0) \tag{2}$$

$$\xi = \frac{\tan(\alpha - \alpha_0)\cos q}{\cos(q - \alpha_0)} \tag{3}$$

$$\eta = \tan(q - \delta_0) \tag{4}$$

Tangential coordinates are related to image coordinates through the projective transformation. At least four common stars in both systems have to be identified in order to estimate transformation parameters. In a case of having more than four common stars, transformation parameters are calculated using a least squares adjustment.

$$\xi = \frac{Ax + By + C}{Kx + Ly + 1} \tag{5}$$

$$\eta = \frac{Dx + Ey + F}{Kx + Ly + 1} \tag{6}$$

The position of the zenith is interpolated through an iterative process. The astronomical coordinates (Φ, Λ) can be calculated according to (Equation 1) using observation epoch *GAST*.

The coordinates of direction of projection center can be calculated using inverted formula

$$\alpha_z = \alpha_0 + \arctan\frac{\xi_z}{\cos\delta_0 - \eta_z \sin\delta_0} \tag{7}$$

$$\delta_z = \arctan\frac{(\eta_z + \tan\delta_0)\cos(\alpha - \alpha_0)}{1 - \eta_z tan\,\delta_0} \tag{8}$$

After a few iterations the difference between coordinates goes below milliarc seconds.

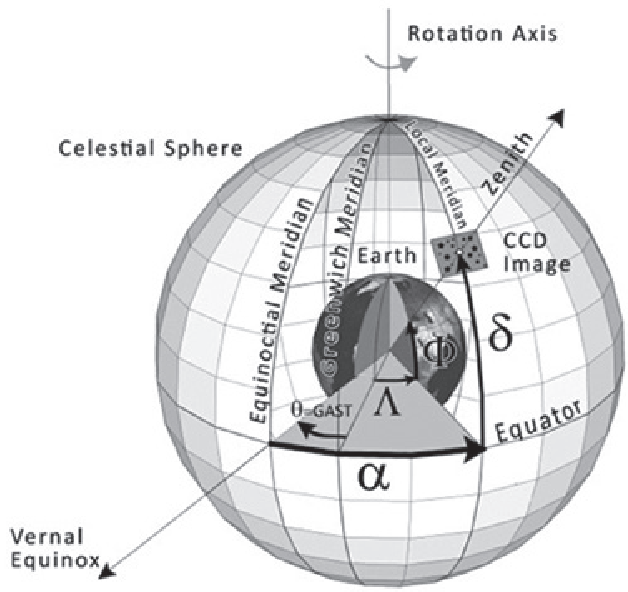

Figure 6: Basic principle of DZCS (modified from Hirt and Bürki (2002))

Finally deflections of the vertical (ξ, η) can be calculated using astronomical coordinates (Φ, Λ) and ellipsoidal coordinates (φ, λ) derived by GPS.

$$\xi = \Phi - \varphi \quad , \quad \eta = (\Lambda - \lambda)\cos\varphi \tag{9}$$

3. Astro-geodetic instruments

It is crucial to determine a cm level geoid in order to use GNSS systems effectively, therefore current studies focus on more precise geoid models. Astro-geodetic technique is one of the oldest fundamental techniques used for geoid determination. Restrictions of analog instruments and time measurements decreased the usage of this method. Previous studies showed that the determination of vertical deflections using traditional optical-mechanical direction measuring systems and time recording devices has an accuracy of ±1".

The first transportable photographic zenith cameras, TZK1 and TZK2 were designed and used in Hannover, Germany (Gessler 1975) beginning from 1970s. These Zenith Cameras achieve an accuracy of 0.5 arcsec. Later on these cameras were modified with modern equipment with collaboration of IfE Hannover and GGL ETH Zurich (Figure 7). Their aim was to determine astro-geodetic vertical deflections especially in mountainous areas. First zenith cameras are equipped with analog sensors on photographic plates and use conventional time determination techniques such as chronographs. The analog system was very successful yet it was very hard to handle the data captured and processed. However, photographic zenith camera was used for many astro-geodetic studies between 1974 and 1984 in Europe. After the invention of CCDs, revolutionary developments appeared in Geodetic Astronomy. Therewith, analog zenith camera systems were also redesigned and equipped with CCD cameras, GPS devices, and precise tilt meters. Institute of Geodesy at Hannover, and ETH Zurich announce high

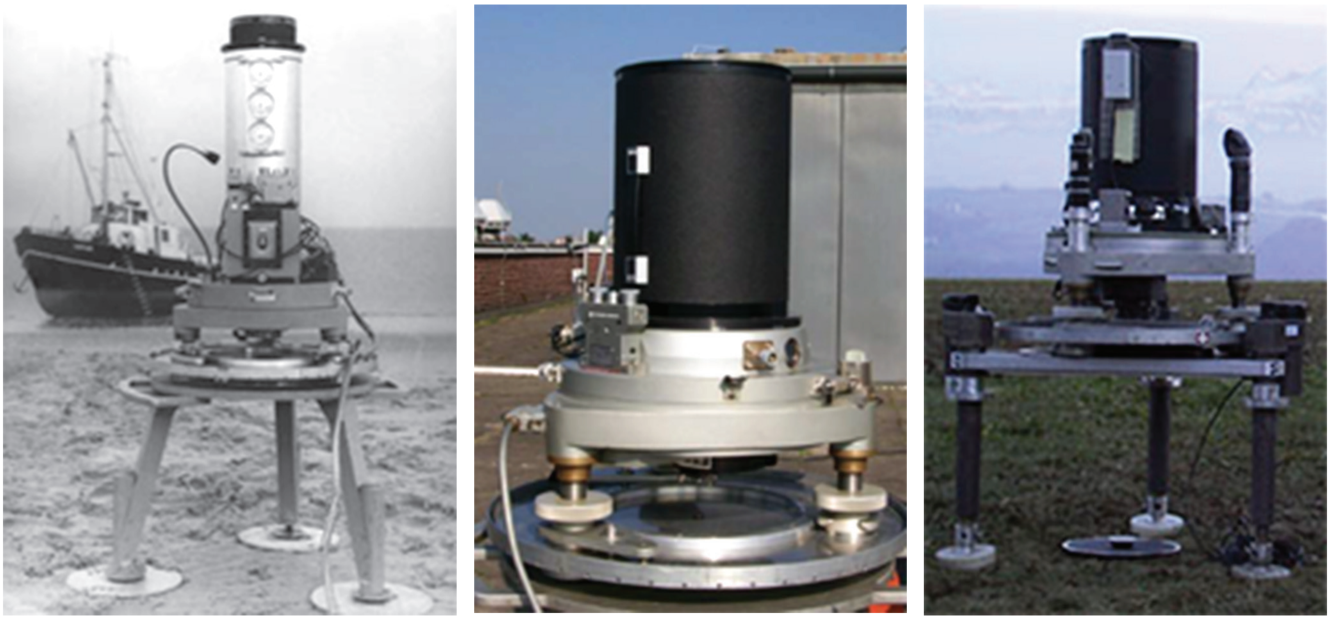

Figure 7: Analog and Digital Zenith Cameras (Gessler 1975; Hirt and Bürki 2006)

precision digital zenith camera systems beginning from the 2000s. These DZCSs have announced deflections of the vertical data at about 900 new stations in Europe since 2003 in order to determine local and regional geoids at mm and cm level (Hirt et al. 2010).

Digital Zenith Cameras at University of Hannover (Germany) and ETH Zurich (Switzerland) performed several astro-geodetic observations in European Countries such as Switzerland (101 digital and 433 analogue observations), Northern Germany- Netherlands (175 observations), Harz Mountains (120 observations), Bavarian Alps (182 observations), Portugal (17 observations), and Greece (28 observations). The accuracy of analogue observations is reported as 0.3-0.5 arcsec whereas digital zenith cameras reached the accuracy of 0.1 arcsec (Hirt and Sebeer 2008). Hirt et al. (2010) used those 1056 observations in order to assess EGM2008 Earth gravitational model and discuss the agreements between astro-geodetic data and EGM2008. Another application of Zenith Camera was performed in 2011. Deflections of the vertical were observed at the Geoid Slope Validation Survey in Texas at 228 stations along 330 km profile. The accuracy of those observations was reported as 0.1-0.05 arcsec (Smith et al. 2011).

The success of these pioneer studies in Germany and Switzerland and the necessity of determining high precise astro-geodetic data motivated other studies at Poland (Kudrys 2009), and Serbia (Ogrizovic 2009) as well as our study in Istanbul. The Zenith Camera System of Turkey is a collaborative study of Istanbul Technical University and Kandilli Observatory and Earthquake Research Institute of Bogazici University, which is funded by The Scientific and Technological Research Council of Turkey.

4. System design and test observations

Several test observations with different hardware combinations were performed during the last year in Istanbul and Antalya. A Schmidt-Cassegrain type telescope with 14 inches aperture, two inclinometers, and a dual frequency geodetic GPS receiver with a computer control unit for data capturing and system control were used during the test observations (Halicioglu et al. 2011; Halicioglu et al. 2012).

After testing different system components, we end up with a final system design with Meade 8” LX200GPS telescope, Leica Nivel 210 inclinometers, Apogee Alta U32 CCD Camera, CNS Clock II, and a dual frequency GPS receiver (Figure 8).

The test observations were performed at a Zenith Camera observatory, which is specially designed for the system in Kandilli Observatory and Earthquake Research Institute (Figure 9).

5. Conclusions

Recently, Turkish National Geodesy Commission coordinates a new project that is still in progress for height modernization in Turkey, which is aiming to achieve 1-cm Turkish geoid model. In this context it is stated that the issues concerning a new, consistent, and precise surface gravity observations, airborne gravity, vertical velocity field and deformations in the leveling network, as well as the establishment of more and stable GPS/leveling stations, topographic density model, and digital terrain model are being investigated (TNUGG 2011). In order to accomplish a high precision geoid model, homogenous data derived from various techniques as stated above have to be used including astro-geodetic measurements. It should be noted that the gaps in measurements result major problems in modeling process. There are some successful solutions that maintain high precise geoid model in Europe such as Swiss geoid model. Combination of different methods including astro-geodetic observations performed in Switzerland beginning from the 2000s. According to EUREF 2004 reports, the results of the Swiss geoid model derived from the combinations of all methods shows an accuracy of 1 to 3 cm. The applications at different countries show that the difference between astro-geodetic solutions and gravimetric solutions are in the order of a few cm only (Marti 2004). The discontinuity of

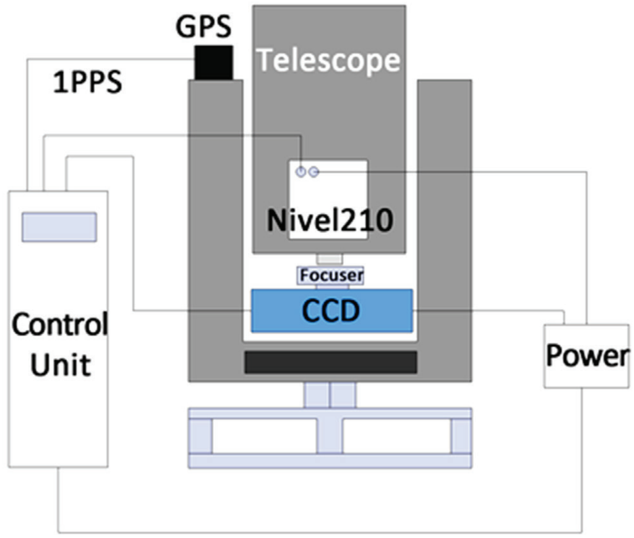

Figure 8: The scheme of zenith camera used in this study

Figure 9: Zenith Camera Test Station

gravity data along coastlines of Turkey cause problems in geoid models because there is a lack of observation on mountains that are particularly at southern and northern coastlines. It is necessary to include gravimetric or astro-geodetic data in mountainous regions and along coastlines. It is possible to collect astro-geodetic data using digital zenith cameras and determine the medium wavelength effects of geoid in order to improve national model. From this point of view, this project on determination of astro-geodetic vertical deflections using DZCS contribute a lot to height modernization studies in Turkey.

6. Acknowledgements

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