Geoid Monitoring by Zenith Camera and Geology

Geoscientific Cooperation Projects of Austria, Slovakia and Hungary

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Abstract: Modern terrestrial or space Geodesy is accurate to *millimetres* and therefore requires a geoid of *cm level*. The new quasigeoid of Slovakia meets this goal due to a dense grid of gravity points [Mojzes 2003], except in some mountainous regions. But in principle, *astrogeodetic* vertical deflections (VD) are more effective for a precise geoid than gravimetry or other methods. About 20 gravity points are necessary to "replace" *one VD* in a certain location [Gerstbach 1996b, Papp 2003]. This was suspected at Austrian and Swiss geoid solutions of 1987-99, too.

The drawbacks of *classical Astrogeodesy* are overcome by electronic methods which fill the "geoid gap" between satellite resolution (150 km) and local networks in the near future. CCD can be automated for high accuracy without observer's experience. In Vienna we construct geodetic Zenith Cameras guided by notebook and GPS: full mobile for tripods (4-10 kg, f~25 cm) they give ±1" within 10^{min}. Field tests of ZC-G1 were made 2003 in the Tatra region. Next summer detailed comparisons with the gravimetric geoid and tests of G2 are planned.

In 2004 the TU Vienna, TU Bratislava and GGRI Sopron will co-operate for a *"geological geoid"* of the border area. To improve the geoid by 50%, the sediment densities of Viennese and Pannonian Basin are to be determined from existing maps, data, or new profiles, and fed into GIS. Special gravity and VD software is already existing.

1 Astrogeodesy and the Geoid in Central Europe

The importance of the geoid for height systems, surveying and physical geodesy is well known since Gauß and Helmert. In practice, Vertical deflections (VD) and other gravity field effects were neglected mostly up to ~1970, because their determination was too difficult. Regional surveys can be distorted by some cm per km, alpine projects up to 20 cm per km.

The first *astrogeoid* was finished 1914 in Germany/ Harz, a global *gravimetric geoid* 1948 (±10 m, in Europe ±2 m). Satellite methods reached meter accuracy ~1975. Austria started the series of *national astrogeoids* 1953 (±60 cm), based on 1st order points. H. Wolf calculated the central europ. network geoid (1956 ±1m). The next milestones were Germany (1969 ±20 cm), Swiss (1973 ±12 cm) and prediction methods for VD integration – necessary for mean point spacing of 48 and 25 km [Gerstbach 1979]. Special projects near Hannover, Vienna, and Tatra mountains reached ±2-3 cm due to narrow point distances <10 km.

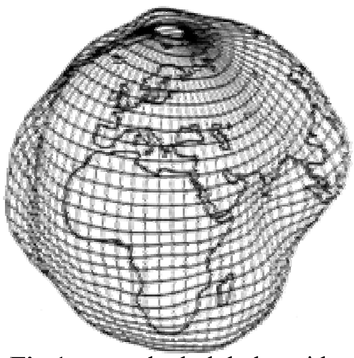


Fig.1: smoothed global geoid, based on potential coefficients

Austria therefore decided to improve the *astrogeoid* by 650 additional VD points, a good DTM (digital terrain model) and GPS levelling. The astro points were measured 1976-83 by Zeiss Ni2 astrolabe (2 nights ➔ ±0.3") and resulted in the Geoid 1983/87 (±6 cm; 1999 ±4 cm). Other countries prefer *gravimetry or combine* with astro, GPS, altimetry, global or regional geoids. For instance, EGG 97 has ±0.3 m precision [IGeS 2002] and serves as a basis for many countries. Croatia or Greece make great use of satellite altimetry when extending the geoid to some islands.

In the last decade Carpatho-Pannonia reached the cm/dm level by a dense gravimetric network. Czechia reports accuracies of ±2 cm, the rms differences between the new *gravimetric* quasigeoid *CR2000* and GPS/levelling at 640 points are ±3.5 cm [Cz Rep. 2003]. In Slovakia the situation is similar [Mojzes 1998, 2003], whereas in Hungary the accuracy is less (~10 cm), mainly for varying density of sediment and gravity data of the Pannonian Basin [Papp 1999/03, Toth 1999]. Partly this may be improved by gravity gradients (readjustment of 50.000 torsion balance data). Additional 200 astro points are considered – which proofed to be very effective in Croatia 1990-2000 [Basic/ Brkic 1999].

1.1 Geoid Résumé:

The central european geoid has a quality of some cm, except in mountainous areas with poor data (e.g. south Germany, parts of Carpathians). The Swiss geoid (300 astro-, 3000 gravity points) yields *"a few cm… only with astro-geodetic observations".* According to my analyses 1996-99 in different european projects, deflections of the Vertical are about 20 times more effective for a cm-geoid than gravity anomalies – see chapter 4. Therefore eventual data gaps should be filled with *astropoints.*

A geoid project of 1000 km² requires 500-1000 gravimetric points to get ±2 cm accuracy, but *only 30* astropoints. The point spacing has to be 1-2 km, resp. ~5 km.

Investigations for a new Austrian geoid [Erker et al. 2003] showed a realistic weight of the 700 astro points (±0.25"), whereas the priori weight of the 86.000 gravity data was too optimistic. According to [Kühtreiber 1999, 2002] the standard deviations were changed from ±0.3 mgal to 1.5 mgal.

1.2 Renaissance of Astrogeodesy – Motivation of new Co-operations

Astrogeodesy was 'out' for 10 or 20 years. Now we see a *Renaissance,* caused by CCD, high efficiency and ideal conditions to combine with geological and satellite data [Gerstbach 1994-99, GFZ 2003]. In alpine regions *Astrogeodesy* has three advantages over gravimetry:

- point spacing of ~5 km can follow the valley (or ridge) structure, whereas gravity profiles have to cross the slopes in a 1-2 km raster.
- Astropoints do *not* need exact tacheometry of the terrain – local terrain reduction can be modelled by an inclined plane [Gerstbach 1996b]. Valley sediment effects are quasi-symmetric ➔ chapter 4.
- No levelling is required. Heights of ±5 m (from map, GPS or barometer) are sufficient.

Other important aspects for the next future are:

- **Automation by CCD** [Gerstbach 1996a, 2000, Bretterbauer 1997]; control software replaces the observer's experience, GPS the fixed points.
- Applications in Geodynamics and Geophysics, density models, sediments [Bretterbauer/ Gerstbach 1983, Schödlbauer 2000, Gerstbach/ Papp 2003].
- Theoretically known, but 'forgotten' in the last decades: Azimuths increase the accuracy and economy of polygons and networks – e.g. 30-50 % by just 5^{min} sun observation [Gerstbach 2001].

o Only drawback of astro-geodetic methods : a 50 % clear sky is required.

2 Vertical Deflection – and Steps to Automation by CCD

CCD (charge coupled device) is the most important type of electro-optical sensors and was developed in the 70'ties. It converts the energy of photons into charges of microscopic semiconductor pixels which can be read out automatically by a PC. CCD plays an important role in natural science and technology; astronomy was one of its pioneer fields. But also many projects in physics or medicine would not be possible without modern electro-optics.

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); 10 % concern Astro or satellites. In future CCD will also speed up surveying and improve accuracy by additional use of stars or sun azimuths.

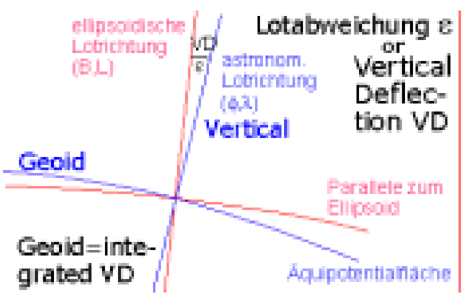


Fig.2: Geoid, ellipsoid coordinates B, L and astronom. Vertical (Deflection VD)

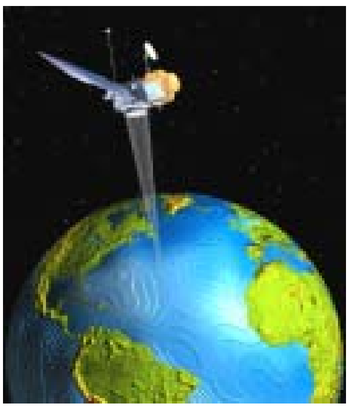


Fig.3: global Geoid – to be refined by Satellite Altimetry

Classical Astrogeodesy (without

CCD) is rather complicated, time consuming, needs experience and heavy instruments – and its accuracy is often higher than required.

The geoid of many developing countries is not better than global solutions (EGM 96 ~30 cm). Geodesists seem to expect that *GRACE* and *GOCE* satellites will fill the geoid gaps in the near future. The accuracy will be sufficient, but *not the resolution* – it 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 (2-10 km), *electro-optical Astrogeodesy* is now the ideal tool.

During the *astrogeoid summit* 1970-90 most VDs were measured by Zeiss astrolabes Ni2; CSSR and other countries also used the Circumzenital. In Austria and Croatia we observed 20 stars per 1 hour; the accuracy of ±0.4" increased to 0.15" by exact modelling of personal and instrumental error types. Special FORTRAN routines improved the used FK4 stars to ±0.05".

Fig.4: Vienna-Sopron Zenith Camera on its turning plate

The *personal equation* (reaction time) of 10 persons varied from 0.1 to 0.4 s but was controlled by *reference data* to ±0.03 s [Brett./Gerstb. 1983]. Tests to eliminate reaction time by using photo diodes, PMP or line sensors gave only ±0.5" [Gerstbach 1996a / 2000].

So we developed a Zenith Camera, like other TU institutes (Hannover, Paris, Graz…). The speciality of our Vienna-Sopron type (f=75 cm, Fig.4) is the axis system. ZCs remove many errors and shorten the field work, but weight (30 kg) and comparator time (2-3 hours) is still high [Torge, Seeber 1985].

Therefore light instruments are required – especially for astropoints in alpine surveys – and automatic evaluation software. During 4 years of my project "CCD and Geodetic Astronomy" we tested several solutions and finally decided for a small Zenith Camera. Other institutes prefer Infotheodolites – they can be used for geoid projects *and* surveying. VD effects in usual surveys are 2-15 cm/ km (VD 5-50"). The resultant *geoids undulations* have similar influences to GPS height transformations and should be known to at least ±2 cm.

Fig. 5: Zenith Camera ZC-G1

3 New Instruments for Astrogeodesy

Nowadays electro-optic sensors instead of photo plates allow much smaller ZC versions. Therefore, at the TU Vienna we construct mobile CCD zenith cameras of only 3-6 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 3-4 cm to ±1-2 cm. Our present Prototype ZC-G1 is guided by a notebook (later evt. palmtop PC) and soon by a small GPS navigation receiver.

The **Zenith Camera ZC-G1** (2002, Fig.5) has a Starlite MX 916 sensor (752 x 580 pixels à 11 x 12 µm) and a 5 / 20 cm lens. Mounted on a special "mini tower" of DurAlu (4 kg) it can be turned exactly by 4 x 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 x 12 µm, because 2x2 pixels are *binned* for higher sensitivity of the sensor. Brighter star images increase the accuracy (~0.03 px) even if resolution is less [Gerstbach 2000].

Exposing 4 zenith images takes 10 min, 4 other control the results. The spirit levels we'll replace by digital vertical sensors. For accuracy < 0.5" a camera G-2 with longer focus is designed 2003/04.

At the same time as our ZC-G1 a greater zenith camera TZK2-D was developed at the Univ. Hannover (f=1020 mm, shortened optics of Maksutov type, CCD 1530x1020). Based upon the photo TZK2 of 1982, its weight may be ~40 kg [Torge/ Seeber 1985, Hirt/ Seeber 2002].

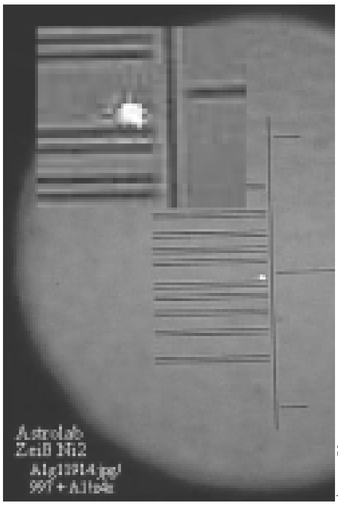


Fig. 6: Zeiss astrolabe Ni2, star transit by external CCD camera; inlay magnified 4x
Fig. 7: Infotheodolite Leica

3.1 Other CCD methods

were tested at the TU Vienna, too: Zeiss astrolabe (±1" within 30^m), Info tacheometers of Leica (Fig.7, ±1") and of Geotronics [Ge.2000]. The time effort depends on sensor, star database and software.

Fig.6 shows a star transit in an astrolabe, recorded by external CCD camera 840 and converted into black & white. The accuracy of such transits is ±1-2" at pixel scales of 9", compared with ±0.5" in *visual modus.* Therefore we stopped the tests after 1 year. The alternative was a system of horizontal *CCD strips* (line sensors) instead of the astrolabe reticule. Several tests gave ±0.2s per transit, less accurate than above; so plans for a step motor astrolabe were postponed. Similar prototypes are described in [Schödlbauer 2000].

Tests with several tacheometers (Fig. 7) were more successful, but only with external cameras (internal CCD sensitivity e.g. of TCA or TM 3000 is not sufficient for stars; appropriate CCD sensors are too large for the focus). A theodolite version that fits for astrogeodesy would be a value adding solution for geodetic instrument producers.

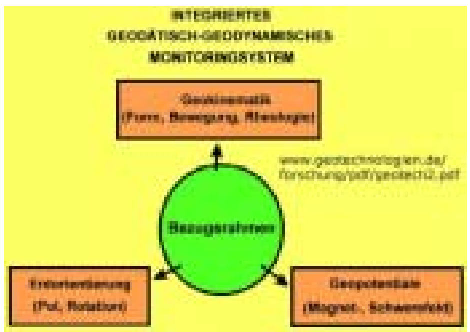
A swiss institution is developing software for "**Star Tacheometry**". Even without CCD but with *visual* measurements, this will speed up the observations by ~50%. Also high experience of the observer is no longer required – which has been a heavy drawback for astro projects in the last decade.

3.2 Modern Surveys and Network Efficiency

Digital zenith cameras are excellent tools to improve the geoid – but CCD theodolites would be more universal, usable also for surveying. Additionally, Sun azimuths can rise the efficiency of polygons and geodetic networks remarkably [Gerstb. 2001]: 5 minutes of measuring directions to the sun reduce the cross error by 30%, if done near the first and last quarter of the traverse. The *time effort* is only 10%. Also 1-2 Polaris azimuths can improve small networks by 20-50%.

Modern surveys ask for reduction to mm level. Flat areas and levelling are troublefree, but steep sightings (civil engineering, 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:

Example: **VD=20"**	Direction red.	Distance red.
Sighting inclined 10 gon (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, Pannonia) VD reaches 15" (5 mgon), in mountains 20-50". GPS also requires a high resolution cm-geoid which exists only in small parts of Europe.

3.3 Earth Monitoring IGGM

In 2001 IAG began to establish the IGGM (integrated geodetic-geodyn. monitoring system), based on space techniques. Concerning the geopotential/ gravity field (bottom right of fig.) that's mainly by new satellites GRACE, GOCE which promise a 1-2 cm geoid, but only regional (~150 km) with *no local details*. Again CCD astrogeodesy will be a good supplement.

4 Geoid, Topography and Geology

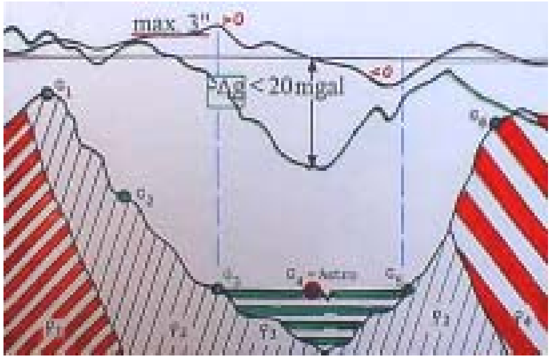
Interpolation of Vertical deflections is a twofold task in precise geodesy – either for geoid integration, or for fixed points without measured ξ, η. VD interpolation is done in a remove-restore-process:

- 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°, η°
- Restore of topographic masses ➔ true VD of the "new points".

Usually topography is gridded as DTM (digital terrain model) of 50 - 500 m raster. Regions with variable geology (mountain ranges, tectonic lines, sediment basins, Graben systems…) should be enhanced by *subsurface density layers* [Gerstbach 1996-99]; a good DTM includes local rock densities.

But different to gravimetry, astrogeoids are less affected by geology (chapter 1.2). The Austrian Geoid 2000 (700 VDs) didn't win accuracy by additional 7.000 gravity points [Kühtreiber 99]. Their lower weight is caused mainly by subsurface sediments which distort the anomalies Δg, but not ξ, η:

Fig.8: Alpine valley, VD and Δg. Variable rock density ($\rho_1 > \rho_2 > \rho_4 \gg \rho_3$, $\rho_2 = 2.65$) cause "reduction anomalies" *up to -20 mgal* 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).



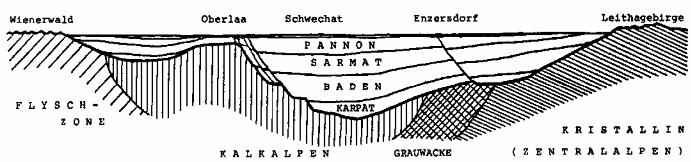


Fig.9: Vienna Basin, cross section NW - SE.

Sediment densities of "young" alpine valleys affect the gravity up to **-20 mgal,** but VD only 1-2", even in broad valleys [Ge.,Tengler 1994]. Similar effects are seen in tectonic features. The Vienna Basin with sunken mountains of 6 km is our test area for *"geologic gravity field interpolation"* [Gerstbach 1999]. At astro point distances of 5 - 8 km it improves the geoid (1-2 cm) to ±5 mm.

In 2003 the TU Vienna, TU Bratislava and GGRI Sopron started cooperations for a *"geological geoid"* of the common border area which covers the western Pannonian Basin. To improve the geoid by 50 %, the sediment densities of the basins are to be determined from existing maps, reports or new profiles and fed into GIS data bases. Special gravity and VD software is already existing.

4.1 The reasons of Astrogeoid's Quality

The effect of fig.8 I found by conclusions of 20 geoid projects in Europe: Vertical deflections should get much higher weight than Δg; the relation for alpine geoids is ~30 : 1, in hilly areas ~20 : 1. Now we extend this conclusion to flat tectonic areas or sediment basins [Papp 2003, Gerstb./ Papp 2003]. There are different reasons. The Plumb line is

a) the only *direct* measure of a geoid orthogonal;

b) a *Vector* instead of a scalar – and is

c) less influenced by subsurface density variations than gravity anomalies or -gradients (see fig. 8)

▶ Therefore Astrogeoids require only 5 % of data points, compared with gravimetric geoids. Further, VD measurements and their topographic reductions need *no exact* local DTM, and no precise levelling. The only drawback of longer observation times is now overcome by CCD.

d) Astrogeoids have no border effects and can be 'glued' directly into regional geoids.

e) They include local inclination details, due to (a).

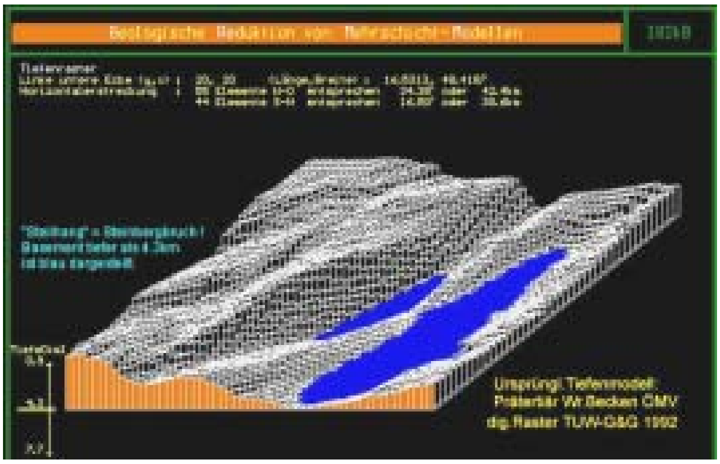


Fig.10: Vienna Basin, small Carpathians and western Pannonia.
Fig.11: Steinbergbruch and Schwechat Tief [Gerstb./Papp 2003].

5 "Austro-Pannonia" – Cooperation of three countries

As shown before, Geology is the limiting factor of geoid accuracy not only in alpine regions but in all tectonic areas. Therefore a good knowledge of the geological layers and their densities is essential. Fig. 10 sketches the active and tectonic lines from the Viennese to the western Pannonian basin. This area was selected for a special cooperation by a group of geoid researchers of the TU Vienna, TU Bratislava and GGRI Sopron:

1) Institute of Geodesy & Geophysics, TU Vienna / Dptm. of Advanced Geodesy –
with special experience in modelling of flat sediments and Vertical deflections (Fig.11);

2) Institute of Higher Geodesy, Technical University Bratislava –
with its Circumzenital, new quasigeoid and present digitalisation of density maps [Mojzes 2003];

3) Geodetic & geophysical Research Institute, Sopron –
and the interdisciplinary team working in gravimetry and upper mantle models (Fig.12).

In stratigraphy, age and petrology the Pannonian basin is similar to the Viennese – pretertiary basement of Flysch, Limestone, Crystalline and Greywacke – but the depths of the sediments reach maxima of more than 8 km. Additionally volcanic structures are found in the near subsurface.

Therefore the rock densities range from approx. 1.9 g/cm³ up to ~3 (Vienna basin 2.0 – 2.7). This may be the reason for some geoid discrepancies near the Austro-Hungarian border [Kühtr. 99, Erker 03].

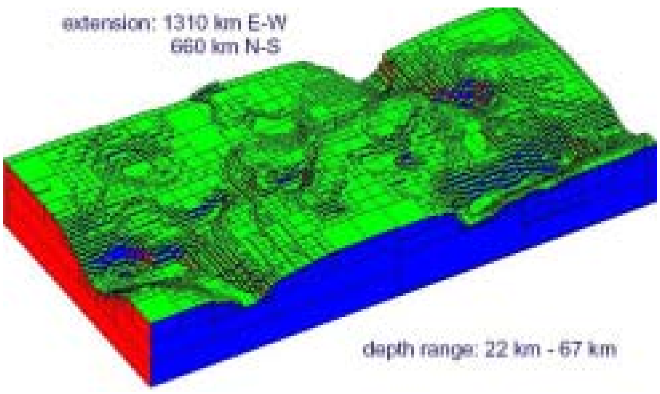


Fig.12: Mantle beneath the Carpathian Basin [Papp 2003].

Fig.13: Density variations in the basin NW of Vienna; 5 vertical districts, progr. GREMMO [Gerstbach 1999].

In a first step we'll discuss the range of surface rock densities and the reliability of gravity field anomalies near the border of our countries. The next step may be a common model of vertical compaction rates (Vienna basin 0.10-0.16 per km) which look different in Pannonia. Based on subsurface data which exist at our institutes, this could aim to a *"2.5-D geological geoid"*. This goal can be supported by the new zenith camera – which is expected to be a suitable "sensor" to measure *inclined layers* in the subsurface.

6 Conclusion

As seen at present, the main goals of the cooperation will be a full 3D **density model** (DDM) and the mutual densification of astro- and gravimetric geoid solutions. Interesting relations to Geoinformation Systems (GIS) and other sciences can be expected.

The gravity field interpretation and collection of useful data for a DDM will be interdisciplinary tasks which require geological support, but also give young colleagues the chance of PhD or Diploma theses with practical relevance [Gerstbach/ Papp 2003, Mojzes 2003]. To **improve the geoid by 50%,** the sediment densities of Viennese and Pannonian Basin are to be determined from existing maps, data, or new profiles, and fed into GIS. Special gravity and VD software is already existing.

Chapter 1-2 pointed out the economy of Astrogeodesy and of deflection of the Vertical (VD), compared with gravimetry or other methods. **Automation by CCD** causes a renaissance of Astrogeodesy and our development of digital zenith cameras. They can be used in high mountains, between high buildings or trees – independent of infra structure, guided by notebook and GPS.

On the other hand we realized **Geology as the limiting factor** in geoid accuracy – even in the flat areas of Pannonia – and therefore we have to investigate the sediments up to depths of 5 or 10 kilometres. A 3D density model is a pre-supposition to get a cm geoid – and to make full use of GPS and other space geodetic methods.

Dedication

It is a honour for me to dedicate this work to Prof. Ján Melicher – *"Maestro"* of Geodetic Astronomy and Space Geodesy – with my congratulations.

A special reminiscence may be next summer during the planned geoid comparison: to proof our zenith camera at some Circumzenithal points he had measured in the Tatra region.

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