Towards a World Height System – a Status Report

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On the Basis of a technical paper prepared together with
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Thomas Gruber, Gunter Liebsch, Urs Marti, Roland Pail, Michael Sideris

History

- IAG WG in the 90ies
- Inter-Commission Project 1.2: Vertical Reference Frames (Conventions for the definition of World Height System, 2003 – 2011)
- GGOS Theme 1: Unified Global Height System (Action Items for the unification Height Reference Systems, 2011 until now)
- ESA project “GOCE+ Height System Unification with GOCE”
- Inventory of standards and conventions used for the generation of IAG/GGOS products by GGOS BSC
- Joint Working Group 0.1.1: Vertical Datum Standardisation (JWG 0.1.1) supported by GGOS Theme 1, IAG Commission 1 (Reference Frames), IAG Commission 2 (Gravity Field) and the International Gravity Field Service (IGFS)

Main Activities in 2014/15

- **The initiative of an action group (authors) in 2014 a position paper “Proposal for the Definition and Realization of an International Height Reference System (IHRS)” was prepared, distributed in Nov. 2014.**
- **The IAG Executive Committee decided in December 2014, to establish an Ad-hoc Group on an International Height Reference System (IHRS): Urs Marti (Chair), Riccardo Barzaghi, Michael Sideris, Johannes Ihde, Laura Sánchez**
- **The objective is to prepare a resolution concerning the definition and realization of an IHRS to be released at the IUGG General Assembly 2015 in Prague.**

Contents

Motivation for a Global Height Reference System

External view

- Climate change is one of the themes debated in politics today and one of the general developments which influence the living conditions of mankind
- Sea level rice is one of the mayor risks for urban regions in many parts of the world
- Changes of the vertical component of the Earth surface and of the Earth gravity field are indicators for global changes of our environment
- A common global vertical reference system is the metrological basis for monitoring effects related to the vertical scale (geometry and Earth gravity field)

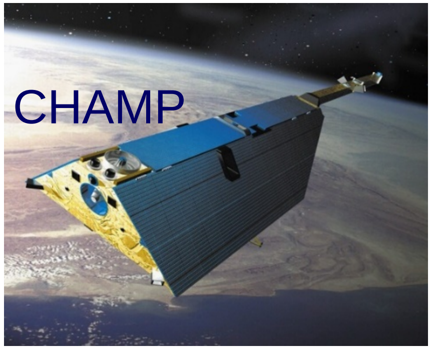
Motivation for a Global Height Reference System

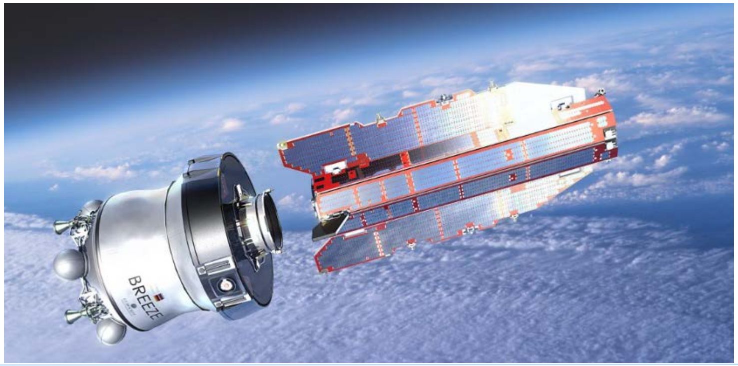
Geodetic view

- Geometric reference and gravity field products and standards are not compatible with each other.
- Inconsistencies between geometric products and products related to the Earth gravity field need to be removed to enable the development of integrated geodetic applications.
- Determination of time-dependent changes of the vertical reference frame needs long term consistent stable reference.
- A common global height reference system is the metrological basis for monitoring effects relate to vertical scale (geometry and Earth gravity field)
- Interaction with disciplines different to Geodesy requiring a global height reference system; for instance hydrography, oceanography, etc.

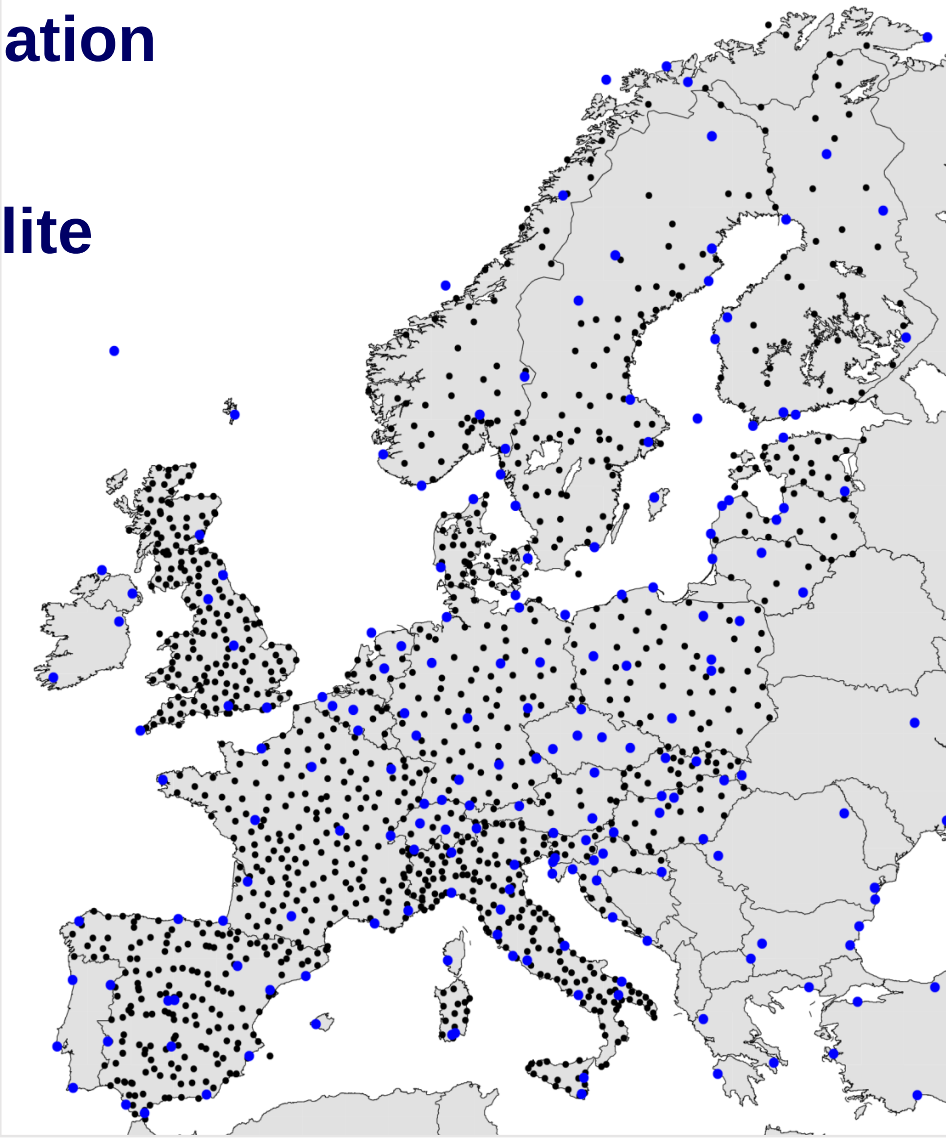
EUVN Densification Action (EUVN_DA)
1200 GNSS/levelling points

- **for European geoid determination EGG07**
- **for the validation of the satellite gravity field missions**





GOCE



Physical Heights and Earth Gravity Field

The representation of the Earth gravity field is independent possible with to different kind of fields.

Both fields

- geo-potential scalar field $W(X)$
- the outer Earth gravity vector field $\vec{g}(X)$

connected by the relationship

$$\vec{g}_P = grad\, W_P = -g_P \begin{pmatrix} \cos\Phi & \cos\Lambda \\ \cos\Phi & \sin\Lambda \\ & \sin\Phi \end{pmatrix} \qquad , g_P = g(X) = |grad\; W_P|$$

X position in natural coordinates: Φ astronomical latitude,

Λ astronomical longitude, W potential of Earth gravity field.

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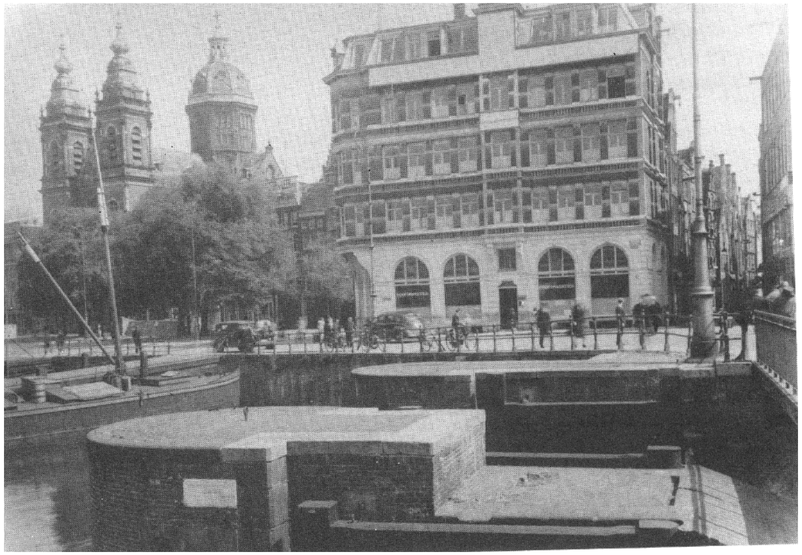
Normals Amsterdams Pail

- an early warning system, to the citizens of Amsterdam to warn of floods and to protect.

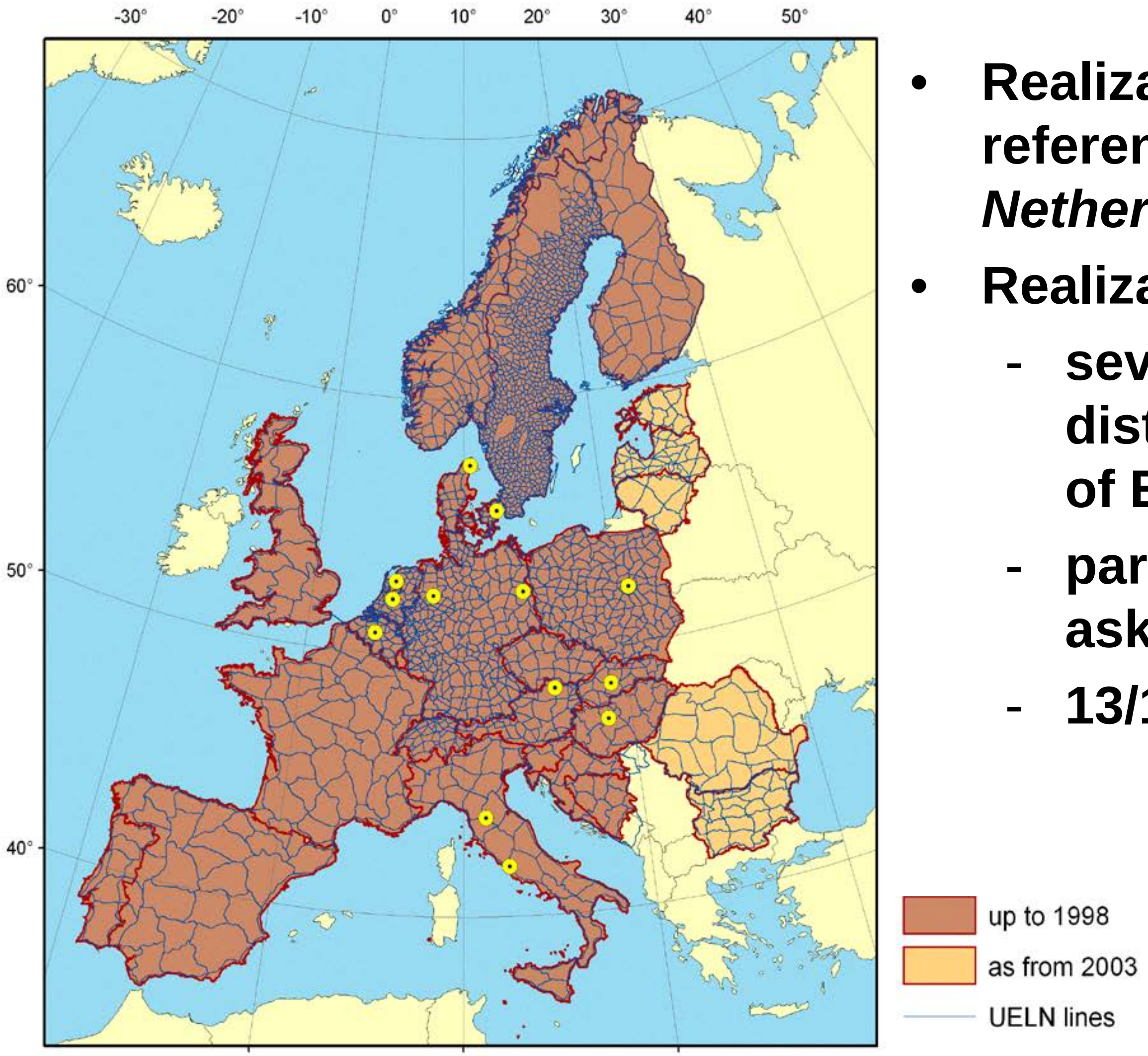
Mathematician and Mayor Johnnes Hudde prompted the measurement of water levels at high and low tide from September 1, 1683 to September 1, 1684

At 8 gates of the new water weir height marks were attached ("dijkpeilstenen" = stones that mark the height of the dike): Inscription: Seedeichhöhe equal to nine feet five inches (= 2,6789m) on city level.



Last original„dykpeilsteen“ in der „Nieuwe Burg“ gate

EVRS: Common adjustments of existing levelling networks



- **Realization of EVRF2000 datum: reference point *000A2530 in the Netherlands***
- **Realization of EVRF2007 datum**
  - **several datum points distributed over the stable part of Europe**
  - **participating countries were asked to propose stable points**
  - **13/19 points have been used**

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Numerical Standards
The GRS80

For all geodetic tasks we need standards, conventions, guidelines, rules!

Geodetic Reference System 1980 (GRS 80) defines major parameters for geodetic reference systems related to a level ellipsoid

- **Agreed by IUGG, IAG and IAU in 1979.**
- **Recommended by IAG for the conversion of ITRF Cartesian coordinates to ellipsoidal coordinates.**
- **Worldwide use for many map projections and million of coordinates, e.g. ETRS89**

Numerical Standards
IUGG GA 1991

- **At the IUGG General Assembly 1991 in Vienna new values for the geocentric gravitational constant GM and the semi-major axis a of the level ellipsoid were recommended.**

- **Since this time these parameters have been used in global gravity models e.g. EGM96**

IERS 2003 conventions

- defines numerical standards (chapter 1.2)
- recommends in chapters 4.1.4 and 4.2.5 the use of GRS80 for transformations

➢ For global gravity models, various inconsistent values are used in practice

➢ The gravitational constants GM of GRS80 and IERS 2003 conventions differ in the metric system by about 0.9 m. The semi-major axis of both standards differs by 0.4 m.

Numerical Standards
IERS Convetions 2010

- **Table 1.1 lists parameters that represent the current best estimations**
- **The best estimates for level ellipsoid parameters have not changed since IERS 2003 Conventions**
- **It is not immediately evident how the 2010 estimates were determined.**
- **Table 1.2 contains the parameters of the GRS80 Ellipsoid. GRS80 is designated as conventional; it is new against IERS Conventions 2003**
- **For the reduction of Cartesian coordinates into ellipsoidal ones, the GRS80 Ellipsoid is recommended for application**

Numerical Standards Conflict

- **In IERS 2003 and 2010 conventions are two sets of parameters of a level ellipsoid in use: In numerical standards and the GRS 80**
- **The gravitational constants GM of GRS80 and IERS 2010 conventions differ by about 0.9 m^3s^{-2}, and the semi-major axis of both standards differs by 0.4 m**
- **Also noteworthy is that the IERS 2010 conventions recommend different level ellipsoid parameters for different applications.**

Numerical Standards
Sets of conventional parameters

ellipsoid	Semi-major axis a in m	flattening f^{-1}	Geocentric gravitational constant GM in $10^8 m^3 s^{-2}$	U_0/W_0 in $m^2 \cdot s^{-2}$	γ_e in $m \cdot s^{-2}$
Int. Ell. 1930 (Hayford)	6 378 388	297	3 986 329		
GRS 67	6 378 160	298.247	3 986 030		
GRS 80	**6 378 137**	**298.257222101**	**3 986 005**	**6 263 6860.850**	**9.78032 677**
WGS 84	6 378 137	298.25722356			
IUGG 91	6 378 136.3 0.5		3 986 004.41 0.01		
IERS 2003 Conventions (zero tide)	**6 378 136.6 0.1**	**298.25642 0.00001**	**3 986 004.418 0.008**	**6 263 6856.0 0.5**	**(9.78032 666)**
EGM96	6 378 136.3		3 986 004.415		
EIGEN CG01C (tide free)	6 378 136.46		3 986 004.415		

Angular velocity of the Earth rotation ω **7 292 115** 10^{-11} rad s^{-1}

IAG has two complete sets of parameters in use

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Numerical Standards
Defining parameters of level ellipsoids (equipotential or mean Earth ellipsoid)

Ellipsoid	Semi-major axis a in m	Flattening f^{-1}	Geocentric gravitational constant GM in $10^8 m^3 s^{-2}$	Normal/geoidal potential U_0/W_0 in $m^2 \cdot s^{-2}$	Normal gravity at equator γ_e in $m \cdot s^{-2}$
GRS 80	6 378 137	298.2572221 ± 01	3 986 005	6 263 6860.850	9.78032677
IERS Conventions (2010) (zero tide)	6378136.6 ± 0.1	298.25642 ± 0.00001	3986004.418 ± 0.008	62636856.0 ± 0.5	
GRS20XX	tbd.	298.25642 ± 0.00001	3986004.418 ± 0.008	tbd.	tbd.

Angular velocity of the Earth rotation ω in	7 292 115 10^{-11} rad s^{-1}

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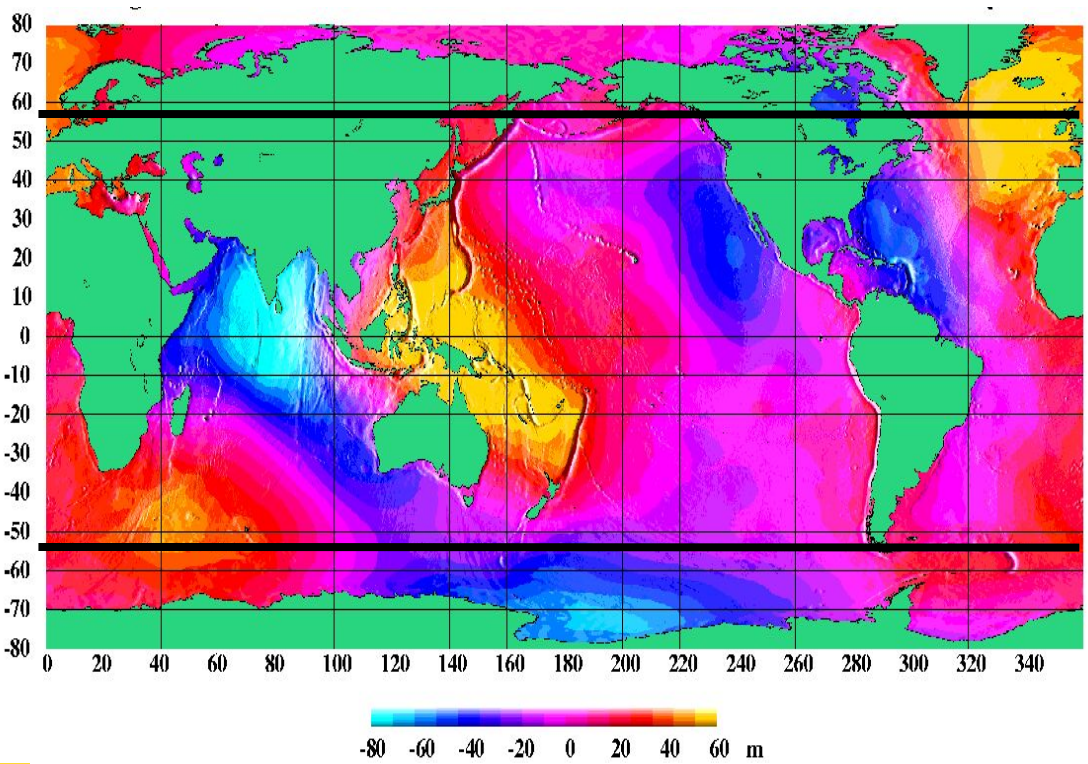
Determination of W_0 of Mean Sea Surface

$$W_S = U_0 + \partial U_0/\partial h \cdot h_{S\,ALT} + T_{S\,GGM}$$



KMS04 MSS model

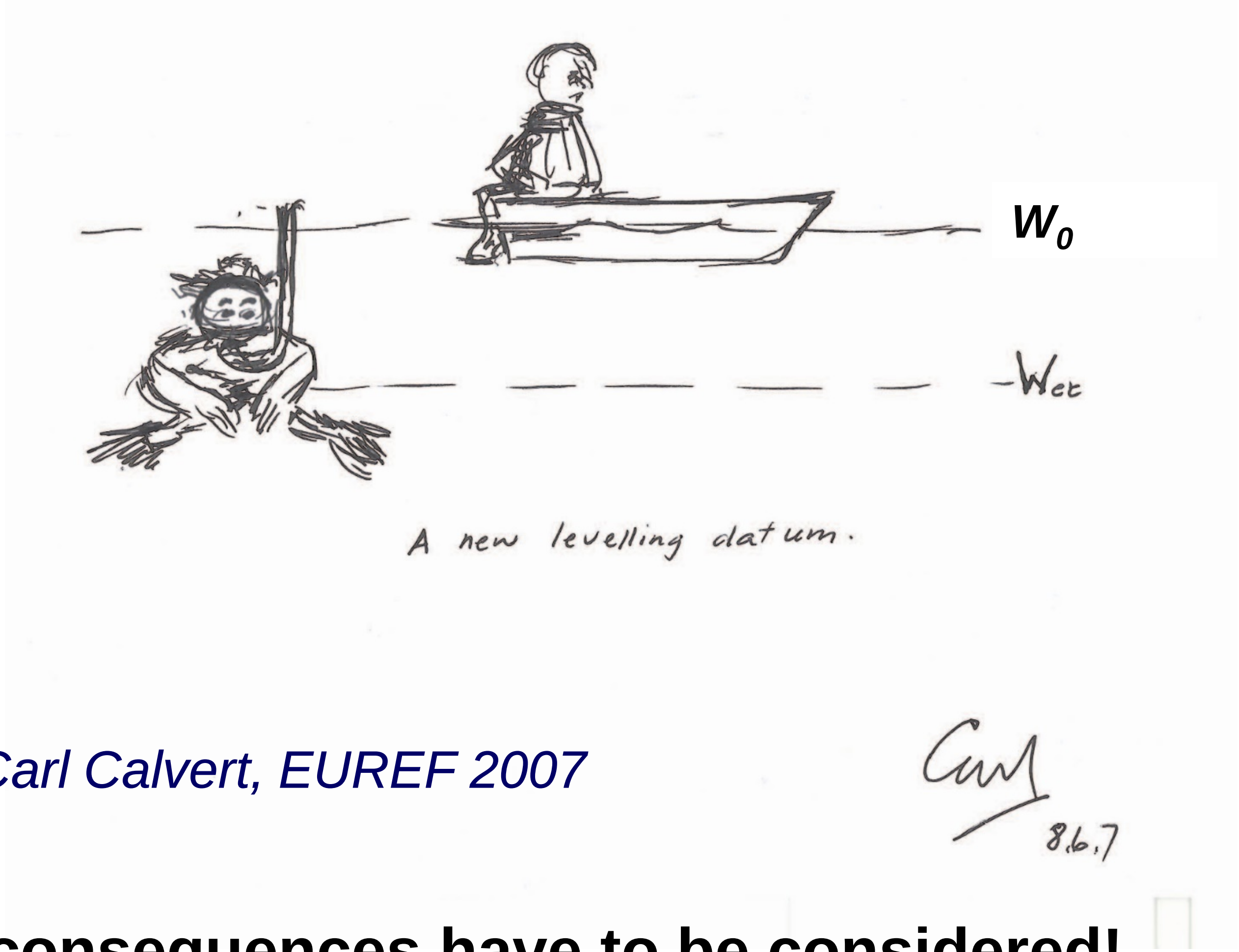
$$W_{0S} = 1/S \iint_S W_S \, dS$$

.

With satellite altimeter observations (ALT) and a global gravity model (GGM)

- **in an agreed area of free oceans**
- **over a defined time period**
- **at a defined epoch.**

Should the W_0 value be changed?



Carl Calvert, EUREF 2007

The consequences have to be considered!

Numerical Standards
Tidal Systems - Reduction of data

	gravity $g/\Delta g$	geoid W/N	levelling height ΔH	altimetry h	mean sea level msl	position X/h
Mean tidal system **Mean/zero crust** (Stokes is not valid if masses outsite the Earth surface)	Δg_m	N_m	ΔH_m	**Relation to N_m for oceanographic studies**	h_{msl}	
Zero tidal system **Mean/zero crust** (Recommended by IAG Res. No. 16, 1983)	Δg_z Stokes ⟶	N_z **(EGG97)**	ΔH_z c_p			
Tide-free system **Tide-free crust** (unobservable, far away from the real earth shape – there is no reason for the non tide)	Δg_n Stokes ⟶	N_n **(EGM96)**				X_n **ITRFxx, ETRS89**

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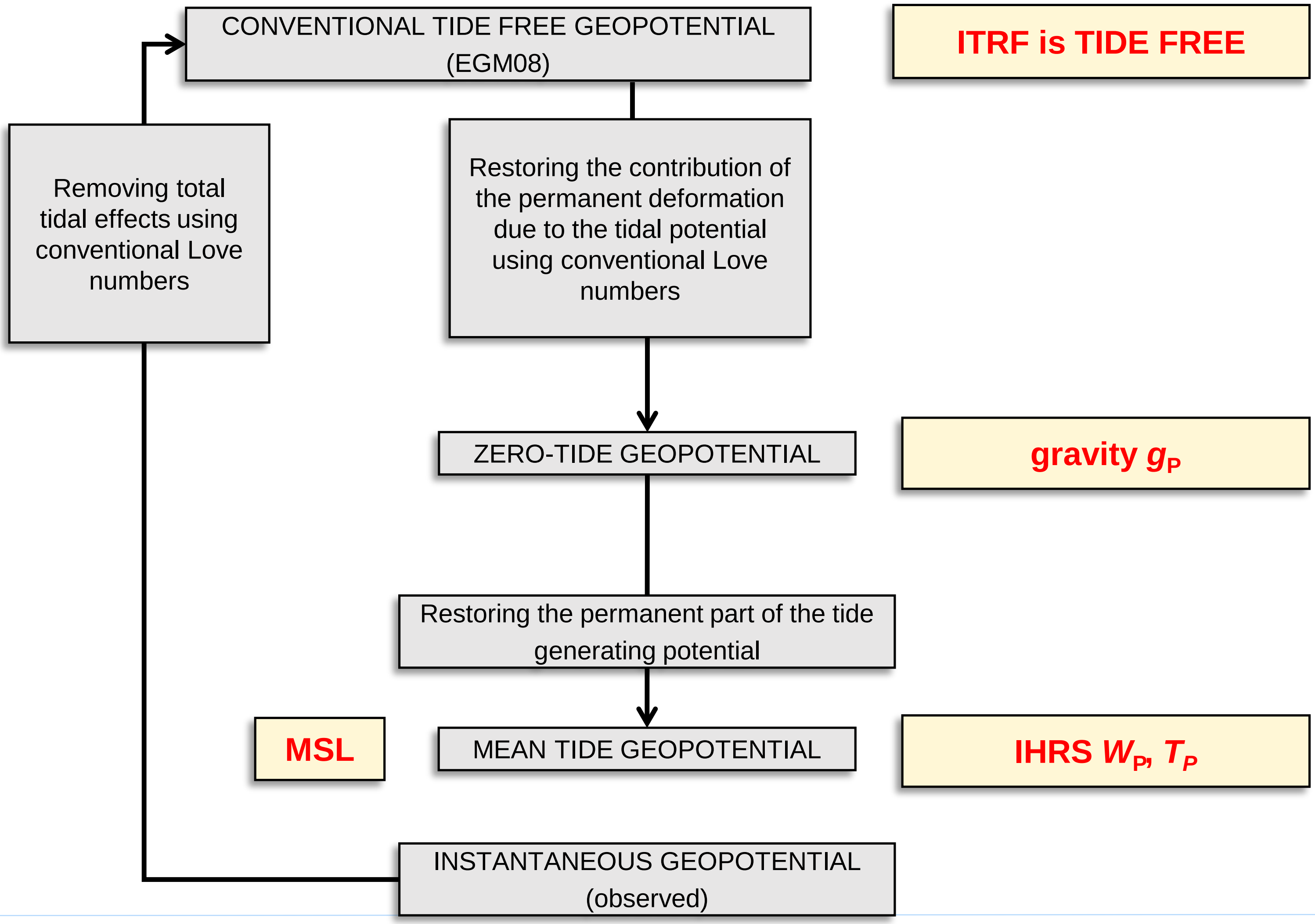
Tidal Systems and Reference Systems



Conclusions

- An „International Earth Gravity and Height Reference System“ should be defined and realized which takes account of both forms of the Earth’s gravity field. In the concepts, consistency has to be brought to the products of the gravity field and the geometry. This includes the definition and realization of a new International Gravity Standardization Network (IGSN).
- The current best-estimated value for W_0 shall be defined (and frozen) as the potential value of the geoid. To ensure the reproducibility and interpretability of changes the procedure of W_0 determination has to be documented in conventions/guidelines.
- To ensure the compatibility of the global products, a new GRSXX with the best-estimated parameters for the level ellipsoid shall be defined, under the constraint that its surface potential is consistent with the conventional W_0 value.
- All height reference system related parameters, observations and products are related to mean tidal system/mean crust. For combinations of gravity field and geometric data as well as special applications, the data can be transformed in another tidal systems.

Definition, realization and unification of height reference systems

- Following the praxis of to handle geodetic reference system concepts we have to consider the definition and the realization of a reference system
- For this we need conventions (standards) and guidelines
- Unification of height systems is part of the realization

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EVRS 2000 definition (Tromsø)

The European Vertical Reference System (EVRS) is a gravity-related height reference system. It is defined by the following conventions:

a) **The vertical datum is the zero level of which the Earth gravity field potential W_0 is equal to the normal potential of the mean Earth ellipsoid U_0:**

$$W_0 = U_0.$$

b) **The height components are the differences ΔW_P between the potential W_P of the Earth gravity field through the considered points P and the potential of the EVRS zero level W_0. The potential difference $-\Delta W_P$ is also designated as geopotential number c_P:**

$$-\Delta W_P = W_0 - W_P = c_P.$$

Normal heights are equivalent to geopotential numbers.

c) **The EVRS is a zero tidal system[1], conforming to the IAG Resolutions No 16 adopted in Hamburg in 1983**

1) In a) and b) the potential of the Earth includes the potential of the permanent tidal deformation but excludes the permanent tidal potential itself.

datum

geocentric, including oceans and atmosphere

W_0 independent from the tidal system (Bursa)

coordinate system

SI units
$m^2 \cdot s^{-2}$

$W_p = U_p + T_p$ ***(BVP)***

$W_p = W_0 - c_p$ ***(levelling)***

$$H_n = \frac{c_p}{\bar{\gamma}}$$

frame

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EVRF2007 definition

The EVRS definition fulfils the following four conventions:

1. **The vertical datum is defined as the equipotential surface for which the Earth gravity field potential is constant:**

   $$W_0 = W_{0E} = const.$$

   And is in the level of the Normaals Amsterdam Peil (NAP).
2. **The unit of length of the EVRS is the meter (SI). The unit of time is second (SI).**
3. **The height components are potential differences ΔW_P , also designated as geopotential number c_P:**

   $$-\Delta W_P = c_P = W_{0E} - W_P \,.$$

   The metric equivalent is the normal height.
4. **The EVRS is a zero tidal system.**

Definition of an International Height Reference System (IHRS)

Five conventions define the IHRS (Status May 2015):

- The vertical reference level is the normal potential (or geopotential at the geoid or the geoid potential parameter) W_0 as an equipotential surface of the Earth gravity field. The relationship between W_0 and the Earth body must be defined and reproducible. $U_0 = W_0$ as a defining parameter of the conventional geocentric level ellipsoid is under discussion.
- Parameters, observations, and data shall be related to the mean tidal system/mean crust. (Under discussion)
- The unit of length is the meter (SI). The unit of time is the second (SI). This scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions, and is obtained by appropriate relativistic modeling.

- The vertical coordinates are the differences $-\Delta W_P$ between the potential W_P of the Earth gravity field at the considered points *P,* and the geoidal potential of an conventional W_0. The potential difference $-\Delta W_P$ is also designated as geopotential number c_P:

$$-\Delta W_P = c_P = W_0 - W_P.$$

- The spatial reference of the position *P* for the potential $W_P = W(X)$ is related as coordinates *X* of the International Terrestrial Reference System.

Realization of an IHRS

Proposal for the elements of an IHRF:

- The **geopotential at the geoid** $\boldsymbol{W_0}$ is developed through best estimates. The procedure of W_0 determination must be documented in conventions/guidelines, to ensure the reproducibility and interpretability of changes.
- The central element of the IHRF is a **Global Gravity Model (GGM).** One (combined) satellite only GGM for homogenous long wavelength approximation of the Earth gravity potential as conventional. One GGM combined with terrestrial data for direct application in sparsely surveyed regions.

Realization of an IHRS

- **A network of geodetic observation stations:** The network includes geodetic observatories, absolute gravity stations, key comparison stations of an IGSN, selected tide gauge stations (TIGA-IGS), time stations.

  At the stations the
  - Earth gravity potential W_P in IHRS
  - Spatial reference X in ITRS
  - Absolute gravity g

  must be determined with highly possible accuracy.

  This are integrated geodetic networks.

Realization of an IHRS - Time Evolution

Time series observations of an global integrated network of the global Vertical Reference Frame and its datum

$$X_P(t) = X_P^0 + \dot{X}_P^0(t - t^0)$$

$$g_P(t) = g_P^0 + \dot{g}_P^0(t - t^0)$$

$$W_p(t) = W_p^0 + \dot{W}_p^0(t - t^0)$$

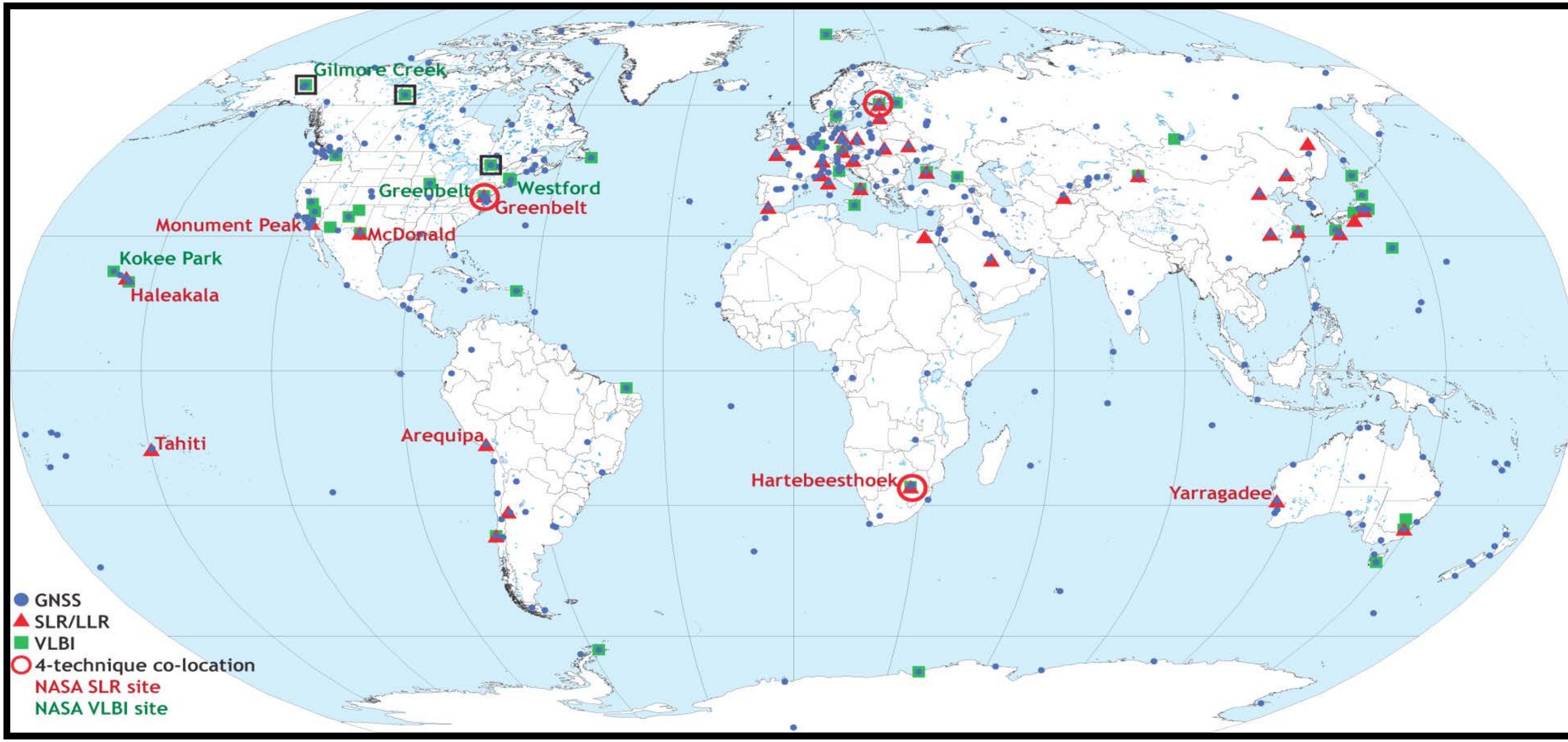
Under the condition

$$v_{hi} = v_{Hi}$$

the velocities of the physical heights H can be derived from time series of the the ITRFxx heights h:

$$H_P(t) = H_P^0 + \dot{h}_P^0(t - t^0)$$

Integrated Networks
Global Network of Geodetic Stations and Observatories



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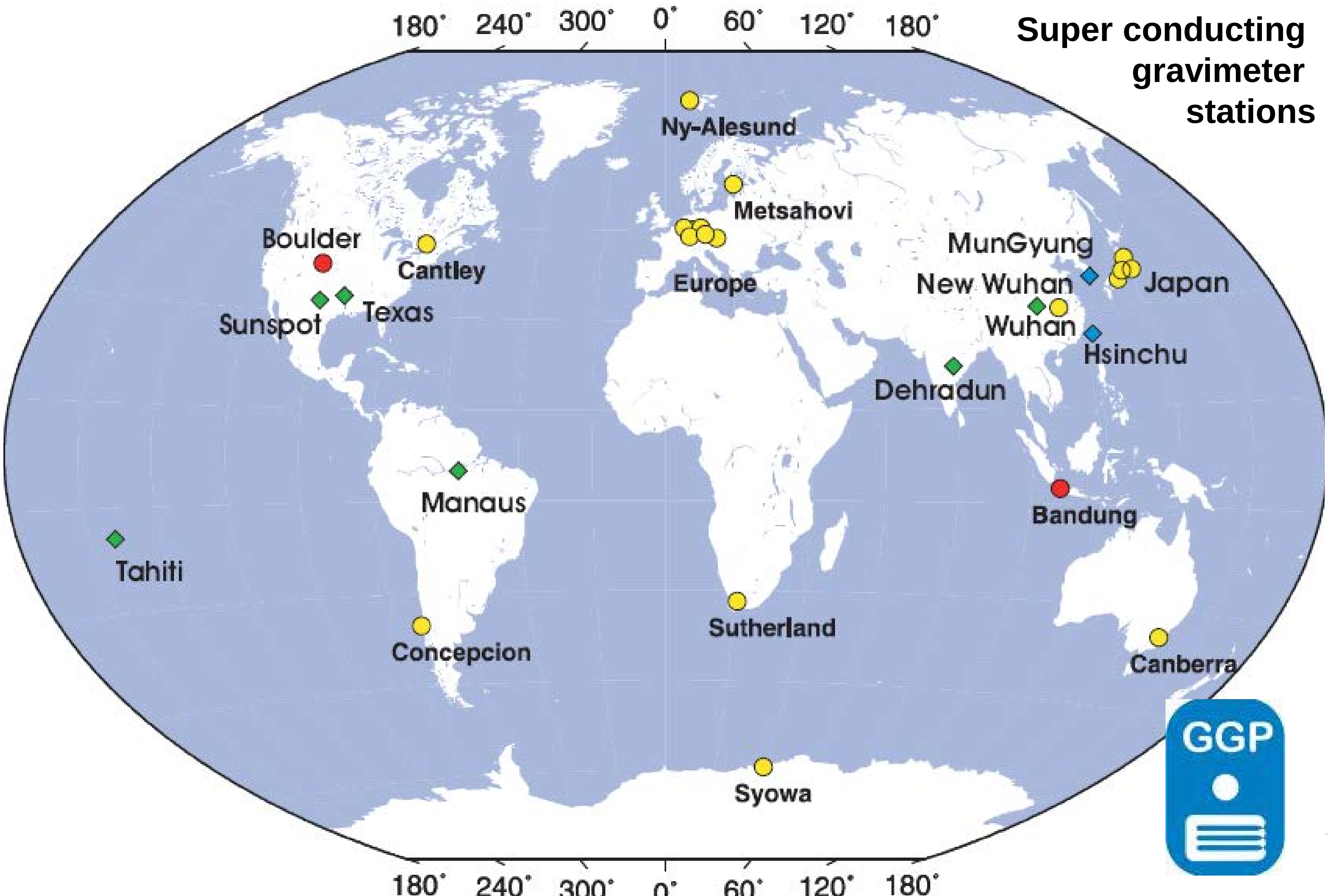
Integrated Networks
Global Geodynamics Project (GGP)

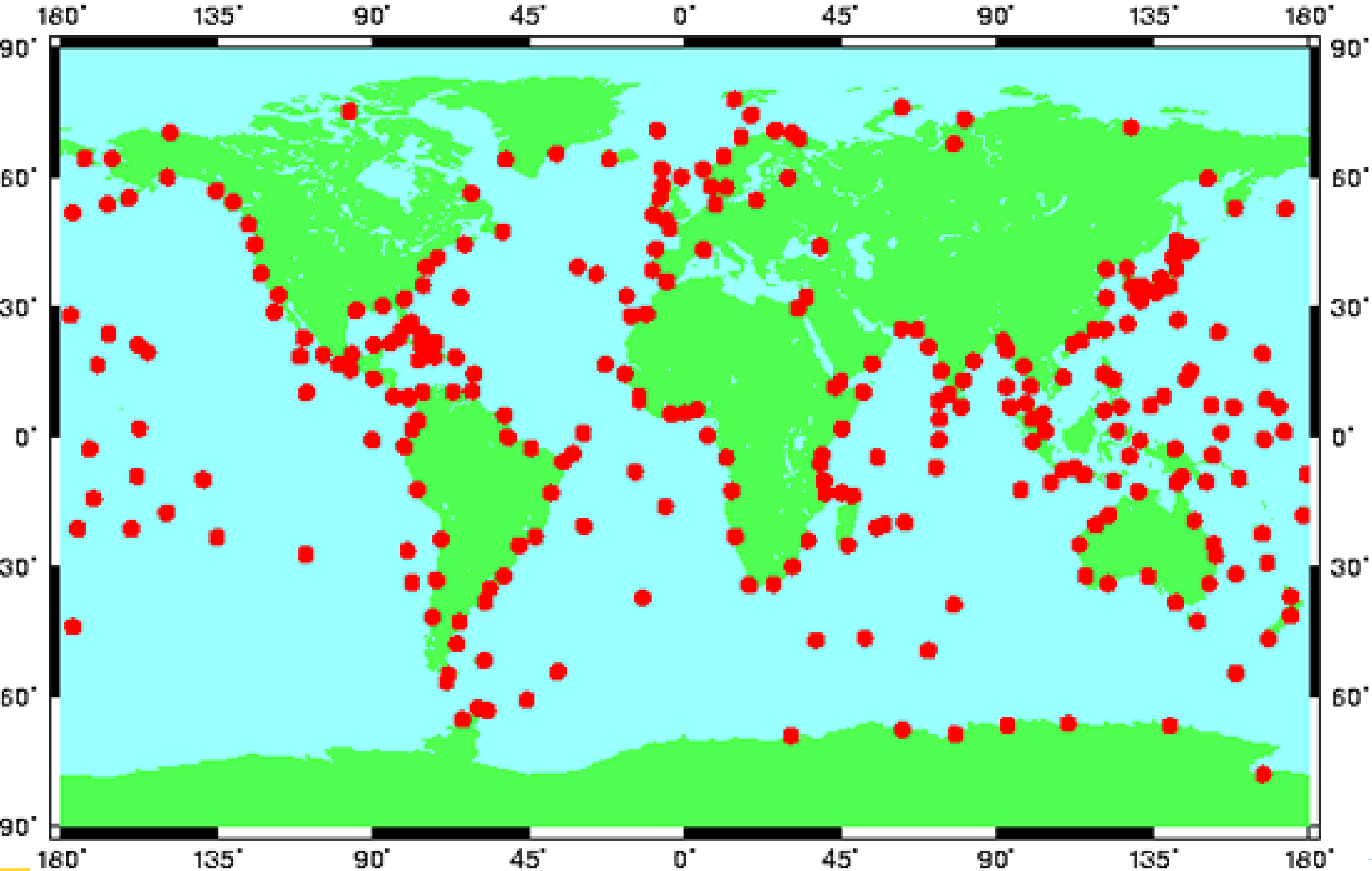
Super conducting gravimeter stations



GGP

Integrated Networks

GLOSS Core Network defined by GLOSS02

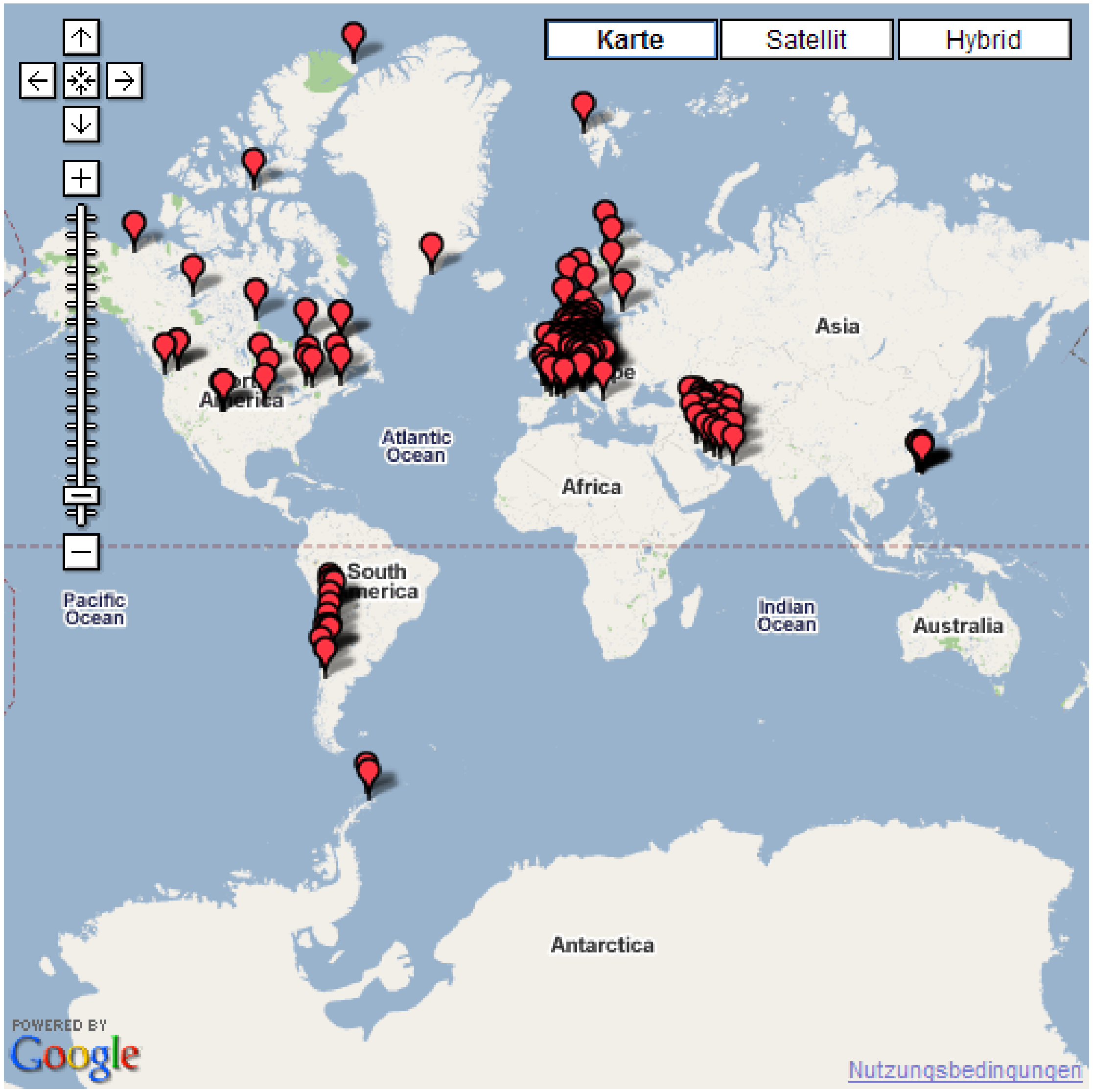


Integrated Networks

AGrav: Absolute Gravity Database - Meta-Data

Map
Meters
Stations
Observations
Institutions
Full Access (login required)
Mirror at BKG

agrav@bkg.bund.de
bgi@cnes.fr



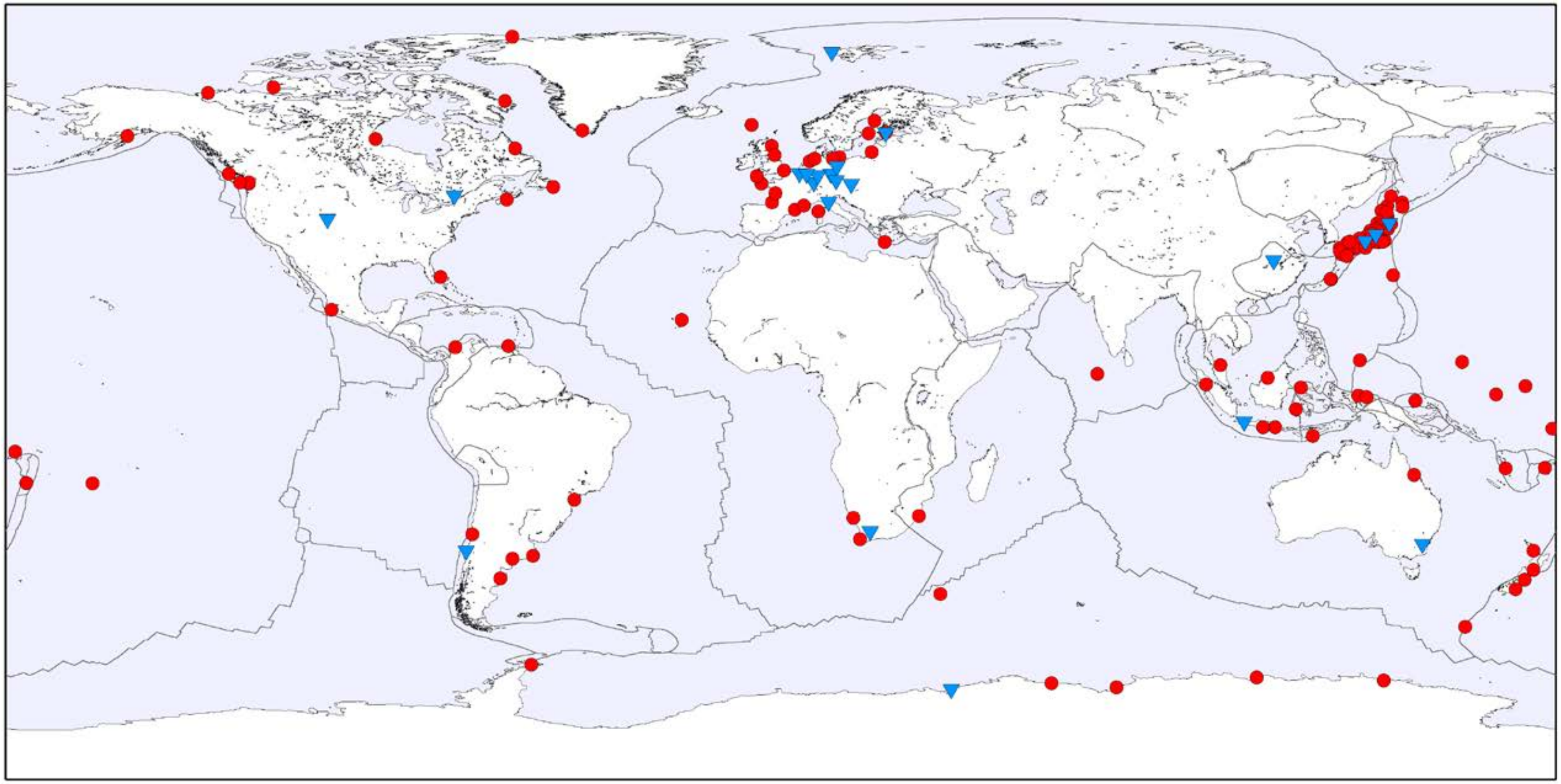
Absolute gravity database established at BGI (Toulouse) and BKG (Frankfurt)

http://bgi.dtp.obs-mip.fr/ and http://agrav.bkg.bund.de/

Activity of the IAG/IGFS „Working Group on Absolute Gravimetry“

Integrated Networks

Stations of IGS TIGA-PP and GGP (and absolute gravimeter)



● GPS/tide gauge stations ▼ super-conducting gravimeter stations

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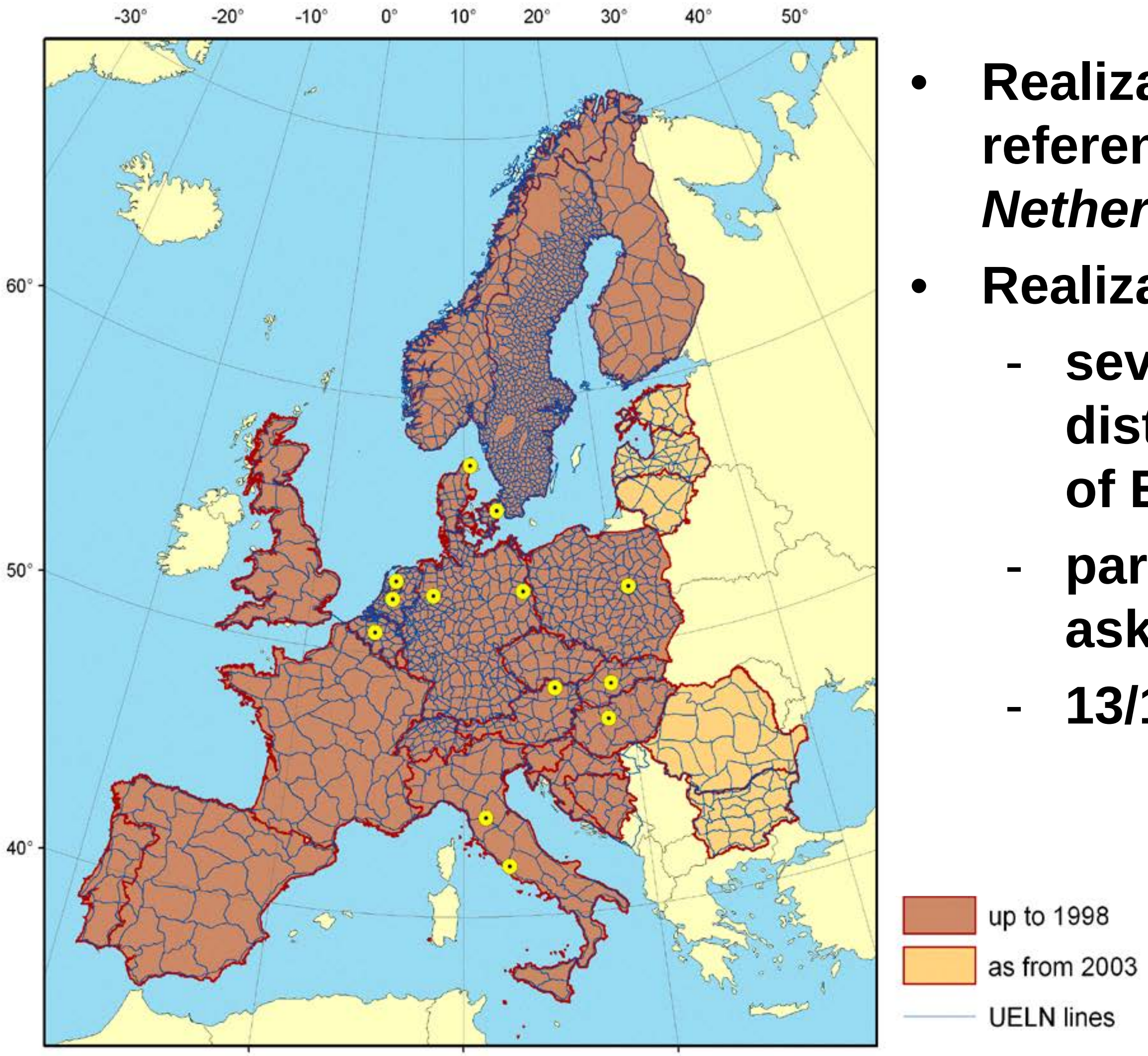
Concepts for unification of height reference systems

General possibilities for the unification

1) On continents:
   by common adjustment of existing levelling networks (cPk)
2) Global:
   general case for realization and unification - combination by global GGM and GNSS/levelling
3) Global Over oceans:
   using a model of mean sea surface topography and tide gauge observations

Combinations are useful and some times necessary

(1) Common adjustments of existing levelling networks



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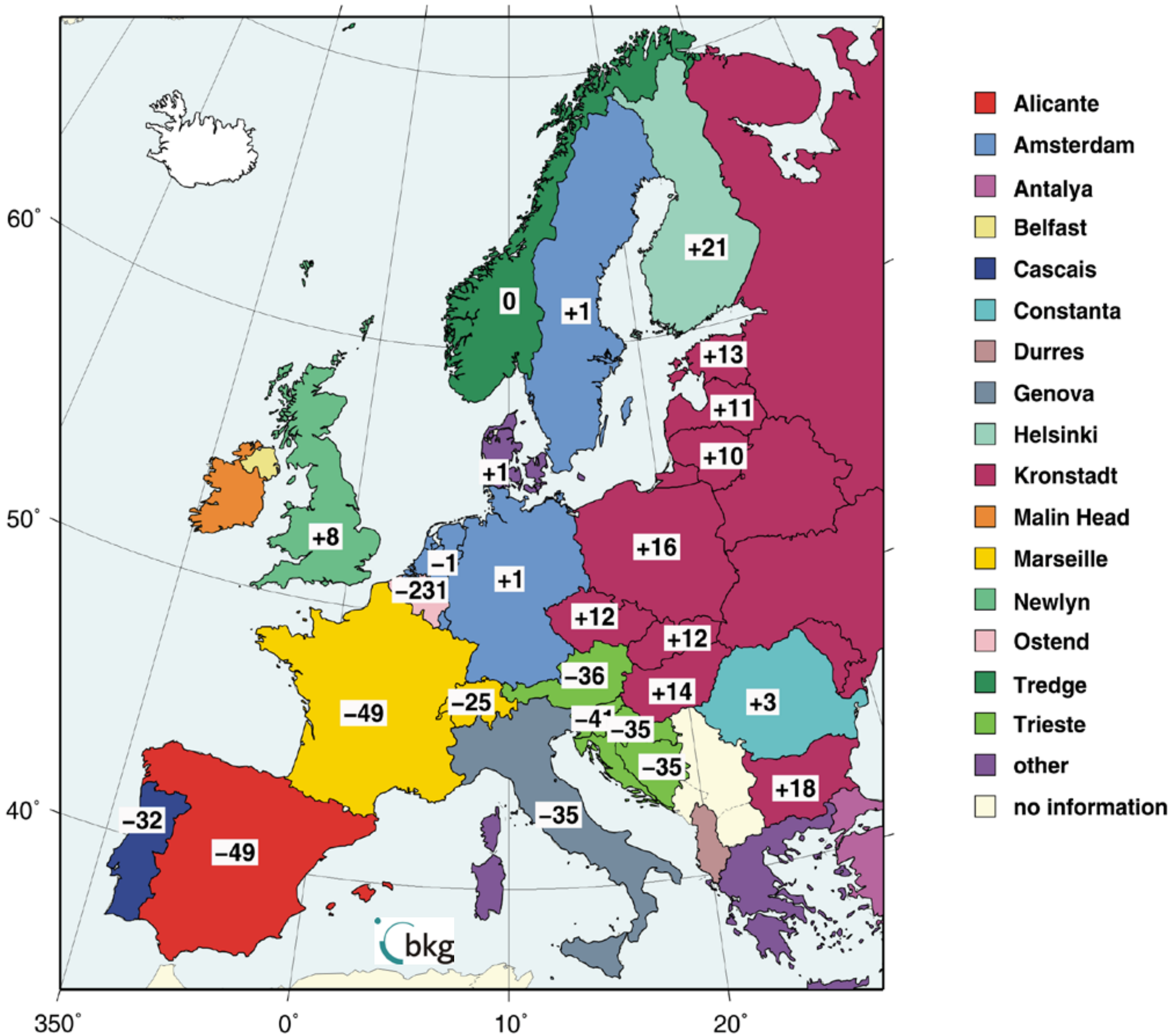
Approximated transformation parameters (only translation) from national height systems to EVRF2000 in cm



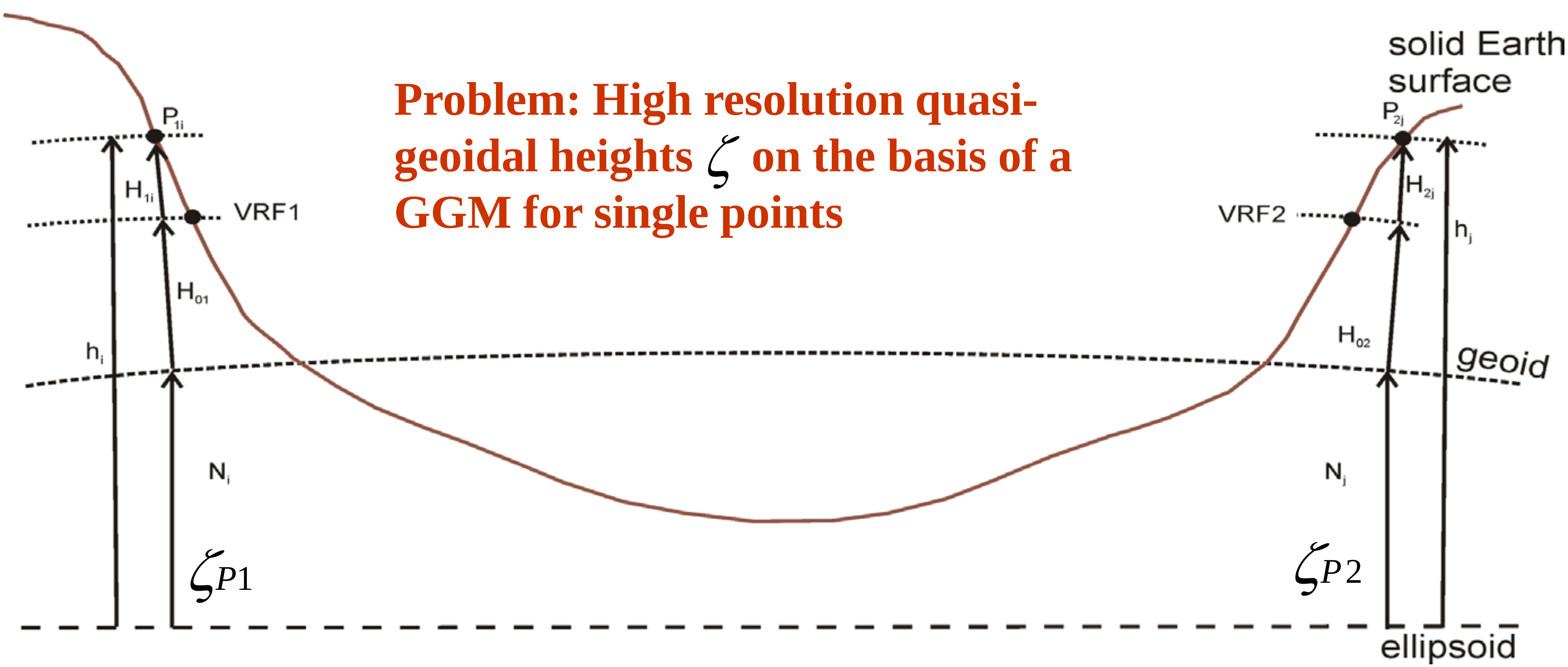
(2) Unification by global GGM and GNSS/levelling

$$H_{0,VRF} = h_{i,ITRF} - H_{i,VRF} - \zeta_{i,GGM}$$ **h and ζ shall global**

VRF realization in single points:

$$H_{VRF} = h_{ITRF} - \zeta_{GGM}$$

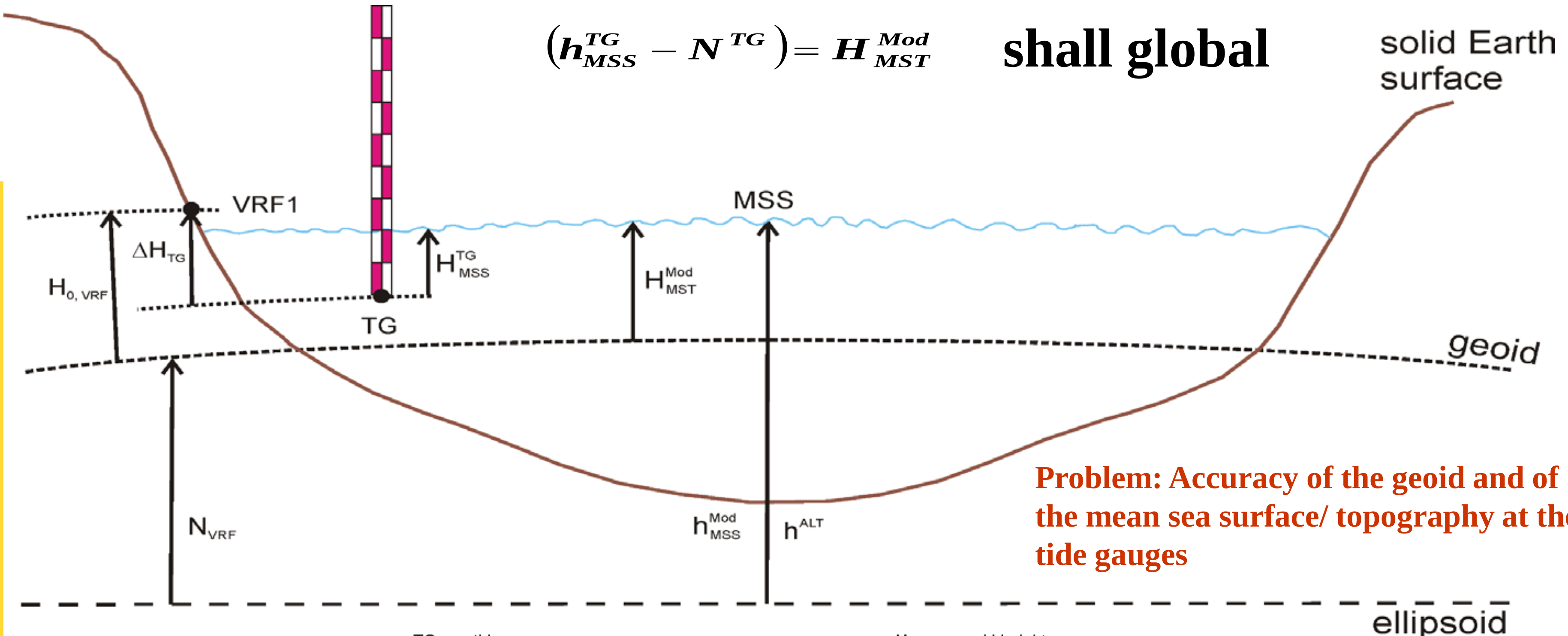
Problem: High resolution quasi-geoidal heights ζ on the basis of a GGM for single points



(3) Unification by tide gauge observations and a mean sea surface topography

$$H_{0,VRF} = \left(h_{MSS}^{TG} - N^{TG}\right) - H_{MSS}^{TG} + \Delta H_{TG}$$
$$= H_{MST}^{Mod} - H_{MSS}^{TG} + \Delta H_{TG}$$

$$\left(\boldsymbol{h_{MSS}^{TG}} - \boldsymbol{N^{TG}}\right) = \boldsymbol{H_{MST}^{Mod}}$$ **shall global**



Problem: Accuracy of the geoid and of the mean sea surface/ topography at the tide gauges

TG	tide gauge
CD	chart datum
MSS	mean sea surface
MST	mean sea surface topography
LAT	Lowest Astronomical Tide

N	geoid height
H	orthometric height
h	ellipsoidal height

$h = H + N$

$h_{MSS} = H_{MST} + N$

Next steps

- Common discussion of the members of the action group and the Ad-hoc Group about the open questions
- Editing of technical papers for the documentation of the conventions
- Preparation of relevant resolutions for the IUGG/IAG GA 2015