The Development of Physical Geodesy during 1984-2014 - A personal view

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CONTENTS

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- My background experiences (before 1984)
- Development of data
- Development of theory
- NKG geoid models
- Gravity inversion
- Conclusions with some remaining problems

My background experiences

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- **Ph.D. training 1971-1975**
  - "The three Swedish kings of Geodesy" (L. Asplund, A. Bjerhammar and E. Tengström)
  - Bjerhammar's book "Theory of Errors and Generalized Matrix Inverses", 1973
  - Molodensky's new theory on physical geodesy: a) surface gravity anomaly b) The quasigeoid
  - T. Krarup's (1969) foundations on ph. geodesy

My background experiences (cont.)

- **With R. H. Rapp at OSU 1977-1978 (15 months**):
  - OSU EGMs; satellite altimetry; collocation, etc.
  - 5 personal OSU reports

- **H. Moritz (1980): Advanced Physical Geodesy**

- **The Int. Symposium on Satellite Geodesy, Cannes, 1980: "Spectral combination"**

- **Spring 1983: AvH-Fellow**, Stuttgart (**VC component estimation)**

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1984-2014

SOME EVENTS:

- **1982-2002: presidium member of NKG**
- **GPS is realized: 1) calls for accurate geoid models; 2) GPS/levelling**
- **Goals for geoid accuracy:**
  1970: 1-2 m; 1980: 2-5 dm; 2000: 1 cm; 2020: 5 mm?

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1984-2014 (cont.)

DATA DEVELOPMENT

- **Earth Gravitational Model developments:**

N_{max} 36 -180 - 360 – 720 - 1800 –- 2160

Models: OSU- EGM96 -- Wenzel –EGM2008

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- **Satellite altimetry**
- From 2000: **dedicated satellite gravity missions** (CHAMP, GRACE, GOCE)
- **Airborne gravimetry**
- **Height data:** regional – global data sets, e.g. Space shuttle experiment, DTM2006, etc, ...

Theoretical developments

- **Combinations of EGM + Stokes**
  (long+ short wavelengths)

- **Collocation (+generalized interpolation; - covariances; - huge systems)**

- **RCR techniques (+works with residual gravity anomalies)**

- **Modified Stokes' methods**
- **1984: Least Squares Modification of Stokes' Formula (first two reports) (+simplified, rigorous corrections)**

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The RCR - technique

$$\hat{N} = \frac{R}{4\pi\gamma}\iint_{\sigma_0} S^L(\psi)\Delta\tilde{g}^M d\sigma + \frac{R}{2\gamma}\sum_{n=2}^{M}\frac{2}{n-1}\Delta\tilde{g}_n^{EGM} + \delta N_{dir,M}^T + \delta N_I + \delta N_I^a + \delta N_I^e$$

$$\Delta\tilde{g}^M = \Delta\tilde{g} - \sum_{n=2}^{M}\Delta\tilde{g}_n^{EGM} + \delta\Delta g_{dir}^T + \delta\Delta g_{dwc} + \delta\Delta g_{dir}^a + \delta\Delta g_{dir}^e$$

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- The IAG Geoid School practices (only) this method; in the past with L=0, and some corrections are ignored or simplified
- The modification by Vanicek-Kleusberg uses L = M and Molodensky type of modification parameters (i.e. minimum truncation error bound)

Least Squares Modification with Additive Corrections (LSMSA)

- **Uses the rigorous rcr formula above, but direct and indirect effects are combined into additive corrections (Sjöberg 2003a).**

$$\hat{N} = \frac{R}{4\pi\gamma}\iint_{\sigma_0} S^L(\psi)\Delta\tilde{g}\,d\sigma + \frac{R}{2\gamma}\sum_{n=2}^{M}\left(Q_n^L + s_n^*\right)\Delta\tilde{g}_n^{EGM}$$

$$+\delta N_{comb}^T + \delta N_{dwc} + \delta N_{atm} + \delta N_{ell}$$

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NKG GEOID MODELS

- The NKG wg on geoid determination was established 1978:

NKG1986	Collocation	0.5 m
NKG1990	FFT	
NKG1996	RCR, FFT	10 cm
NKG2002-2004	-”-	
NKG2014?	?	1 cm?

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The Geoid – Quasigeoid Separation

- **H/M (1967):** $$N-\zeta \approx \frac{\Delta g_P^B}{\bar{\gamma}} H$$
- **Fleury/Rummel (2009):** $$N-\zeta \approx \frac{\Delta g_P^B}{\bar{\gamma}} H + \frac{V_g^T}{\gamma_0} - \frac{V_P^T}{\gamma_Q}$$
- **Sjöberg (2010, 2012) [arbitrary compensation model]:**

$$N-\zeta = \int_0^{H_P} \frac{\Delta g}{\gamma} dh = \frac{\Delta g_P^C}{\bar{\gamma}} H + \frac{dV_g^C}{\gamma_0} - \frac{dV_P^C}{\gamma_Q} + res$$

$$res = \int_0^{H_P} \frac{\Delta g^c}{\gamma} dh - \frac{\Delta g_P^c}{\bar{\gamma}}$$

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W0= the geoid potential

- Data: 1) Satellite altimetry (only on oceans)
  2) EGM (T0 is missing or chosen ⇒ only relative geoid heights)
- Methods:
  - direct integration over the oceans.
  - geometric methods for ref. ellipsoidal parameters a and b ⇒ U0=W0.
- Sjöberg (2013) a, b and W0 jointly

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The SITE =

"the secondary indirect topographic effect"

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- **The boundary condition**:

$$\Delta g \approx -\frac{\partial T}{\partial r} - 2\frac{T}{r}$$

- **The topographic signal**:

$$\Delta g^{T} \approx -\frac{\partial V^{T}}{\partial r} - 2\frac{V^{T}}{r}$$

- **DITE SITE**

THE SITE

- Δg^B reduces only for DITE and not for the SITE

Needs for new / rigorous gravity anomalies:

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- **No-topography gravity anomaly**

$$\Delta g^{NT} = \Delta g^{B} + 2\frac{V^{T}}{r}$$

- **Rigorous isostatic gravity anomaly**

$$\Delta g^{I,new} = \Delta g^{I} + \frac{2\left(V^{T} - V_{C}\right)}{r}$$

Gravity Inversion

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- **Bouguer vs. no-topography gravity anomaly: B. is <u>not</u> a rigorous anomaly - NT. is**
- **The Bouguer anomaly is <u>not</u> consistent with the Bouguer gravity disturbance**
- **Traditional vs. rigorous isostatic gravity anomalies**
- **Vening Meinesz- Moritz (1990) isostatic model**
- **Gravimetric/Isostatic Moho determination vs. CRUST2/1 seismic models**

Conclusions

- **1984-2014 saw very exciting developments in physical geodesy:**

- **GPS stimulates improved modelling of the (quasi)geoid (technical needs)**
- **Geophysical science pushes satellite gravity missions (science needs)**
- **Ultra-high-degree EGMs**
- **EGM+ Stokes towards 5 mm geoids?**
- **Rigorous gravity anomalies**
- **Gravity inversion, e.g. VMM Moho models**

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SOME REMAING PROBLEMS

- The SST bias in satellite altimetry?
- The geoid vs. the quasigeoid?
- W0 is still to be improved
- Future GNSS/levelling without height fixes?
- The bad economy in physical geodesy training and research

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THANK YOU FOR YOUR ATTENTION!