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Reference Frame in Practice
Manila, Philippines 21-22 June 2013

Gravity and World Height System

2013.06

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Sponsors :

Contents

I Earth's Representation

II Height

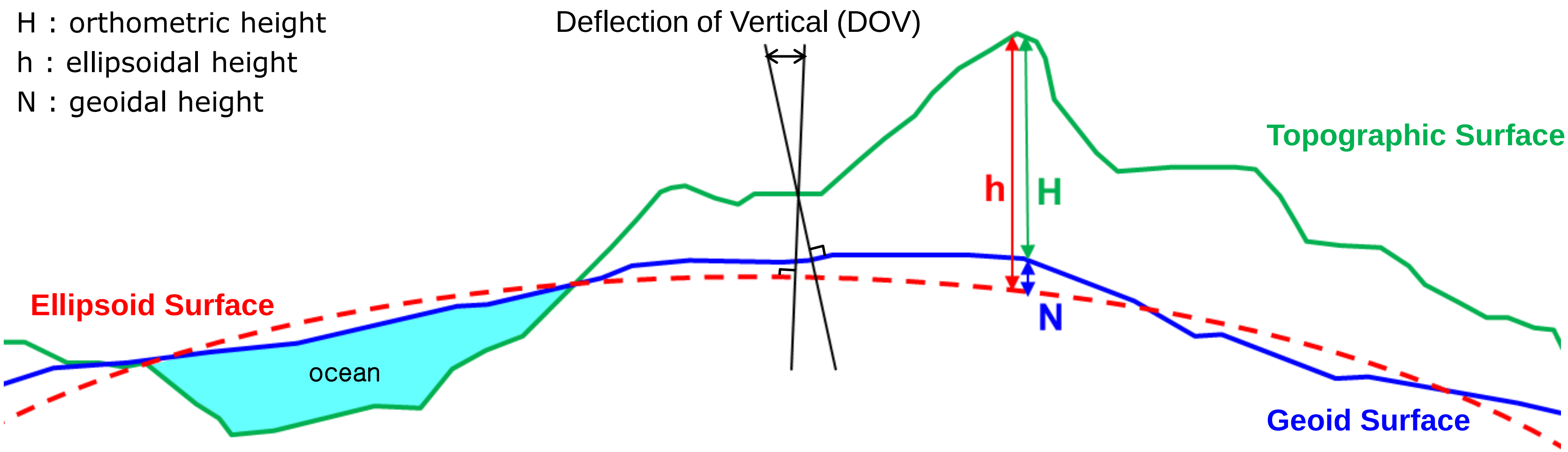
III Geoid

IV Height Unification

I Earth’s Representation

I-1. Earth's Representation

- **Topographic Surface**
  - Real physical surface of the earth
  - Irregular and complex
- **Ellipsoid Surface**
  - Mathematically modeled, best fitted ellipsoid to the earth
  - Useful for geospatial referencing
- **Geoid**
  - Equipotential surface of gravity field that *closely approximates the mean sea level*



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II Height

01 Definition

02 Problem of Traditional Leveling

03 Geopotential Number

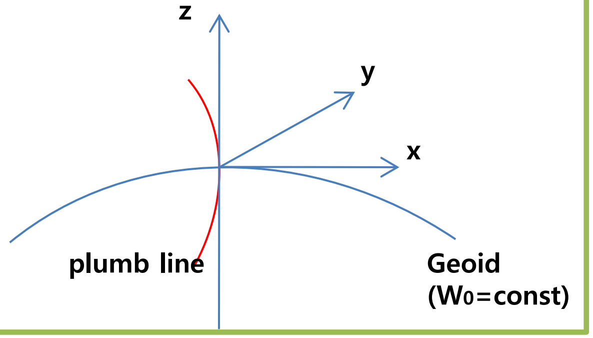
04 Heights

III-1. Definition

- **Definition of Height**
  - Height is the quality of being tall
  - **A height is a high position or place above the ground**
  - When an activity, situation, or organization is at its height, it is at its most successful, powerful, or intense

<Collins Cobuild Advanced Learner's English Dictionary>

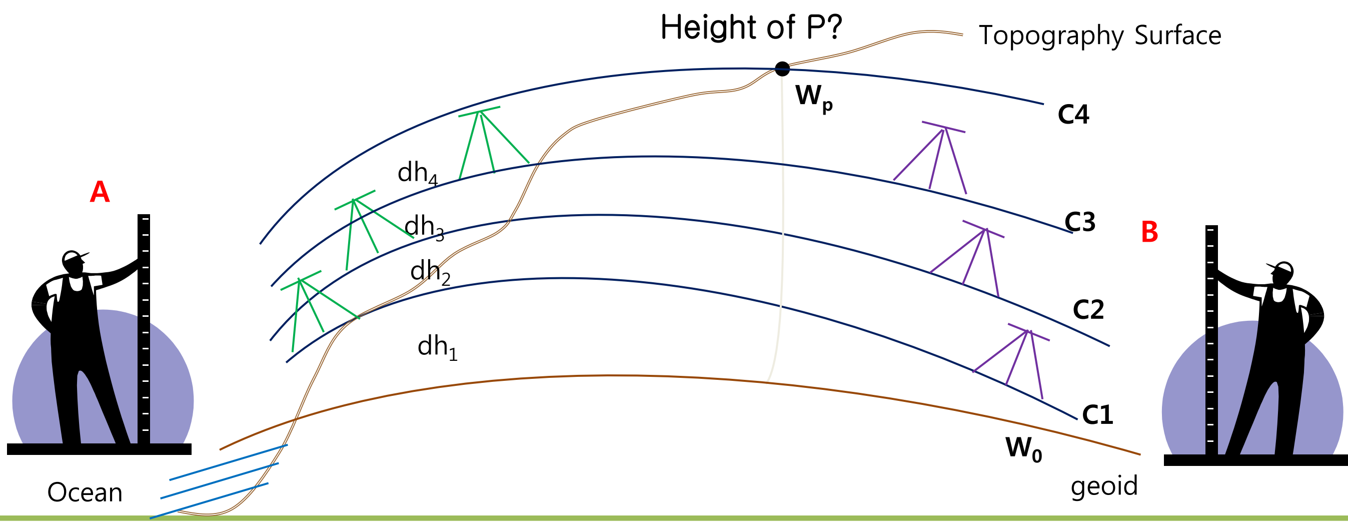
- **Geometric Height**
  - Height difference between two points
  - The elevation above reference surface (ex : ellipsoidal height)
- **Physical Height (=Geopotential Height)**
  - The elevation related to earth gravity field
  - Water always flow down
- **Orthometric Height (= Geometric + Physical)**
  - *The height of a point above sea level measured along the curved plumb line, starting from the geoid*
  - It is determined by leveling and gravity surveying



III-2. Problem of Traditional Leveling

- **Traditional Leveling Survey**
  - Height differences between the consecutive locations of backward and forward rods correspond to the local separation between the level surfaces through the bottom of the rods, measured along the plumb line direction
- **Problem**
  - *The sum of the measured height differences along the leveling path between point A and B is not equal to the difference in orthometric height between point A and B*

$$\sum dh_A \neq \sum dh_B \neq H$$



III-3. Geopotential number

- **Necessity of Geopotential Number**
  - **Orthometric heights are not constant** on the equipotential surface
  - Points on the same level surface would have different orthometric height
  - Thus, **alternative concept independent on the path of integration** is necessary

- **Geopotential Number (C)**
  - Potential difference between the geoid level W_0 and the geopotential surface W_P through point P on the Earth surface

$$\int_0^P g\,dh = C = W_0 - W_P = g_m \times dh$$

where, g is the gravity value along the leveling path

dh is height difference calculated based on leveling data

g_m is mean value of gravity along dh

  - **Geopotential number is constant for the geopotential (level) surface**
  - Geopotential numbers can be used to define height and are considered a natural measure for height

Height = C / gravity

- **Orthometric Height**
  - Height measured along the curved plumb line with respect to geoid level
  - Both physical and geometric aspect are exist

$$H = C / g_m$$

- **Normal Height**
  - Height measured along the normal plumb line (does not depend on crustal density)

    - *"normal" refers to the line of force direction in the gravity field of the reference ellipsoid*
  - Both physical and geometric aspect are exist

$$H = C / \gamma_m$$

- **Dynamic Height**
  - Use normal gravity, γ_{45° , defined on the ellipsoid at 45 degree latitude
  - No geometric meaning (only physical)
  - Thus, water always flow from one point (high) to the other (low point)

$$H = C / \gamma_{45^\circ}$$

III Geoid

01 Gravity and Potential

02 Level surfaces and Geoid

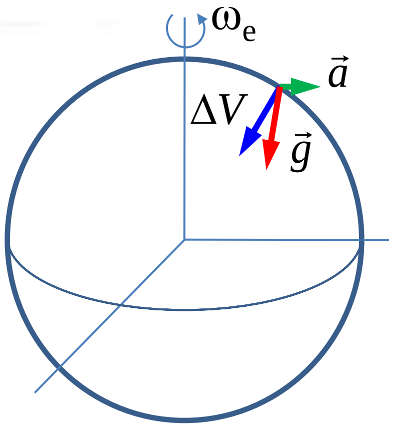
03 Geoid Modeling

04 Issues on Geoid Construction

05 Korean Geoid Construction

II-1. Gravity and Potential

- **Gravity ($\vec{g}$)**
  - The force acting on a body at rest on the Earth's surface
  - Sum of **gravitational force**(∇V)and the **centrifugal force**($\vec{a}$) of the Earth's rotation



$$\vec{g} = \nabla V + \vec{a}$$

where $\vec{g} = \nabla W \equiv \begin{pmatrix} \frac{\partial W}{\partial x} & \frac{\partial W}{\partial y} & \frac{\partial W}{\partial z} \end{pmatrix}$, $\nabla V = G\iiint_{earth} \rho \nabla \frac{1}{l} dv$, $\vec{a} = \begin{pmatrix} \omega_e^2 x & \omega_e^2 y & 0 \end{pmatrix}$

- **Gravity Potential (W)**
  - The Potential associated with the gravity
  - Sum of the potentials of gravitational force(V) and centrifugal force(Φ)

$$W = V + \Phi$$

where, $V = G\iiint_{earth} \frac{\rho}{l} dv$, $\Phi = \frac{1}{2}\omega_e^2 (x^2 + y^2)$

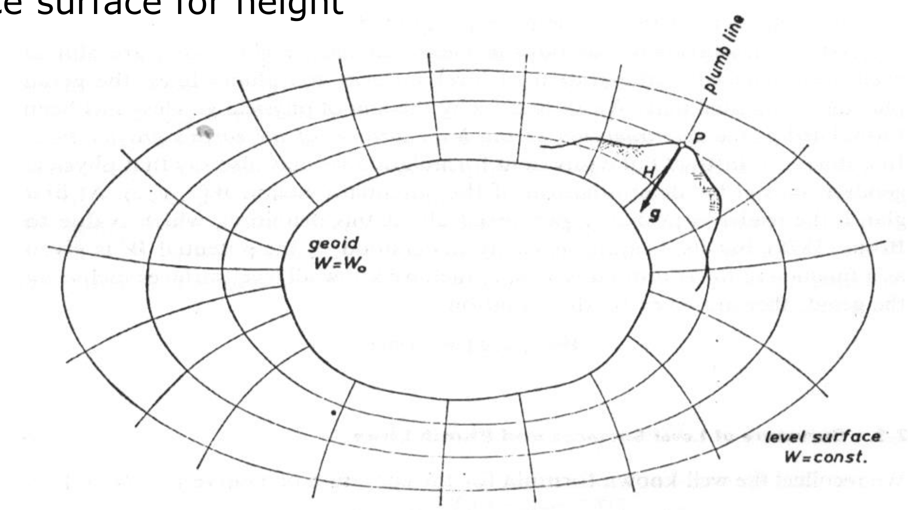
II-2. Level surfaces and Geoid

- **Level Surfaces (=Equipotential Surfaces)**
  - The surfaces on which the *potential(W) is constant*

$$W(x, y, z) = const$$

  - The gravity vector is always perpendicular to a level surface
  - Level surfaces are not parallel (in general) because $\nabla W = \vec{g}$ varies along the surfaces

- **Geoid**
  - Equipotential surface of gravity field that *closely approximates the mean sea level*
  - It is reference surface for height



Heiskanen and Moritz (1967), Physical Geodesy

II-3. Geoid Modeling

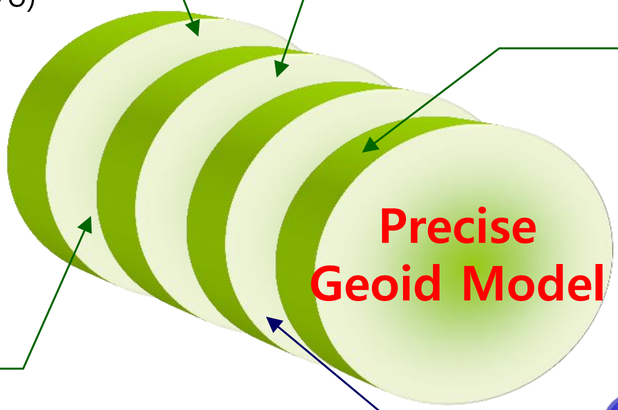
Key Elements

Geopotential Model

- Model selection
- Space mission: CHAMP, GRACE, GOCE
- Affecting factor : Resolution (d/o)

Gravity Data

- Data selection
  : ground, airborne, shipborne
- Affecting factor : Distribution, Density, Quality



GPS/Leveling Data

- Correction for localization
- Affecting factor : Distribution, Quality

Topography Data

- Data selection : local, global (ex : SRTM)
- Terrain correction model
  : airy-isostasy, RTM, helmert 2nd Condensation
- Affecting factor : Resolution, Quality

Algorithm

- Data processing
- Gravity data fusion
- Geoid calculation

II-3. Geoid Modeling (Data)

Global Gravitational Model (1)

- **Definition**
  - *Mathematical approximation* to the external gravitational potential of an attracting body
  - Set of numerical values for certain parameters and statistics of the errors

$$\Delta g = \frac{GM}{R^2}\sum_{n=2}^{N_{\max}}(n-1)\sum_{m=0}^{n}(\bar{C}_{nm}\cos m\lambda_P + \bar{S}_{nm}\sin m\lambda_P)\bar{P}_{nm}\sin\phi_P$$

where, $GM = 3{,}986{,}005\times10^8 m^3/s^2$, $R = 6{,}371{,}008.7714m$, n, m: degree/order

$\bar{C}_{nm}, \bar{S}_{nm}$ and $\bar{P}_{nm}$: normalized spherical harmonic coefficients and Legendre function

ϕ_P, λ_P : position of point P

- **Usage / Applications**
  - Geoid undulation computations
  - Orbit determination
  - Trajectory determination of airplanes and missiles
  - Oceanographic applications (ex: dynamic ocean topography estimation, ocean circulation)
  - Geophysical prospecting applications (ex: underlying density distribution determination)

II-3. Geoid Modeling (Data)

Global Gravitational Model (2)

- **Base Data**
  - **Satellite tracking data** from space missions(CHAMP, GRACE, GOCE)
  - **Gravity data** : altimeter and ground gravity data

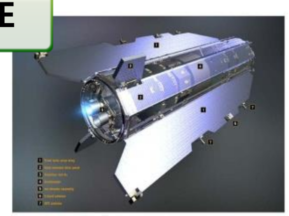
CHAMP

- Developed by GFZ
- Objective : Gravity and magnetic fields, Atmospheric Sounding
- Operation : 2000. 7 ~ 2010. 9
- Sensors : 3-axis STAR accelerometer, GPS, SLR
- Altitude / Orbit : 450km / 87°
- Outcome : EIGEN-CAHMP03S, ENGEN2 (Resolution : 650km)

GRACE

- Developed by NASA, DLR
- Objective : Gravity field and its temporal variation
- Operation : 2002. 3 ~ Now
- Sensors : 3-axis accelerometer, GPS, SLR, K-band satellite ranging
- Altitude / Orbit : 485km / 89°
- Outcome : GGM02S (Resolution : 300km)

GOCE



- Developed by ESA
- Objective : Gravity field recovery
- Operation : 2009. 3 ~ Now
- Sensors : 3-axis accelerometer forming gradiometer, GPS, SLR
- Altitude / Orbit : 250km / 96.5° (Sun-synch)
- Outcome : EGM_GOC_2 (Resolution : 100km)

Global Gravitational Model (3)

- **Models**
  - Model type : satellite-only, combined model (satellite + altimeter + ground gravity)
  - no. models : over 100 models (first model : SE1 developed in 1996)
  - New models based on the GOCE satellite data are being produced

unit : m

Model	Year	d/o	Data	Precision		
				Korea	Australia	Japan
EIGEN-6C2	2012	1949	S(Grace, GOCE), G, A	0.066	0.214	0.080
GOCO03S	2012	250	S(Grace, GOCE, CHAMP, SLR)	0.251	0.355	0.500
EIGEN-6C	2011	1420	S(Grace, GOCE), G, A	0.068	0.219	0.082
GOCO02S	2011	250	S(Grace, GOCE, CHAMP, SLR)	0.271	0.371	0.516
EGM2008	2008	2190	S(Grace), G, A	0.061	0.217	0.083
ITG-Grace03	2007	180	S(Grace)		0.603	0.752
EIGEN-GL04C	2006	360	S(Grace, Lageos), G, A		0.244	0.321
EIGEN-GL04S1	2006	150	S(Grace, Lageos)		0.464	0.952
GGM02C	2004	200	S(Grace), G, A		0.376	0.555
GGM02S	2004	160	S(Grace)		1.356	1.030
PGM2000A	2000	360	S, G, A		0.286	0.362
EGM96	1996	360	EGM96S, G, A		0.298	0.364
OSU91A	1991	360	GEMT2, G, A		0.453	0.561

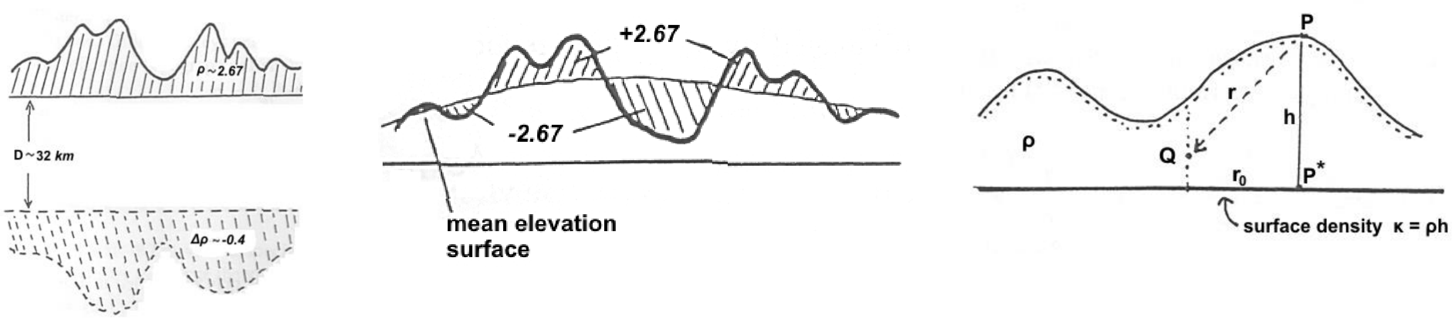
II-3. Geoid Modeling (Data)

Terrain Data

- **Type**
  - Local topography : generated by local government office
  - Global topography : generated by research institute, cover whole of the world (e.g. SRTM)

- **Necessity and Importance**
  - To remove and restore terrain effect in geoid modeling
  - Terrain correction model
    ① Airy-isostasy : terrain reduction based on airy-isostasy mass model
    ② RTM (Residual Terrain Model) : terrain effect reduced at the mean elevation surface
    ③ Helmert 2nd Condensation : terrain mass condensed into a surface layer (Faye

<Airy−isostasy> <RTM> <Helmert 2nd Condensation>



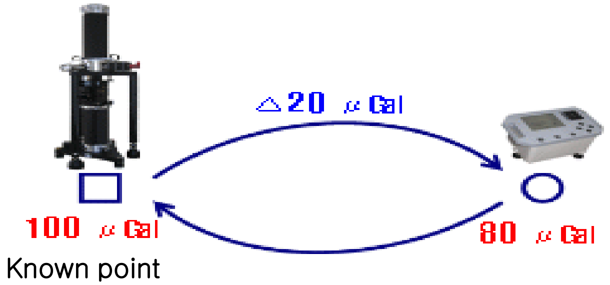
Forsberg (2008), Terrain Geodesy effects + GRAVSOFT and geoid fitting, Geoid School

  - cting factor on the geoid : resolution, quality

II-3. Geoid Modeling (Data)

Gravity Data : Ground

- **Method**
  - Absolute : directly determine absolute gravity
  - Relative : measure the difference of gravity and calculate the absolute gravity depending on the known point



- **Instruments :** absolute gravimeter, relative gravimeter

- Manufacturer : Micro-g LaCoste
- Model : FG5, FG5-X, A-10
- Reading Resolution : 0.002mGal
- Precision : 0.15mGal/√Hz

- Manufacturer : Micro-g LaCoste
- Model : CG-05
- Reading Resolution : 0.001mGal
- Precision : 0.005mGal

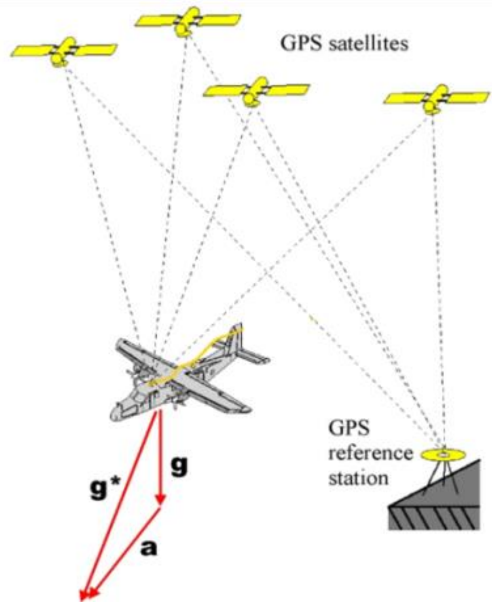
- **Procedures of data processing :**

Tide correction ► Instrument height correction ► Drift correction ► Atmospheric correction ► Free-air / Bouguer correction

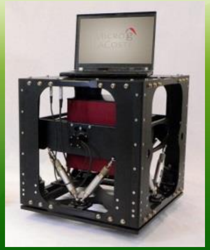
Gravity Data : Airborne

- **Principle**
  - Calculate the gravity by subtracting airborne gravimeter measurement from acceleration derived from GPS

$$g = g^{*}_{airborne} - a_{GPS}$$



- **Advantages :** cost and time effective, consistent data quality
- **Instruments**



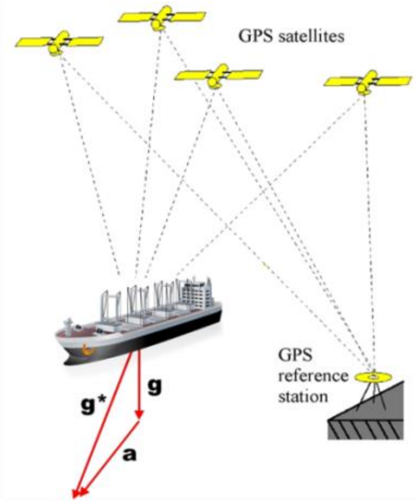
- Manufacturer : Micro-g LaCoste
- Model : TAGS-6
- Reading Resolution : 0.01mGal
- Static Repeatability : 0.02mGal
- Accuracy : 0.6mGal or better

- **Procedures of data processing :**

  k-factor correction ► Eötvös correction ► Cross-coupling correction ► Drift correction ► Lever-arm correction ► Filtering ► Free-air / Bouguer correction

II-3. Geoid Modeling (Data)

Gravity Data : Shipborne



- **Principle**
  - Calculate the gravity by subtracting shipborne gravimeter measurement from accelerometer derived from GPS

$$g = g^{*}_{shipborne} - a_{GPS}$$

- **Advantages :** more dense and precise than altimeter data
- **Instruments**

- Manufacturer : Micro-g LaCoste
- Model : Air-Sea Gravity System
- Reading Resolution : 0.01mGal
- Static Repeatability : 0.05mGal
- Accuracy : 1mGal or better

- Manufacturer : ZLS
- Model : Dynamic Gravity Meter
- Reading Resolution : 0.01mGal
- Static Repeatability : <0.1mGal
- Accuracy : 1mGal

- **Procedures of data processing :**

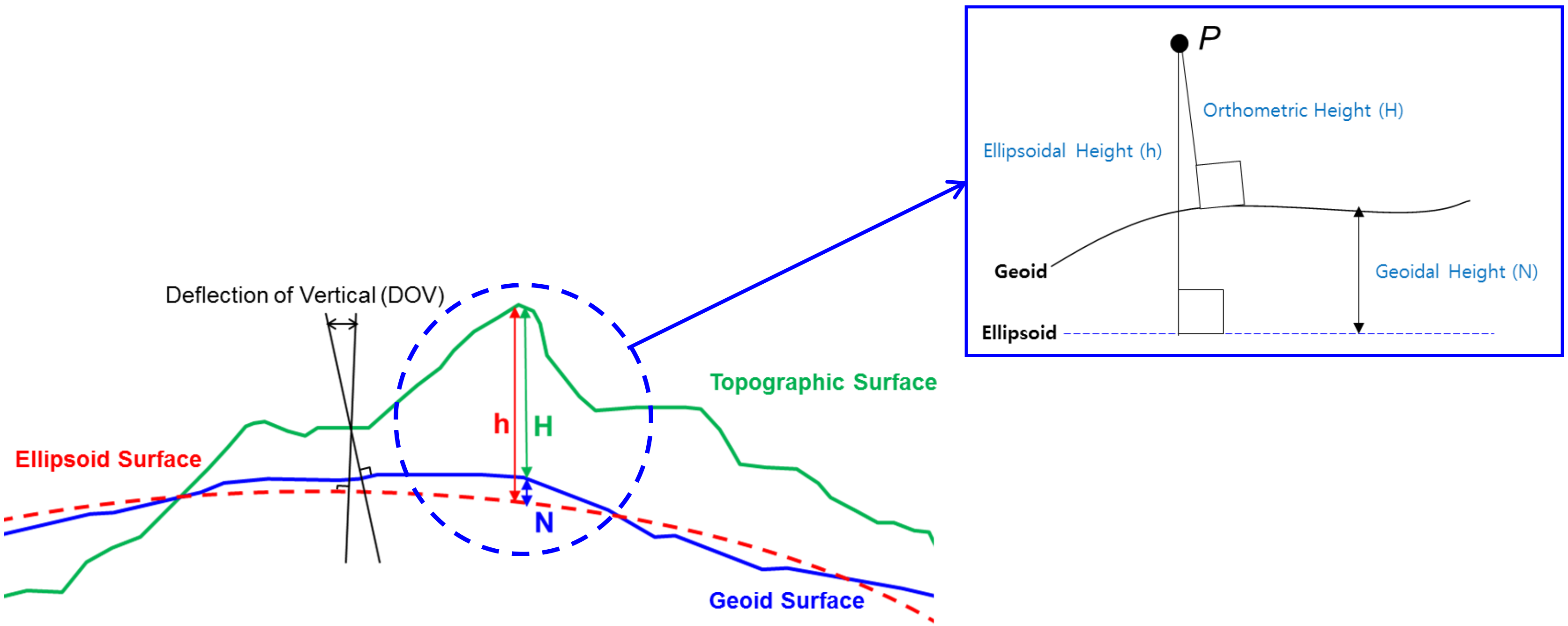
Tide correction ► Drift correction ► Removal of turning point ► Filtering ► Eötvös correction ► Cross-over point adjustment ► Free-air / Bouguer correction

GPS/Leveling Data

- **Definition**
  - Data having both ellipsoidal and orthometric height information

$$N_{GPS} \simeq h - H$$

- **Role of the Data :** verification of geoid, basic data for hybrid geoid calculation



II-3. Geoid Modeling (Algorithm)

Algorithm (1)

- **Data Processing**
  - Global Gravitational Model : calculation of gravity anomaly and geoid at certain degree and order
  - Gravity data : error sources correction, calculation and verification of gravity anomaly
  - Topography data : extraction and verification of DEM

- **Data Combination**
  - Necessity : different resolution and precision of gravity data
  - Methods
    - ① Weighted Mean
    - ② LSC(Least-Square Collocation)
  - **Key of the study**
    - ① Selection of gravity data considering distribution and quality
    - ② Removal of bias among gravity data

II-3. Geoid Modeling (Algorithm)

Algorithm (2)

- **Geoid Modeling : FFT, LSC**, Fuzzy Logic

$$N = \frac{R}{4\pi\gamma_0} \iint_{\sigma} \Delta g S(\psi) d\sigma$$

Data Processing → **Input Data**

- Global Gravitational Model
- Gravity Data
- Topography Data

- Type
- Resolution
- Quality

Remove

- Removal low and high frequency effect
- Outcome : residual gravity anomaly

$$\Delta g_{res} = \Delta g - \Delta g_{GM} - \Delta g_h$$

- Maximum d/o
- Terrain remove Method / Radius

Data Combination → **Downward Continuation**

- Conversion flight altitude to geoid surface

$$\Delta g_{res(h=flight\ height)} \rightarrow \Delta g_{res(h=0)}$$

- Method : FFT, LSC

Restore

- Calculation of residual geoid undulation
- Restoration low and high frequency effect
- Outcome : gravimetric geoid

$$N = N_{res} - N_{GM} - N_h$$

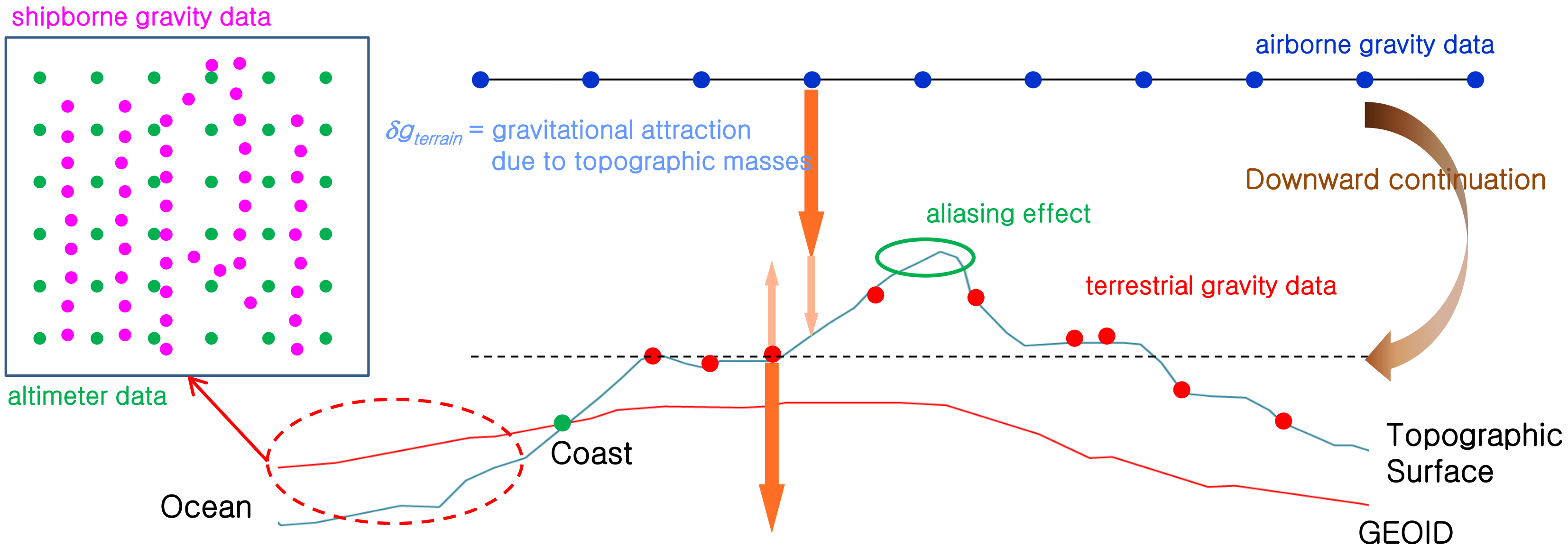
- Stokes' integral radius
- Wong-Gore Kernel
- Terrain restore radius

Hybrid Geoid

- Calculation of local hybrid geoid by combining GPS/Leveling data

II-3. Issues on Geoid Construction

- **Issue 1 : Downward continuation for airborne gravity data**
  - *Unstable procedure* compared to upward continuation
  - Methodology : Poisson's integral, least-square collocation, radial basis function, 1st-order and multiple-order gradient formulation
- **Issue 2 : Data fusion of various gravity data**
  - Different factors : distribution, quality, mass attraction, levels of measurements
  - Aliasing effect should be considered



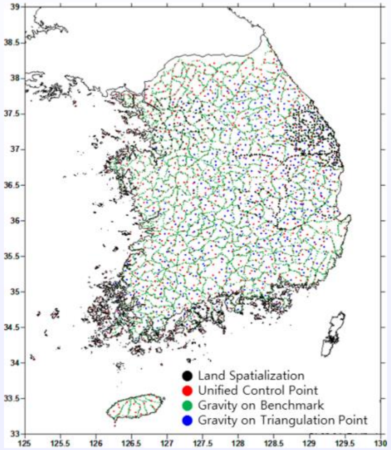
II-4. Korean Geoid Construction (1)

Data

- Global Gravitational Model : EGM2008
- Topography Data : NGII, SRTM
- Gravity Data : **ground, airborne**, DTU10(Ocean)

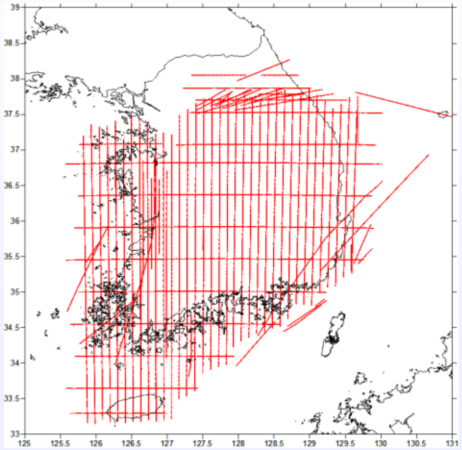
Ground Gravity

- obtained by NGII, few institutes and univ.
- no.data : 8,778
- precision : 0.05mGal



Airborne Gravity

- obtained by KLSP
- no.data : 27,343
- flight height : 3,000m
- precision : 1.56mGal



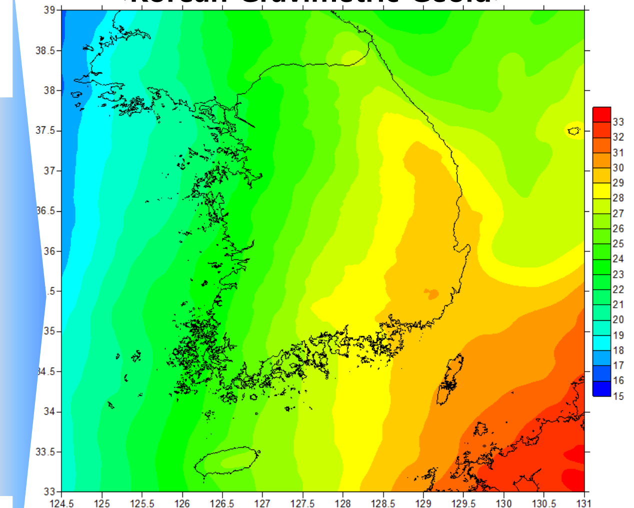
II-4. Korean Geoid Construction (2)

Algorithm and Geoid

- **Geoid Calculation Method :** remove and Store, **FFT**, LSC for downward continuation

Remove	• Low frequency effect : EGM08, 360° • High frequency effect : NGII DEM+SRTM, RTM, 200km
Downward Continuation	• Method : LSC • Bjerhammar Sphere Depth & Attenuation factor : 10km
Stokes' Integral	• Stokes' Integral : FFT, 0.3° • Modified Wong-gore kernel : 170~180°
Restore	• Low frequency effect : EGM08, 360° • High frequency effect : NGII DEM, SRTM, 200km

<Korean Gravimetric Geoid>



(unit: m)

Range	Mean	STD
16.96~33.45	25.62	3.80

- **Precision of Gravimetric geoid with respect to GPS/Leveling data : 5.85cm**
- **Precision of Hybrid geoid**
  - Absolute : 3.33cm (half-fitting : 3.60cm)
  - Relative (baseline = 15km) : 2.74cm

IV Height Unification

01 Necessity and Objectives

02 Methodology

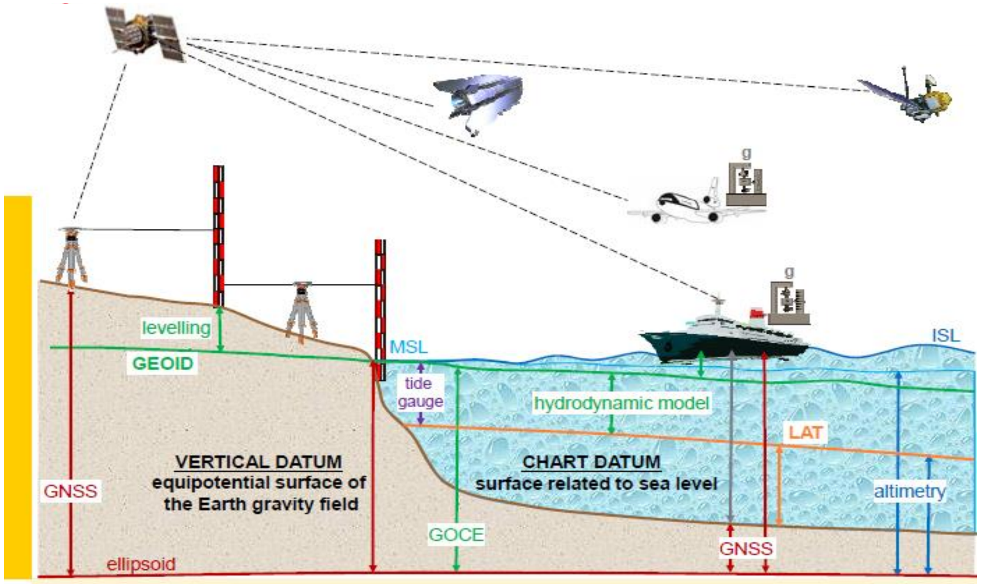
03 WHS and APRHSU

04 Issues of Height Unification

05 Applications

IV-1. Necessity and Objectives (1)

- **The vertical component plays a special role for the global monitoring of the topography of the Earth body**
  - Sea level change
  - Change of the sea surface topography
  - Post glacial uplift
  - Ice melting etc.
- **There is no vertical reference surface which is suitable for all applications and users**



Ihde (2010), Realization of a Global Unified Height System and its advances for Hydrographic Survey and for Coastal Mapping, HYDRO 2010

IV-1. Necessity and Objectives (2)

Background and Necessity

- **Disadvantages of the existing height systems = *Discrepancies***
  - Discrepancies can reach up to +/- 2m in a global frame
  - Source of discrepancies : error propagation of spirit leveling with the distance, applying different gravity reduction methods
  - They do not allow the data exchange in international projects, because they are only compatible with themselves
  - They do not support the reliable realization of h=H+N in world-wide scale

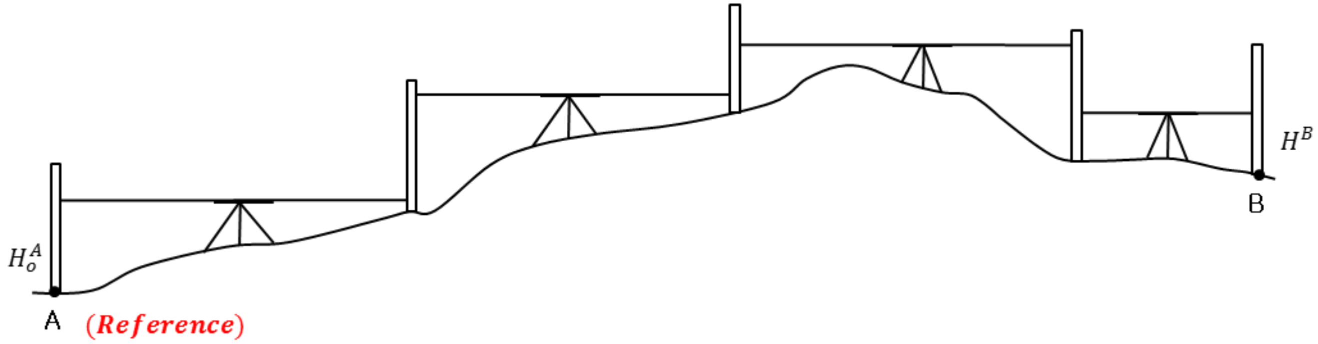
Objectives

- **Supports geometrical (h) and physical heights (H), as well as their combination (h=H+N) with a cm precision**
- Globally allows the unification of the existing physical height systems
- Provides high-accuracy and long-term stability of the vertical/radial components with cm accuracy

IV-2. Methodology (1)

- **Case1 : Classical approach**
  - Data : spirit leveling data, global gravitational model or local gravity data
  - Methodology : adjust leveling network and determine local equipotential surface

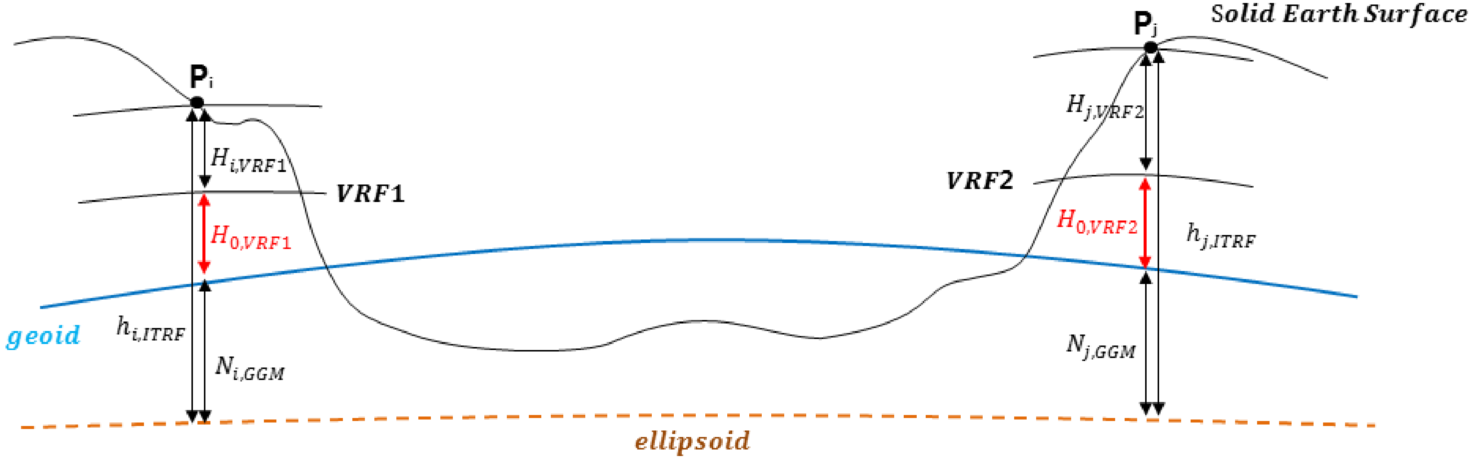
$$W_P = W_0 - c_P \Leftrightarrow H_n = \frac{c_P}{\bar{\gamma}}$$



  - Limit : apply only on continents
  - Example : EVRF2007
    - 27 European countries
    - 7,939 nodal points and 10,347 measurements were used
    - Geopotential numbers and normal heights were calculated
    - 13 points were used for fitting to the level of EVRF 2000 : $\sum_{i=1}^{13}(c_{EVRF\,2000} - c_{EVRF\,2007}) = 0$

- **Case2 : General approach**
  - Data : GNSS, spirit leveling data and global gravitational model
  - Methodology : calculate the local geoid based on GNSS and leveling data
    determine local offset with respect to global geoid

$$H_{0,VRF} = h_{i,ITRF} - H_{i,VRF} - N_{i,GGM}$$

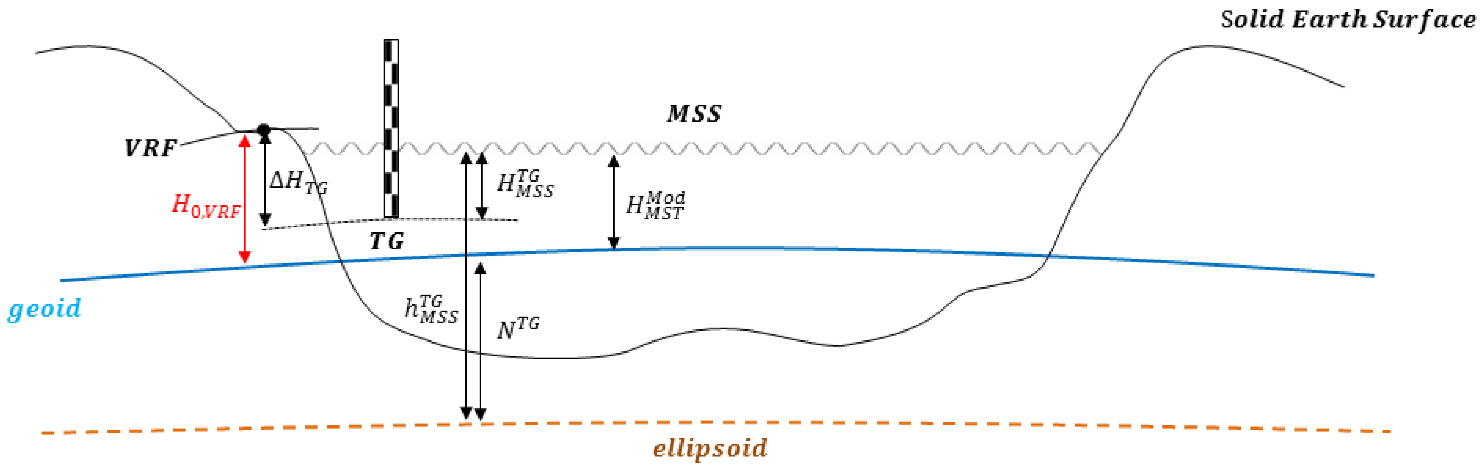


- *general case for realization and unification (cost and time effective)*

Ihde (2010), Realization of a Global Unified Height System and its advances for Hydrographic Survey and for Coastal Mapping, HYDRO 2010

- **Case3 : Oceanographic approach**
  - Data : mean sea surface topography, tide gauge observations
  - Methodology : calculate the local mean sea level based on tide gauge
    determine local offset with respect to mean sea surface topography

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



  - Limit : apply only tide gauge observations available

Ihde (2010), Realization of a Global Unified Height System and its advances for Hydrographic Survey and for Coastal Mapping, HYDRO 2010

IV-3. WHS and APRHSU (1)

WHS (World Height System)

- **Proceed by GGOS of the IAG(International Association of Geodesy)**
- **GGOS (Global Geodetic Observing System)**
  - Established by IAG in July 2003
  - Since April 2004, GGOS represents IAG in the Group on Earth Observation (GEO) and GGOS is IAG's contribution to the GEOSS(Global Earth Observation System of Systems)
  - Theme 1 of GGOS : Unified Global Height System

IV-3. WHS and APRHSU (2)

UN-GGIM-AP and APRHSU

- **APRHSU (Asia-Pacific Regional Height System Unification) is a one of the project of Working Group 1 in UN-GGIM-AP**

UN-GGIM-AP
REGIONAL COMMITTEE OF UNITED NATIONS GLOBAL GEOSPATIAL INFORMATION MANAGEMENT FOR ASIA & THE PACIFIC

Working Group 1 : Geodetic Reference Framework for Sustainable Development

- Fundamental goal of the UN-GGIM-AP WG 1 is to **achieve the recommendations in the Resolution adopted by 19th UNRCC-AP**
- Mission
  - create and maintain a densely realized and accurate geodetic framework
  - encourage data sharing and facilitate technical exchange towards regional height system development
  - support regional capacity building in national geodesy

Proejct 1 Asia-Pacific Reference Frame (APREF)

Proejct 2 Asia-Pacific Regional Geodetic Project (APRGP)

Proejct 3 ***Asia-Pacific Regional Height System Unification (APRHSU)***

Proejct 4 Asia-Pacific Geodetic Capacity Building (APGCB)

Working Group 2 : Data Sharing and Integration for Disaster Management

Working Group 3 : Place-Based Information Management for Economic Growth

IV-3. WHS and APRHSU (3)

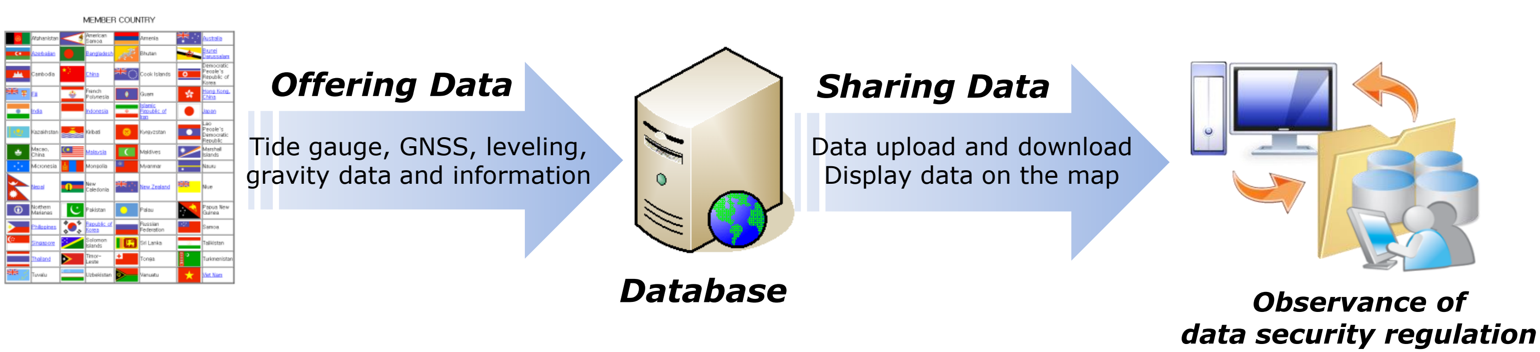
Work Plan of APRHSU

- **Purpose**
  - *Encourage data sharing and facilitate technical exchange* towards height system development
- **Mission**
  - Data Sharing : tide-gauge observations, GNSS observations at tide-gauges, geodetic leveling, terrestrial gravity observations
  - Technical Exchange : geoid determination, height system definition
- **Considerations**
  - Encourage participation of the organizations from many countries in Asia-Pacific region
  - Develop possible project to support APRHSU or to utilize the product of APRHSU.
- **Schedule**
  - ~ June, 2013 : organize the steering committee
  - ~ July, 2013 : prepare and disseminate call for participation on APRHSU
  - ~ August, 2013 : prepare questionnaire to collect information
  - August, 2013 ~ : collect data related to the height system

IV-4. Issues of Height Unification (1)

Data

- **Status Investigation and Data Collection**
  - Target data : tide gauge, GNSS, spirit leveling, gravity data
  - Survey entry : history, observer information, number of data, distribution, quality
  - Questionnaire survey
- **Data Standardization and Database Construction**
  - Data format : naming, significant digit etc. (e.g. latitude and longitude : float, 6 digit)
  - Database construction depending on country or type of data
- **Data Sharing and Service**
  - Database searching and up/download of data
  - Result display on the map
  - Setup the security regulation of data

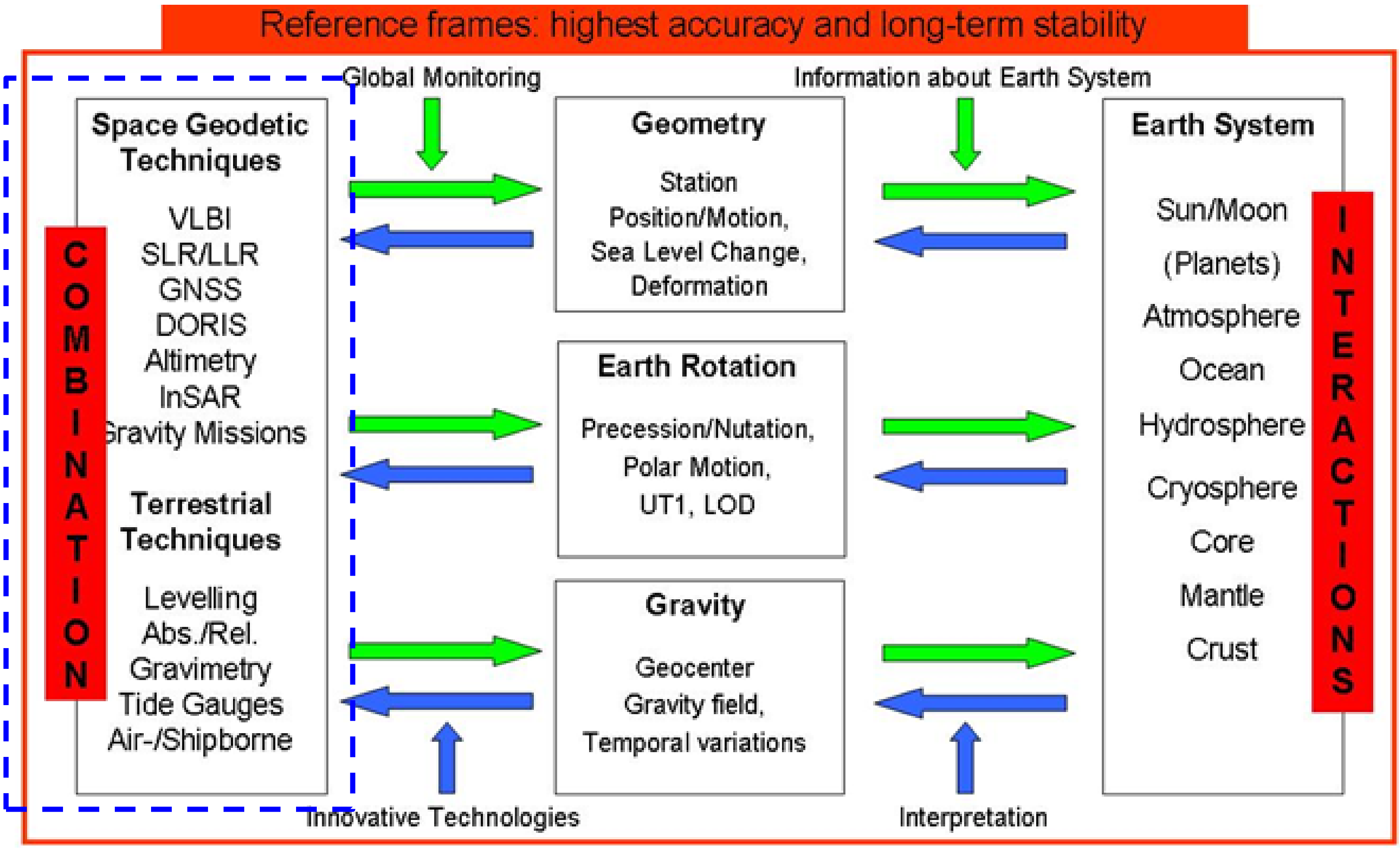


IV-4. Issues of Height Unification (2)

Technical Exchange

- **Determination of Methodology**
  - Methodology : classical, general, oceanographic approach
  - Analysis of strengths and weakness
  - Feasibility test considering status of data

IV-5. Applications



GGOS, Measuring and Modeling the Earth's System, http://192.106.234.28/Applications/Applications.html

THANK YOU!

Question?

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