Publ. Astron. Obs. Belgrade No. 75 (2003), 221 - 228 *Contributed paper*

A SMALL CCD ZENITH CAMERA (ZC-G1) - DEVELOPED FOR RAPID GEOID MONITORING IN DIFFICULT PROJECTS

G. GERSTBACH[1] and H. PICHLER[2]
[1] *TU Vienna, Inst. of Geodesy & Geophysics, A-1040 Wien, Gußhausstr. 27-29 / 1281*
E–mail ggerstb@luna.tuwien.ac.at

[2] *A-2351 Wiener Neudorf*
E–mail hpichler@utanet.at

Abstract. Modern Geodesy by terrestrial or space methods is accurate to *millimetres* or even better. This requires very exact system definitions, together with Astronomy & Physics – and a *geoid* of cm level. To reach this precision, astrogeodetic vertical deflections are more effective than gravimetry or other methods – as shown by the 1st author 1996 at many projects in different European countries and landscapes.

While *classical Astrogeodesy* is rather complicated (time consuming, heavy instruments and observer's experience), new *electro-optical* methods are semi-automatic and fill our "geoid gap" between satellite resolution (150km) and local requirements (2-10km):

With CCD we can speed up and achieve high accuracy almost without observer's experience. In Vienna we construct a mobile zenith camera guided by notebook and GPS: made of Dur-Al, f=20cm with a Starlite MX-sensor (752×580 pixels à 11μm). Accuracy ±1" within 10min, mounted at a usual survey tripod. Weight only 4kg for a special vertical axis, controlled by springs (4×90°) and 2 levels (2002) or sensor (2003).

Applications 2003: Improving parts of Austrian geoid (±4cm→2cm); automatic astro-points in alpine surveys (vertical deflection effects 3-15cm per km). Transform of GPS heights to ±1cm. Tunneling study: heighting up to ±0.1mm without external control; combining astro-topographic and geological data.

Plans 2004: Astro control of polygons and networks – to raise accuracy and economy by ∼40% (Sun azimuths of ±3"; additional effort only 10-20%). Planned with servo theodolites and open co-operation groups.

1. CCD AND THE RENAISSANCE OF ASTRO GEODESY

The theoretical importance of the geoid for height systems, geodetic measurements and physical geodesy is well known since the 19th century (Gauß, Helmert...). In practice, Vertical deflections and other gravity field effects were neglected in most cases up to ∼1910, because their determination was too difficult. Regional surveys can be distorted by some cm per km, alpine projects up to 20cm per km (Bauer 1995, TU München 2002).

The first *global geoids* were calculated by *gravimetry* in the Thirties (±2-10m), *Astrogeoids* ∼1960. 1970-85 *satellites* gave ±5...1m. The regional and local features were determined by astro, gravi- and altimetry → at present global geoids like EGG

97 have ±0.3m (IGeS 2002). Many countries reached this level in a long *Astrogeoid era* ~30 years before – which will be continued now: by using microchip sensors *CCD* which convert photons into electrons, to be read off automatically by a PC.

1a) Astrogeodesy had a *Geoid summit* 1970-90. Then a *descent* began: innovations were missed – and gravimetry, GPS and satellite missions became more effective... But 1999 CCD caused a renaissance (Gerstbach 1996, Bretterbauer 1997, Weinwurm 1998): chances for automation, software instead of observer's experience, DTMs and local details for satellite geoids.

1b) Additional astro motivation came from an interesting effect of alpine Geoids (Austria, Swiss, Croatia): Vertical deflection information is 20 times better than gravimetry (Gerstbach 1996, Kühtreiber 1999, Papp 2003).

1c) Theoretically known, but forgotten in the last decades: Azimuths increase the accuracy and economy of polygons and networks remarkably, e.g. 5 min sun by ¿30% → Chapter 4.

2. VERTICAL DEFLECTION, GEOID – AND ZENITH CAMERAS

CCD plays an important role in natural sciences and technology; Astronomy was one of its pioneer fields [Esa, Nasa Websites]. But also many projects in physics or medicine would not be possible without modern electro-opticals.

Against these broad applications, 90% of CCD geodesy is Laser tracking with only ±1-3" accuracy (sensor types like *Cid, Ctd, Psd* are *not* used). 5-10% concern Astro or satellites, Fig.1-2. Chapter 4 shows that future chances of CCD are not only geoid monitoring, but also speeding up and higher surveying accuracy by additional use of stars or sun azimuths.

Classical Astrogeodesy – without CCD – is told to be complicated, time consuming, needs experience and heavy instruments – and it equally yields high accuracy...

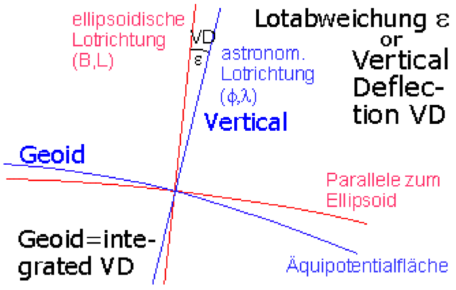

Figure 1: Geoid, ellipsoid coordinates B,L and astronom. Vertical (Deflection VD).

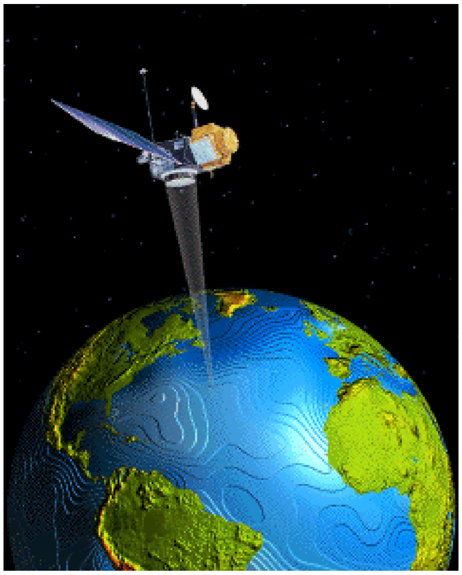

Figure 2: Global Geoid (smoothed) and Satellite Altimetry.

Many geodesists seem to think: "*automatic* satellite methods will fill the geoid gaps in the near future". But the resolution of satellite geoids is not sufficient (Fig.2) and will need terrestrial measurements for many decades. To fill this "data gap" between satellite resolution (~150 km) and local requirements of surveying or GPS transforms (2-10km), *electro-optical Astrogeodesy* is now the ideal tool.

During the astrogeoid summit 1970-90 most VDs were measured by Zeiss Astrolabe Ni2 (20 stars / 1 hour; 1977 the 1st author could increase the accuracy from ±0.4" to 0.15"). The *personal equation* (reaction time, 0.1 to 0.4s) is controlled by *reference data* to ±0.03s (Bretterbauer and Gertstbach 1983). Tests 1985-95 to eliminate it by photo diodes or PMP gave only ±0.5" (Schirmer 1994, Gerstbach 2000. et al.)

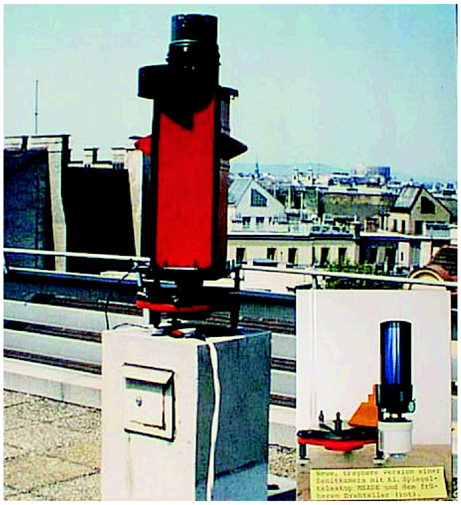

Figure 3: Vienna-Sopron Zenith Camera f = 75 cm, with turning plate ~ 30 kg. *Right:* ETX f = 90 cm + ^{1094}CCD.

TU institutes (Hannover, Paris, Vienna-Sopron Fig.3, Graz etc.) built *Zenith Cameras* to remove these errors and field work, but weights (20-40kg) and comparator time (2-3 hours) were high [To.85, Ma.95].

Only now electro-optic sensors instead of photo plates allow much smaller ZC versions. Therefore, at the TU Vienna we construct mobile and light CCD zenith cameras of only 5 kilograms which can be used even in high mountains or in difficult projects. The most important aim is to improve the Austrian Geoid by more than 50% – from 3-4cm to ±1-2cm. Our present Prototype ZC-G1 is guided by a notebook (later evt. palmtop PC) and by a small GPS navigation receiver.

Automatic astropoints in alpine surveys – measured by our system – are also ideal for Vertical deflection reduction of polygons, surveying networks or free points. These effects are caused by Topography and Geology (VD 5-50", effects 2-15cm /km, see Chapter 5). The resultant *geoid undulations* have similar influences on GPS height transformations and should be known to at least ±2cm.

3. NEW INSTRUMENTS FOR ASTROGEODESY

The Zenith Camera ZC-G1 (2002, Fig.4) has a Starlite MX 916 sensor (752×580pixels à 11 × 12 μm) and an objective 5/20cm. Mounted on a special "mini tower" of DurAlu (4kg) it can be turned exactly by 4 × 90 °, even in complete darkness, which is controlled by special springs to ±2'. Star field images with 20-40 Tycho stars give ±0.5-1" accuracy with 2D Gauß *point spread functions* [Pichler 2002].

Usually we don't use the full pixel resolution of 11 × 12 μm, because 2×2 pixels are *binned* for higher sensitivity of the sensor. Better star images increase the accuracy (~0.03 px) even if resolution is less (Gerstbach 2000).

Figure 4: Zenith Camera G1.

Figure 5: Infotheodolite Leica.

Exposing 4 zenith images takes 10min, 4 other control the results. The spirit levels we'll replace by digital vertical sensors. For accuracy ¡0.5” a long focus camera G-2 is designed.

Other methods with *external* CCDs were tested, too: Zeiss astrolabe (±1”, 30^m), Info Tachymeters of Leica (Fig.5, ±1”) and Geotronics (Gerstbach 2000). The time effort depends on star database and software. 2003 I plan semiaut. CCD tests with servotheodolites – for polygon or net azimuths by *Sun or bright Stars* and 4D database (handling $^3/_3$ quicker; time series i of star coord. $d_i \times_{jk}$ (k=1..n, j=1..3). Interested institutes are invited to cooperate, e.g.:

CCD servo theodolite: chip tests, sun filters, star error programs, automatic evaluation...

Zenith camera G-2: higher sensitivity software, market & geoid tests, production series.

Autovideo methods (Mischke TUWien) use 2 servotheodolites to intersect points / lines after Förstner. Active targets are found by quick filters, but CCD sensitivity is not sufficient for stars. So we'll test the system by manual PC selection and by sun: 2 azimuths of ±3” will increase traverses and networks by 30% → Table 4a.

4. MODERN SURVEY ACCURACY – AND BAD REDUCTION MODELS?

We see: azimuths are *useless at center,* but optimal (d) at 25 and 75% of the polygon length → time effort 10% gives 30% effect! *”Sun in quarters”* is also optimal when fixpoints have no sightings, for open traverses or small networks.

A single Polaris Azimut can improve a 5-point network by 20-50% (Gerstbach 2001). But different from polygons, in a *network* the azimuths should be observed *directly at the weakest point(s).* By this way, crustal deformation projects can decrease the level of significant point movements by 40 or 60%.

Table 4a: The Effect of 1-2 Azimuths in Polygons (Traverses) or Networks Cross error of an elongated polygon 10 × 500m (±1mgon, fixed points No.10, 20), shown at the first 5 points. Point errors of 16-19 are symmetric, those with sun azimuths underlined [Gerstbach 2001].

Polygon	accuracy	each 2 sun azimuths ± 1 mgon				4 Azim.	2-5 azimuths ± 0.2 mgon		
Point	**a) no Az.**	b) 14,16	c) 13,17	**d) 12,18**	e) 11,19	f)12,14..	g) 11,19	h) 4 Az.	i) 5 alt.
11	±9.2mm	8.8	8.8	**±8.6mm**	7.5	8.3	±6.5mm	7.8	6.3
12	17.2	16.0	15.8	**14.2**	12.6	13.4	9.4	11.6	8.5
13	23.8	21.7	20.0	**17.1**	17.9	16.0	14.4	12.2	11.1
14	28.0	24.8	21.0	**19.5**	21.9	17.9	18.5	13.5	11.4
15	29.5	25.2	21.3	**20.5**	23.3	18.2	20.0	13.1	12.3

Table 4b: Modern surveys require for reduction to mm level. Flat areas and levelling are troublefree, but steep sightings (civil eng., alpine projects) are very affected by Vertical deflections. Directions, slant distances (zenith angles) must be VD-corrected, not to loose the accuracy and ellipsoidal relation:

Vertical deflection **VD=20"**	Direction red.	Distance red.
Sighting inclined 10gon (9 °)	1 mgon (3.2")	15 mm / km
Steep sighting 50 gon (45 °)	6 mgon (20")	69 mm / km

In flat or hilly tectonic areas (basins, Rhine valley, west.Hungary..) VD reaches 15" (5mgon), in mountains 20-50". GPS requires a high resolution cm-geoid too, which exists only in 2 of Europe (parts of D, A). A few % have ±3cm, Western & Central Europe 5-15cm.

New satellites (CHAMP, GRACE..) promise a 1-2cm geoid, but only regional (~150km) with *no local details* – helpful just for flat areas with easy geology → 90% of Europe still needs a gravimetric or astro-geoid. For (1.b) the latter is ~10 times more economical → our small zenith camera G1 is ideal for quick astro profiles, steep valleys, tunnelling control or between high buildings. Additionally VD can be inverted for *density structures* of the Earth's crust (Gerstbach and Tengler 1994, Gerstbach 1999).

Contrary to fixed sites these and other field methods need no high accuracy but *quick procedures* to get data at many points. CCD speeds up the observation, guided by PC & GPS. For Engineering with polygons or networks, economic methods by Servo theodolites and sun azimuths are forthcoming.

5. GEOID, TOPOGRAPHY AND GEOLOGY

Interpolation of Vertical deflections (VD; ξ, η) is the main task in precise geodesy – either for geoid integration, or for VD calculation at points of a survey which are *not* astropoints (measured ξ, η). VD interpolation is done in a remove-restore-process:

- Remove of topographic VD effects of surrounding astropoints *(reduction radius e.g. 20 km)*
- Interpolation of VD (ξ, η) at all important points within this *smoothed vector field* ξ^0, η^0
- Restore of topographic masses → true VD of the "new points".

Usually topography is gridded as DTM (digital terrain model) of 100-500m raster. Regions with variable geology (mountain ranges, tectonic lines, sediment basins, Graben systems…) should be enhanced by *subsurface density layers* (Gerstbach 1999); a good DTM includes local rock densities.

In distinction to gravimetry, an astrogeoid has *no border effect.* Additional GPS / levelling points give very stable accuracy across the whole network. So the Austrian Geoid 2000 (700 VDs) didn't rise accuracy by additional 20.000 gravity points [Kühtreiber 99]. The low weight of gravimetry is caused mainly by valley profiles which distort the Anomalies Δg, but not ξ, η) (Gerstbach 1997):

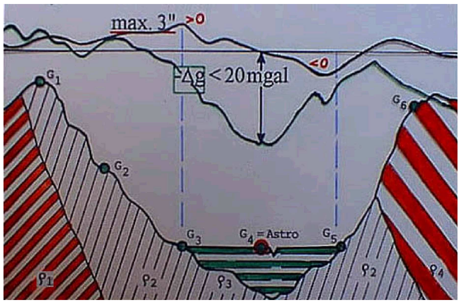

Figure 6: **Alpine valley and VD, Δg.** Variable rock density ($\rho_1 > \rho_2 > \rho_4 >> \rho_3$, $\rho_2 = 2.65$) cause "reduction anomalies" *up to -20mgal* at valley floors (sediment $\rho_2 \approx 2.0$). At 4 of 6 points $G_1 - G_6$ Δg is *systematic* negative, but VD is < 2" and quasi-random (astropoint G_4 ∼ symmetrical).

Sediment densities of "young" alpine valleys or basins affect the gravity up to **-20mgal,** but VD only 1-2", even in broad valleys [Ge/Te.94]. The Vienna Basin with sunken mountains of 6km is our test area for "Geologic Gravity Field Interpolation" (Gerstbach 1999). At Astro point distances of 5-8km improves the geoid (1-2cm) to ±5mm.

In the 90's I analyzed many European geoid projects and discussed with Torge, Sünkel, Wenzel et al.: Astrogeoids of cm accuracy level require only 6-10 VD points per 1000 km^2, but gravimetry 100-500 Δg points – depending on topography [Gerstbach 1997]. →

My conclusion since that time is: Vertical deflections should get much higher weight in geoid projects than Δg; the relation for alpine geoids is ∼30:1. There are different reasons. The Plumb line is

- the only *direct* measure of a geoid orthogonal;
- a *Vector* instead of a scalar – and is
- less influenced by subsurface density variations than gravity anomalies or – gradients.

▶ Therefore Astrogeoids require only 5% of data points, compared with gravimetric geoids.

- VD measurements and their DTM reductions (→ start of Chapter 5) need *no exact* topographic model of the near surrounding, and no precise levelling.

○ But up to 2002 VD observations were ∼3 times longer than gravimetry.

5. 1. ALPINE GEOID TESTS

Let's compare the official Austrian Geoid (sector Salzburg, summits ∼3300m, accuracy ±5cm per 100km) with a local geoid: **Fig. 7** Geoid [Sünkel 1996], **Fig. 8** Test "Hohe Tauern" [TU Wien].

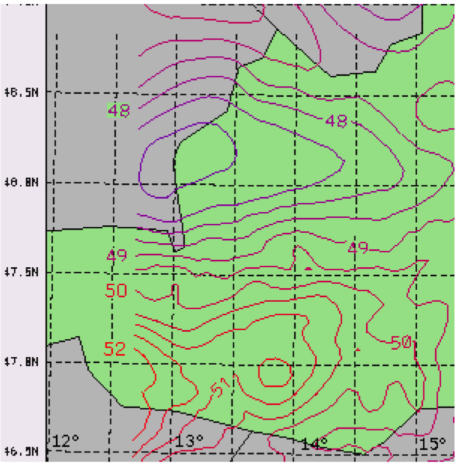

Figure 7:

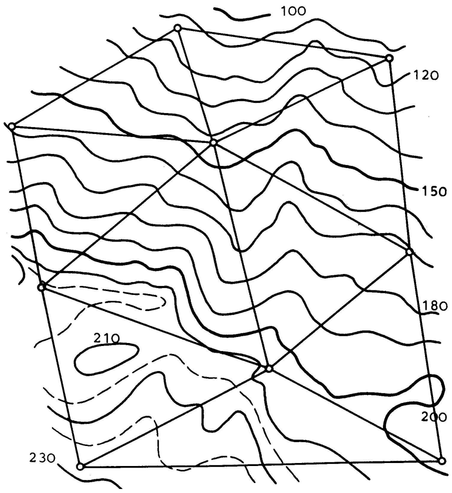

Figure 8:

Fig. 8 is located in the center of fig.7, B=47-47.6 ° and uses a "slope formula" [Ge./ Holaus; see Fig.9] instead of a gridded DTM. After trend reduction the 2 geoids differ by ±20cm (up to 50cm) – for local mountain effects and required *filtering* of a *regional* geoid file like that in Fig. 7. In case these mountain ranges (Rauris-, Gastein Valley) would be highly asymmetric (or their relative heights ¿1.5km), such "*filtered plots*" can have errors of 50cm, unfiltered original data less.

This may be *one of the reasons* of the interesting discrepancies reported by Ogrizovic et al., [2002]. *Another* could be a slight distorsion of Δg data due to military interests – a problem e.g. of Albany or Hungary, too (Gerstbach 1997).

The mentioned 30:1 relation corresponds to a true economy relation of circa 20:1, because gravimetry is still 30% faster than astrogeodesy (and more independent of weather conditions). On the other way it is almost *impossible* to cross alpine slopes in a *1km grid* (and to measure valley profiles with cm..dm accuracy).

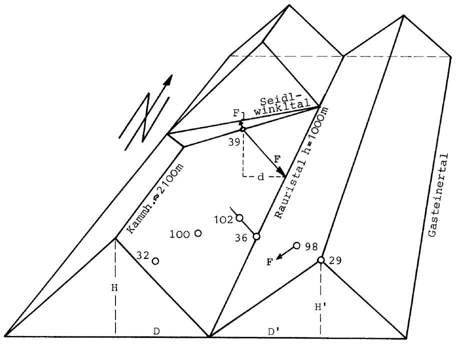

Figure 9: Horizontal prisms for alpine valleys (Salzburg) to get VD by a "slope formula".

6. CONCLUSION

Above we have discussed some *forgotten facts:* the economy of Astrogeodesy and Deflection of the Vertical (VD), compared with Gravimetry or other gravity field monitoring. VD measurements can now be automated by CCD, which causes a Renaissance of Astrogeodesy. These are our reasons to **give priority to the development of zenith cameras, which can be used in high mountains, between**

power stations, parking cars or protected trees –
independent of infra structure problems, gates or electricity. Our new instrument is transportable even in a small rucksack, with modern but independent computers, navigated traditionally *or by GPS* – and in contact with the eldest but "best friends" of our rotating Earth, THE STARS.

References

Bretterbauer, K.: 1997, Eine Renaissance der Astrometrie in der Geodäsie. *VGI* 1/97, p.15-20, Wien.

Bretterbauer, K., Gerstbach, G.: 1983, Die astro-geodätischen Arbeiten der TU Wien. Das Geoid in Österreich, *ÖKIE neue Folge Band III*, S. 61-72, Graz.

Bauer, Ch.: 1995, Bestimmung eines Geoidprofils in Tirol mittels GPS und Nivellement. *Diplomarbeit Abt. Höhere Geodäsie* (Dptm. Advanced Geodesy), TU Wien.

Gerstbach, G., Tengler, T.: 1994, Interaktive geologische Modellierung von Bruchzonen mit Lotabweichungen. *Österr. Beiträge zu Met. u. Geoph.* **8**, p.143-160, Wien.

Gerstbach, G.: 1996/97, How to get an European Centimeter Geoid ("astro-geological geoid"). *Physics and Chemistry of the Earth* **21/4**, p.343-346, Lindau / London.

Gerstbach, G.: 1999, Inversion of Vertical Deflection Data by the Program GREMMO. *Bolletino di Geofisica teorica ed applicata* **40**, p.461-468, Trieste.

Gerstbach, G.: 2000, CCD und Astro-Geodäsie. Unterwegs zur automatischen Lotrichtungsmessung. *Geowiss. Mitt. der TU Wien, Vol.* **50** (Festschrift Bretterbauer), p.40-57, Wien.

Gerstbach, G.: 2001, CCD Geodesy: not only LASER, also Stars! *Proc. Hydr. &Geotech. Timis.*, Akad. Rom. **Vol.9**.

Hirt, Ch., Seeber, G.: 2002, Astrogeodätische Lotabweichungsbestimmung mit dem digitalen Zenitkamerasystem TZK2-D. *ZfV 127 Heft 6.* Abstract:
www.dvw.de/content/zfv/2002/11_12_c.htm

IGeS : 2002, Files: Europ.(Quasi)Geoid EGG97. *IGeS Files Repos.*, H. Denker 1997, http://www.iges.polimi.itt/

Kühtreiber, N., 1999: Combining Gravity Anomalies and Deflections of the Vertical for a precise Austrian Geoid. *Bolletino di Geofisica teorica ed applicata* **40**, p.545-553, Trieste.

Marti, U., Bürki, B., Kahle, H.G.: 1995, National Geoid Investigations in Switzerland. New Geoids in the World *(IAG Bull. 77, IGES Spec. Issue 4)*, p.181-190, Milano / Toulouse.

Ogrizovic, V. et al.: 2002, Analysis of Vertical Deflection Differences obtained by Astrogeodetic and Gravimetric Methods. *Proceedings XIII. Conf. of Yug. Astr., 17-20 Oct. 02,* in print, Beograd. *Presented in Sect. 4.* Separata of Authors 7p., Oct. 2002.

Papp, G.: 2003, Geoid accuracy – gravity anomalies vs. Vertical deflections and Geology. *Seminarvortrag TU Wien (Jan.* 2003) und vorangehende Diskussionen, Sopron/Wien.

Pichler, H.: 2002, Automatische Lotrichtungsmessung mit einer mobilen CCD- Zenitkamera. *Diplomarbeit, Abt. Höhere Geodäsie* (Dptm. Advanced Geodesy), 88 p., Okt. 2002, TU Wien.

Schirmer, W.: 1994, Universaltheodolit und CCD-Kamera - ein unpersönliches Meßsystem für astronomisch-geodätische Beobachtungen. *DGK Reihe C/427,* 93 S., München.

Sünkel, H.: 1996, Austrian Geoid and Quasi-geoid, GRS80. http://www.iges.polimi.it/ *Subfile Austria.*

Torge, W., Seeber, G.: 1985, Zum Einsatz transportabler Zenitkameras für die Lotabweichungsbestimmung. *ZfV* **110**, p.439-450, Stuttgart.

TU München : 2002, Schwerefeld der Erde.
http://step.iapg.verm.tu-muenchen.de/groups/testnetz/framedef.html

Weinwurm, G.: 1998, CCD-Astrometrie zur Beobachtung künstlicher Erdsatelliten. *Diplomarbeit, Abt. Höhere Geodäsie* (Dptm. Advanced Geodesy), TU Wien.