# Introduction to Vertical Reference Frames


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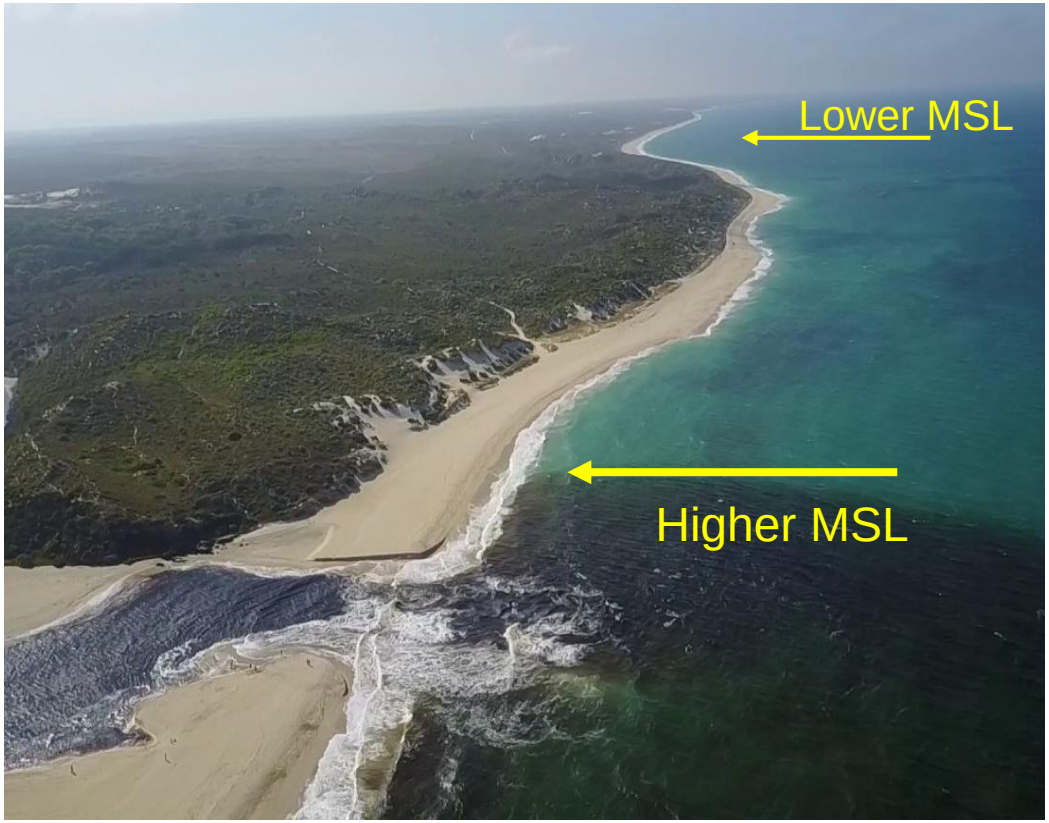
# Contents:

- Vertical datum and VRF.
- Gravimetric -vs- geometric Geoid.
- VRF for dynamic heights.
- Trend from global reference frames.

# A definition for Vertical datum:

A **vertical datum** is a base measurement point (or set of points or a horizontal surface) from which all elevations are determined by convention.

## Datum tied to mean sea level




Example: river discharge is one modifying factor to the MSL

## Mean sea surface: is the layer describing the average elevation of the sea, as is.

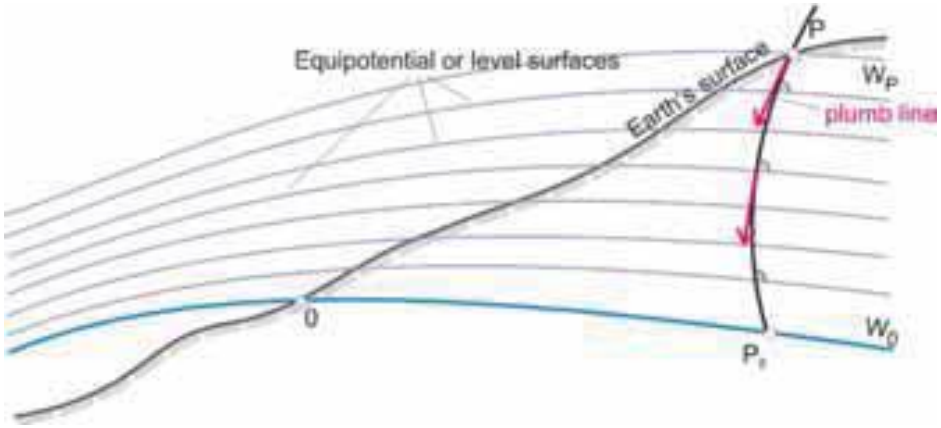
The local mean level depends on the period of observation and the environmental average local conditions like:

- atmospheric preasure,
- direction of the ocean current,
- wind direction,
- tide,
- thermohaline effect,
- river discharge,
- changing bathimetry,
- eustatic rise (climate change),
- ... and more.

## Datum by the gravity field.

A level surface determined by the gravity field.

It can be chosen to fit with a local mean sea level or as the average MSL from several observation points.



# Distinction of concepts

## Level surface:

- Determined by the gravity field as: equipotential surface.
- Only big changes in gravity can modify this surface.
- Water would not flow!

## Mean sea surface:

- Can be observed by tide gauges or by satellite altimetry.
- Affected by environmental changes.
- Water would flow over a layer of MSL!

A **vertical reference system** is a set of conventional definitions and parameters, adopted as a basis to determine height values which are compatible and comparable for geodetic positioning.

Elements:

- Define the way Datum is reached or calculated,
- Define the type of height to be observed,
- Determine the units of measure,
- Determine the tide system,
- Determine the reference frame for positioning,
- Define the normal gravity field to be used,
- Define the way time variations are considered.

A **vertical reference frame** is a realization of the system, consisting of a dataset of height values associated to a corresponding set of physical marks and some declaration of the uncertainty in such values to allow users propagate the conventional heighting measure by relative observations.

It should contain:

- Site descriptions and associated height values,
- Declaration of uncertainty,
- Description of the methodology implemented,
- An estimate of time variations in Datum or heights.

Datum propagation by leveling

Leveling networks are characterized by the increasing uncertainty of heights in terms of the distance reckoned from the datum point.

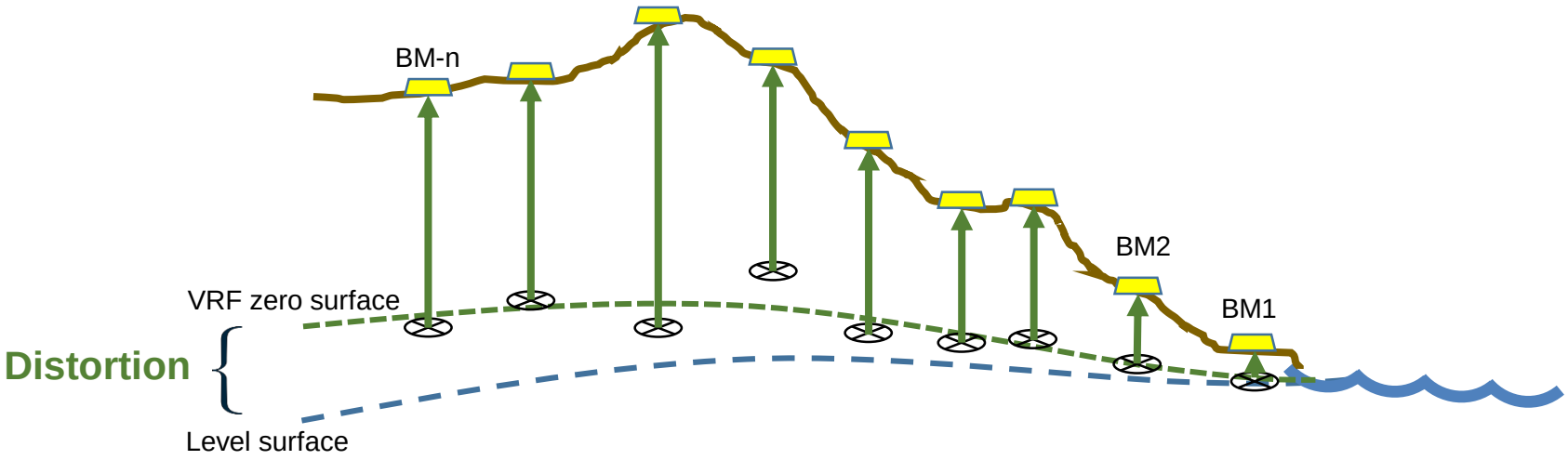
Over short distances (few tens of Km) leveling remains as the best quality technique.

Larger the distance --> larger uncertainty

## Datum and distortions

The error in heights from a vertical reference frame, can be interpreted as an actual error in the datum propagation; i.e. an estimate of the datum distortion.

Datum distortion: is the systematic part of the error in the datum track.



Datum and distortions

GNSS observations on pairs of benchmarks are the best source to detect **gross errors** in any of these:

- Orthometric heights,
- Geoidal heights,
- Geodetic heights.

Height differences tend to be **more reliable** than absolute height values!

Recommendation: Compare height differences!

Within error bars

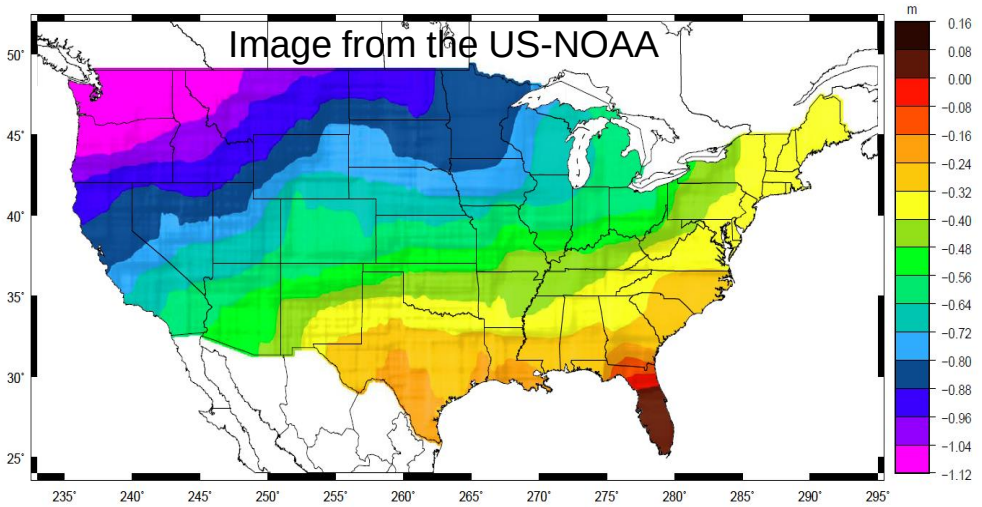
$$\Delta h = (h_2 - h_1) \approx (H_2 + N_2) - (H_1 + N_1)$$

$$\Delta H = (H_2 - H_1) \approx (h_2 - N_2) - (h_1 - N_1)$$

$$\Delta N = (N_2 - N_1) \approx (h_2 - H_2) - (h_1 - H_1)$$

Datum and distortions

Depending on the extension and complexity of the study area, plus the type of gravity corrections applied to leveling, the datum distortion can grow from cm to metre level.

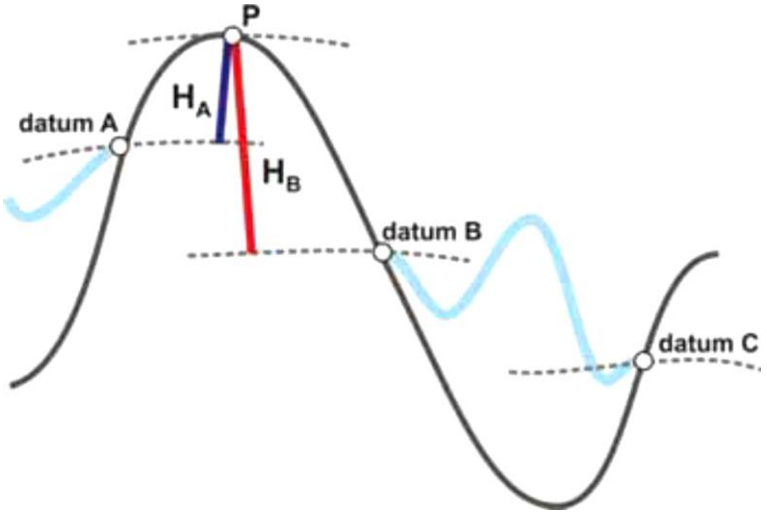



An example of well documented case of datum distortion, corresponding to the VRF named NAVD88 over the US territory.
It was measured by differencing GPS/BM geoid height versus a satellite-derived geoid of low resolution.

Datum and distortions

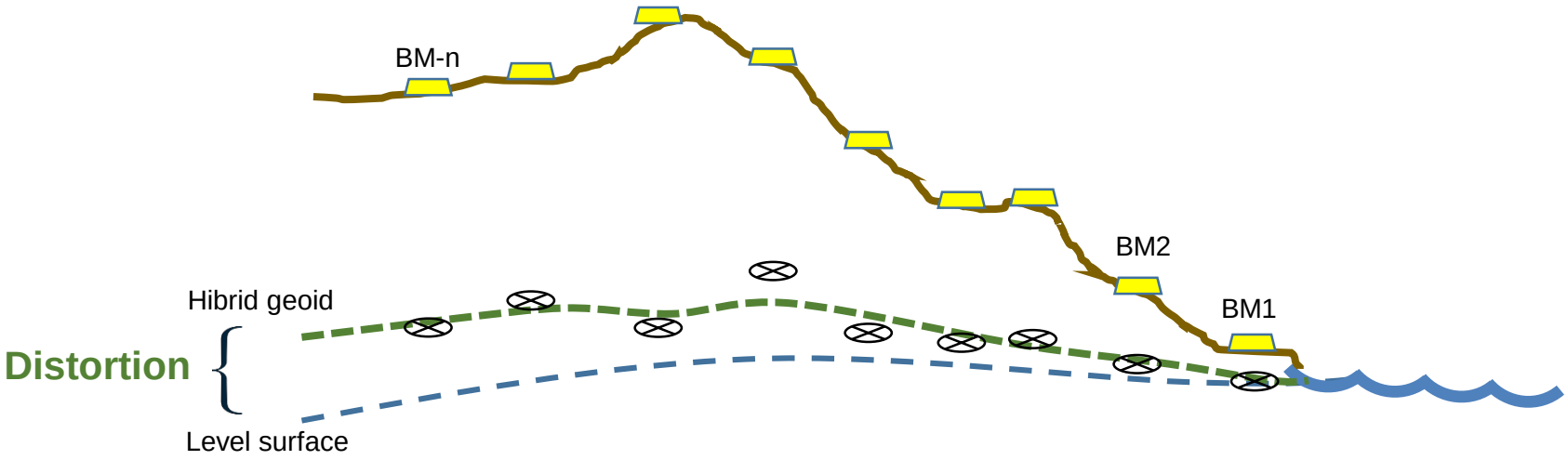
Documented disadvantages on VRF realized by leveling (geometric geoid):

- Significant datum distortions.
- May refer to different levels.
- May determine different types of height.
- Vertical variations not supported.
- Improper combination h-H-N.
- Leveling loop missclosure is treated as measurement error.



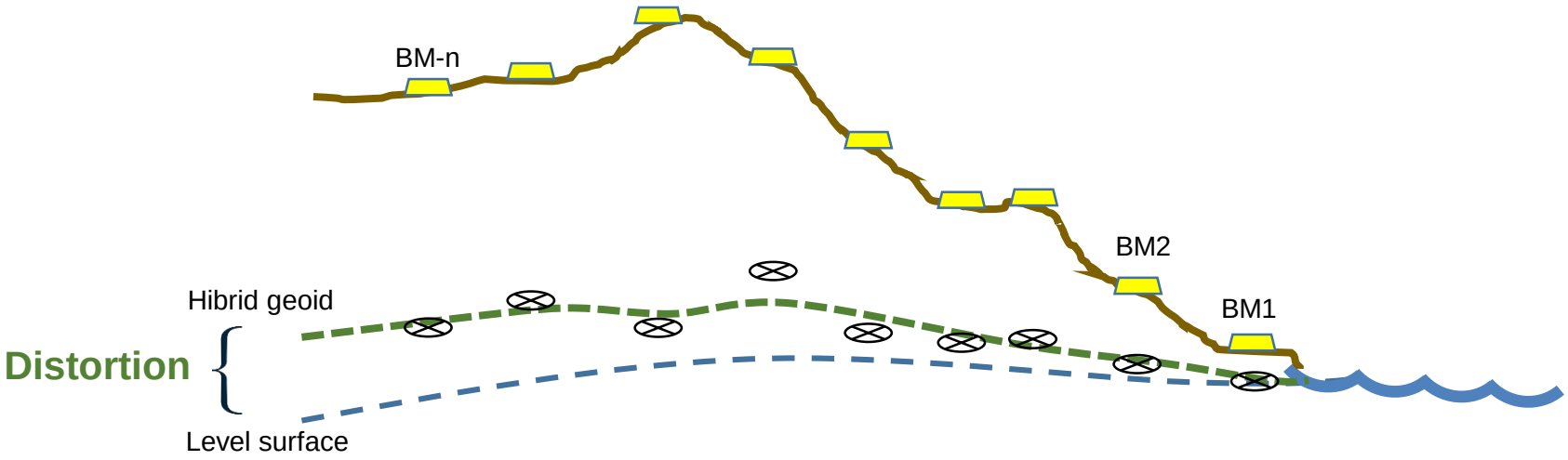
Datum and distortions

Hibrid geoid: is a geoid model produced from gravimetric information and constrained to fit the geometric geoid heights from a leveling network.



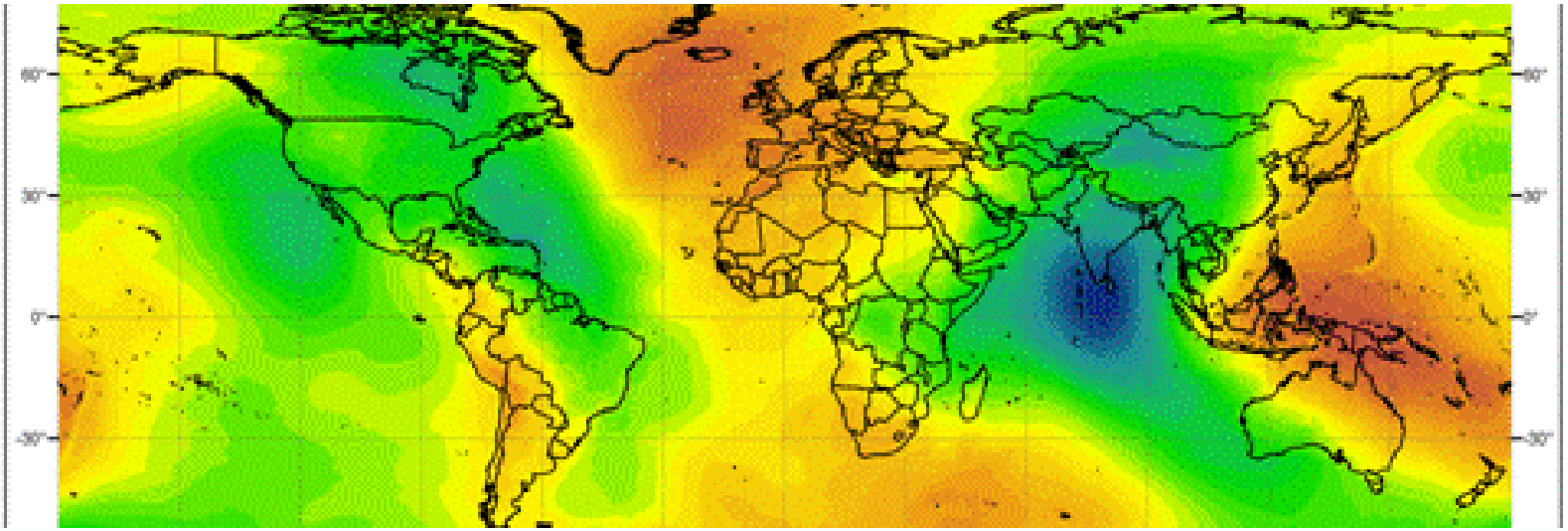
## Datum and distortions

Note: hybrid geoids are characterized by a reproduction of the distortions in the leveling network.



Gravimetric geoid: produced uniquely from gravimetric data and assigned to represent some predefined reference level or height.

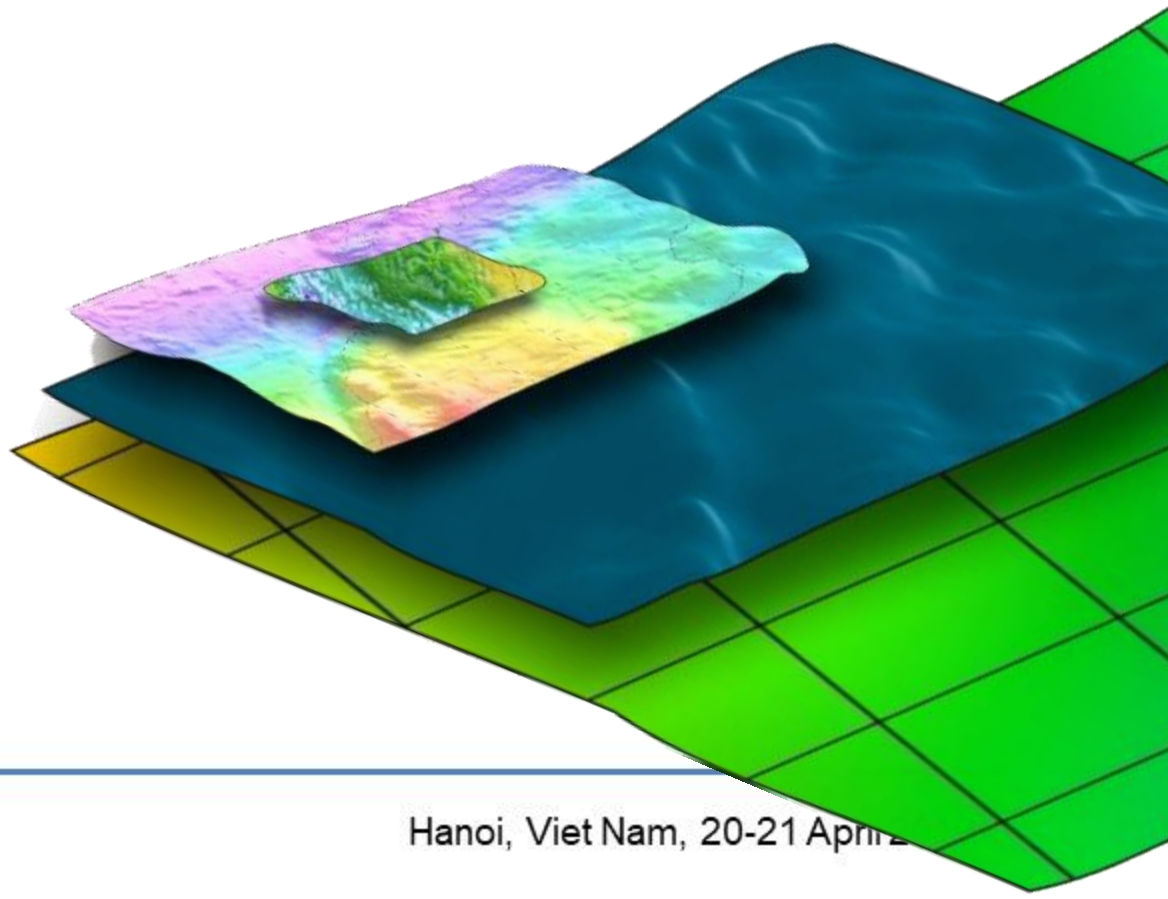
It can span through the oceans!



A level surface

Gravimetric geoids or quasigeoids are typically built under different assumptions and parameters.

It matters to know such differences to account for the offset!



# A geoid model as vertical datum

**Pros:**

- Permanence of the VD over time.
- No errors due to leveling observations.
- No need to re-level the hole area.
- Direct access to the VD through GNSS... faster, cheaper.

**Cons:**

- Terrestrial gravimetry surveys are necessary.
- Lower accuracy than leveling in relative heighting at short distances.
- Legal aspects related to other techniques or standards for heighting.

# A geoid model as vertical datum

Further considerations

- It is necessary to guarantee the permanent operation of a CORS network with some specification of spatial distribution.
- The datasets available to assess the quality of precise geoid models is scarse.
- For high precission, the tide-system can be determined as "the same used in GNSS processing".
- The most popular technique to create the input gravity model is combination of satellite / terrestrial data.
- The transition from any VD to another should be accompanied by a transformation surface to allow traceability to the old standard.

# Changing heights: not new.

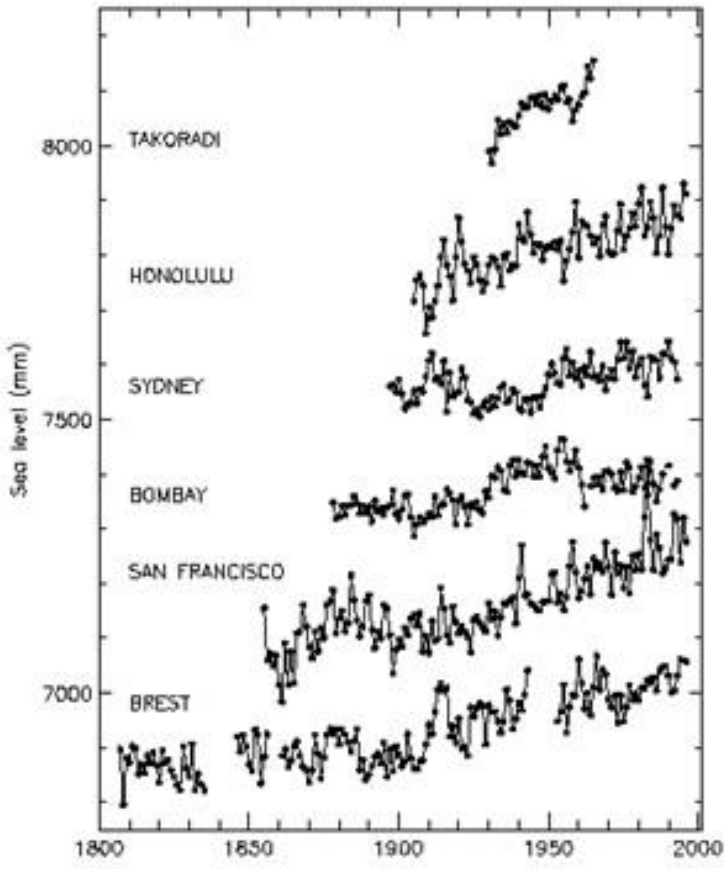
Heights do change in time, due to land movement or datum change!

Datum changes mainly due to global sea level rise,
while land can move for several reasons.

Static VRFs are unable to support height variations,
and therefore, unable to guarantie high precision.

**Sea level rise** (eustatic rise) is a proven fact, determined from a large amount of observation points and different techniques.

- It is interpreted as consequence of climate change and hidrological cycle.
- Its effects on coastal areas are economic, social and environmental.
- It can be observed by well controlled tidegauges or by satellite altimetry over long time series.




Historical sea level variations (source: PSMSL).

# Land movement


Land subsidence produced by an earthquake (Sumatra).

## Subsidence or uplift.

Multiple reasons:

- Ground fluids or solids extraction,
- Tectonic activity,
- Post-glacial rebound.

Can be observed by:

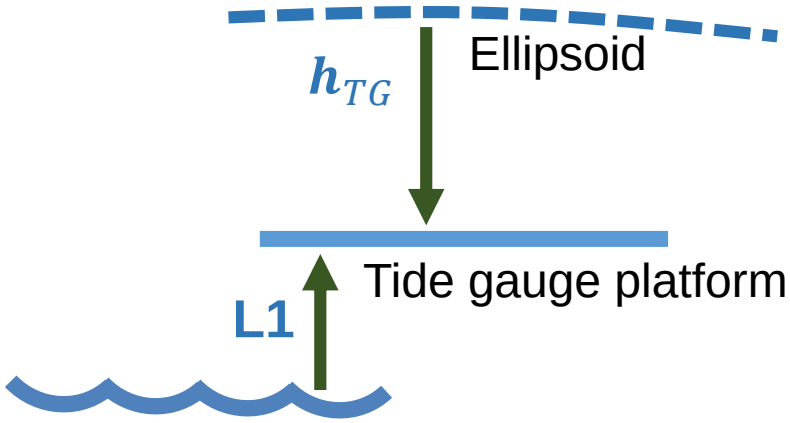
- GNSS repeated positioning (continuous or eventual),
- Leveling + GNSS,
- Satellite radar interferometry (InSAR).

# Source of the vertical change

**Tide gauge:**
Registers the water level change with respect to the concrete platform.

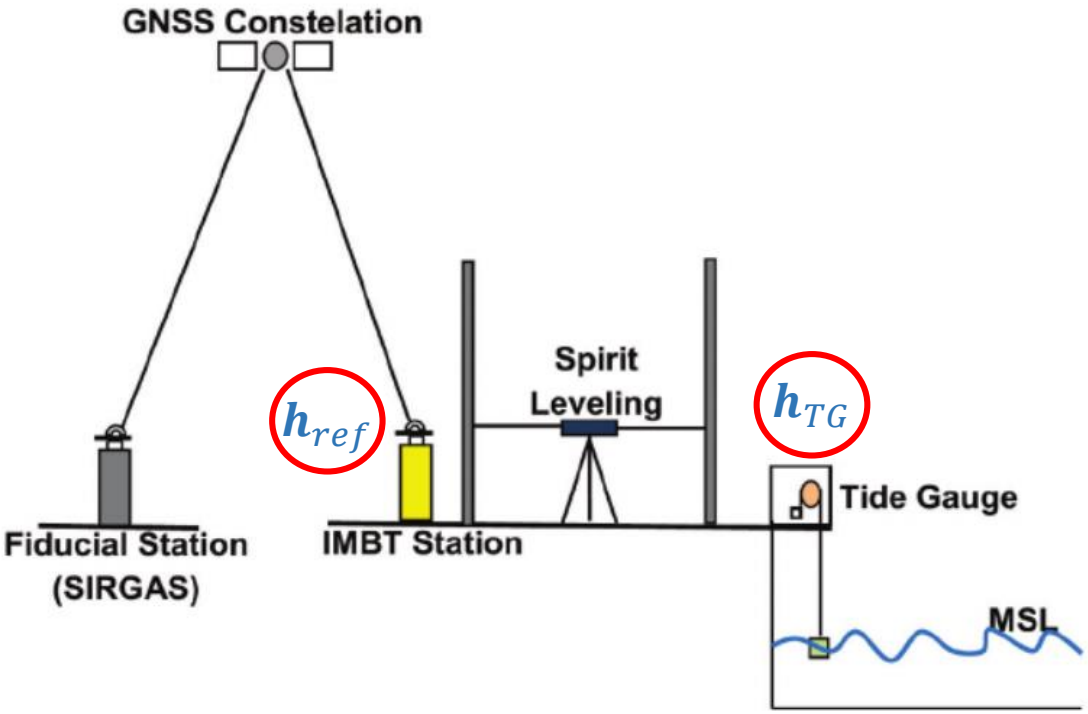
**GNSS:**
Registers any height variation of the concrete platform with respect to the ellipsoid.

$$\frac{d}{dt}\boldsymbol{MSL} = \frac{d}{dt}\boldsymbol{h_{TG}} - \frac{d}{dt}\boldsymbol{L1}$$



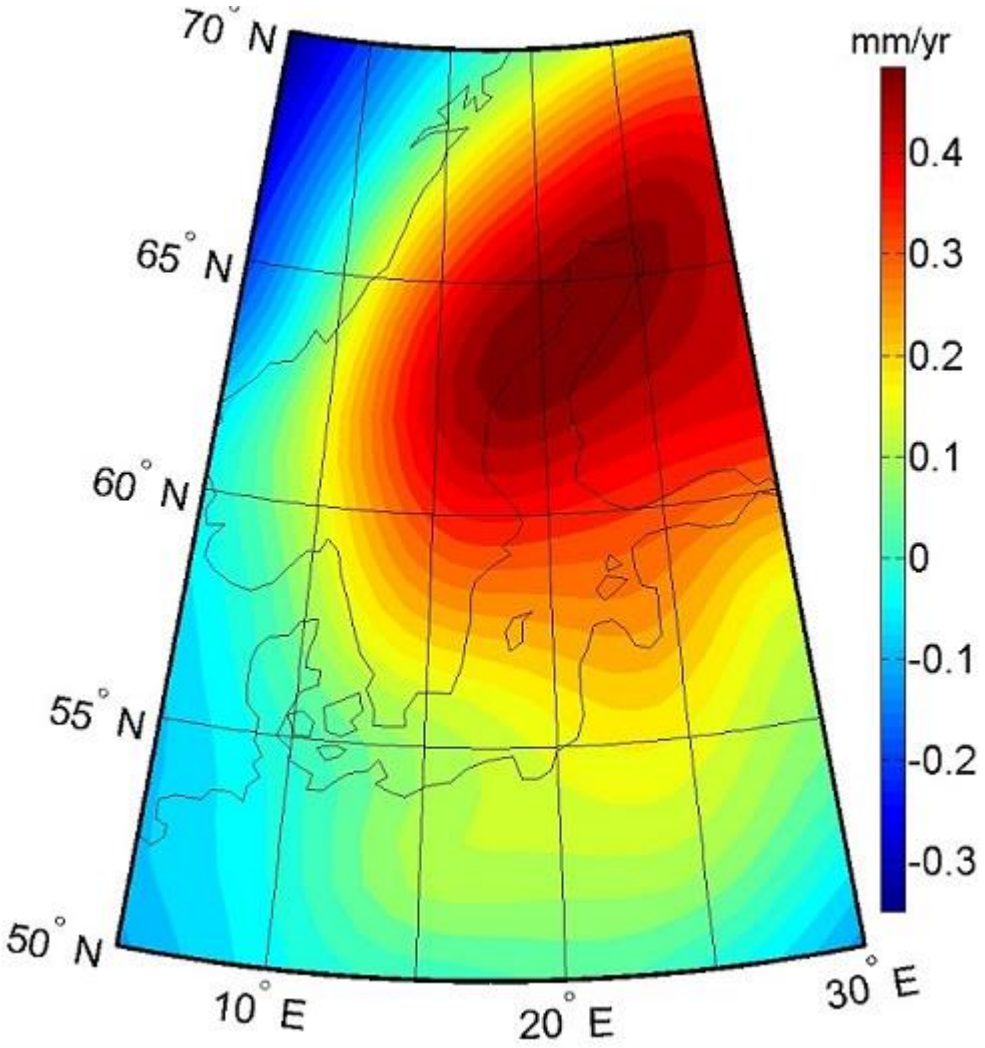

Picture from the tide gauge service, Mexico.

# Source of the vertical change




When GNSS is not co-located on the tide gauge, a **periodic leveling** campaign helps resolving the variable dh/dt.

A model dN/dt
can be provided as component of the national VRF to enable the support to high precisión applications.



UN-GGIM
UNITED NATIONS INITIATIVE ON GLOBAL GEOSPATIAL INFORMATION MANAGEMENT

From the United Nations, it has been encouraged the participation of national geodetic agencies to construct international geodetic reference frames and to adopt them as part of their geo-spatial infrastructure.

For the **vertical component** it is required to establish a series of fundamental stations to make the link between the national VRF and the international height reference system (IHRS).

Such stations are expected to support the observation of sea level change.

UN-GGIM
UNITED NATIONS INITIATIVE ON GLOBAL GEOSPATIAL INFORMATION MANAGEMENT

# GGRF

## ITRF
horizontal

9th versión: 2014

Requires:
CORS

## IHRF
vertical

First versión, 2019?

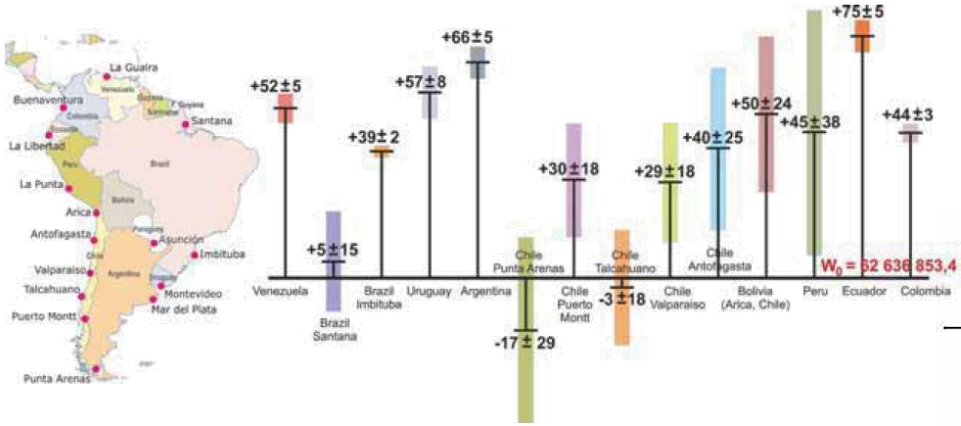
Requires:
IHRF stations
-Grav. absolute and relative
-CORS
-Leveling

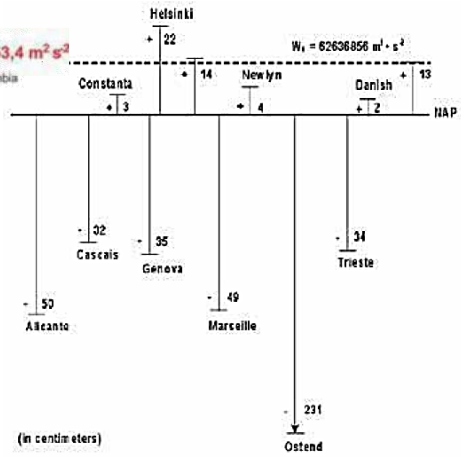
## IAGBN
gravity

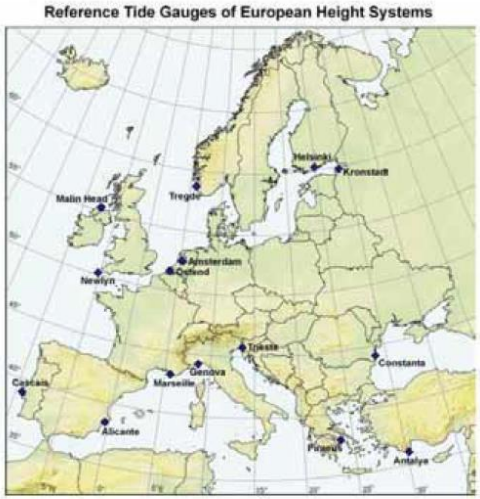
Second versión, 2020?

Requires:
Absolute gravity

There are more than 100 national datums, all with significant differences.



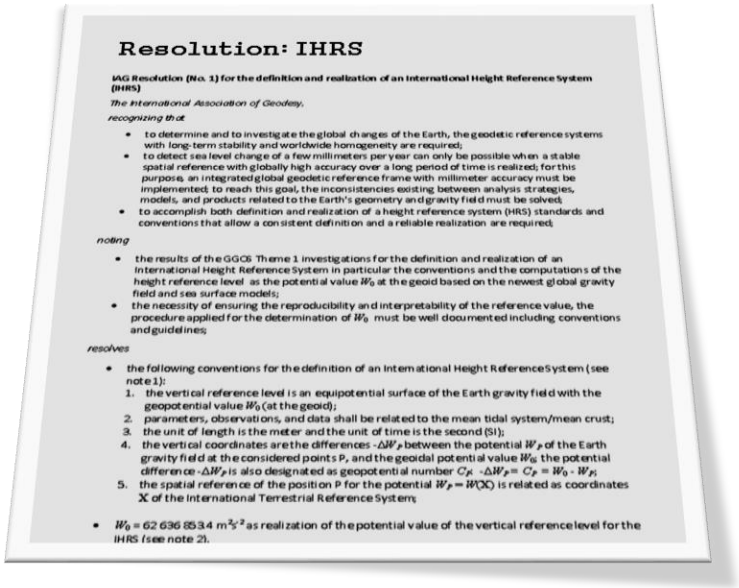




Source: http://www.bkg.bund.de/geodIS/EVRS/

IAG Resolución, 2015:

- New reference frames are required with appropriate characteristics to research changes in the Earth.
- It is necessary to define a height system, as well as another for the gravity field.



**Resolution: IHRS**

**IAG Resolution (No. 1) for the definition and realization of an International Height Reference System (IHRS)**

*The International Association of Geodesy,*

*recognizing that*

- to determine and to investigate the global changes of the Earth, the geodetic reference systems with long-term stability and worldwide homogeneity are required;
- to detect sea level change of a few millimeters per year can only be possible when a stable spatial reference with globally high accuracy over a long period of time is realized; for this purpose, an integrated global geodetic reference frame with millimeter accuracy must be implemented; to reach this goal, the inconsistencies existing between analysis strategies, models, and products related to the Earth's geometry and gravity field must be solved;
- to accomplish both definition and realization of a height reference system (HRS) standards and conventions that allow a consistent definition and a reliable realization are required;

*noting*

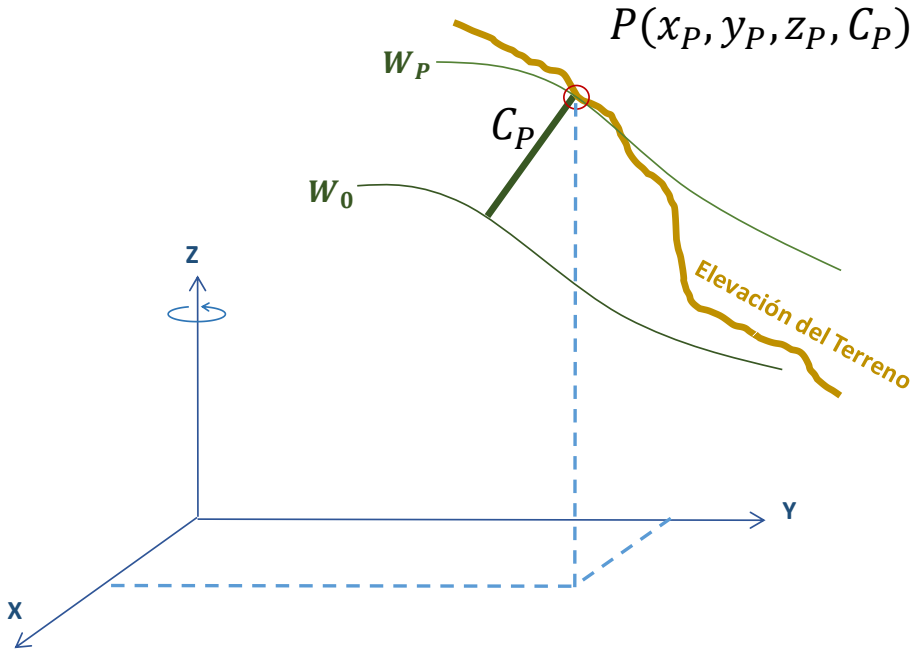
- the results of the GGOS Theme 1 investigations for the definition and realization of an International Height Reference System in particular the conventions and the computations of the height reference level as the potential value $W_0$ at the geoid based on the newest global gravity field and sea surface models;
- the necessity of ensuring the reproducibility and interpretability of the reference value, the procedure applied for the determination of $W_0$ must be well documented including conventions and guidelines;

*resolves*

- the following conventions for the definition of an International Height Reference System (see note 1):
  1. the vertical reference level is an equipotential surface of the Earth gravity field with the geopotential value $W_0$ (at the geoid);
  2. parameters, observations, and data shall be related to the mean tidal system/mean crust;
  3. the unit of length is the meter and the unit of time is the second (SI);
  4. 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 value $W_0$; the potential difference $-\Delta W_P$ is also designated as geopotential number $C_P$: $-\Delta W_P = C_P = W_0 - W_P$;
  5. 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;
- $W_0 = 62\,636\,853.4\ m^2 s^{-2}$ as realization of the potential value of the vertical reference level for the IHRS (see note 2).

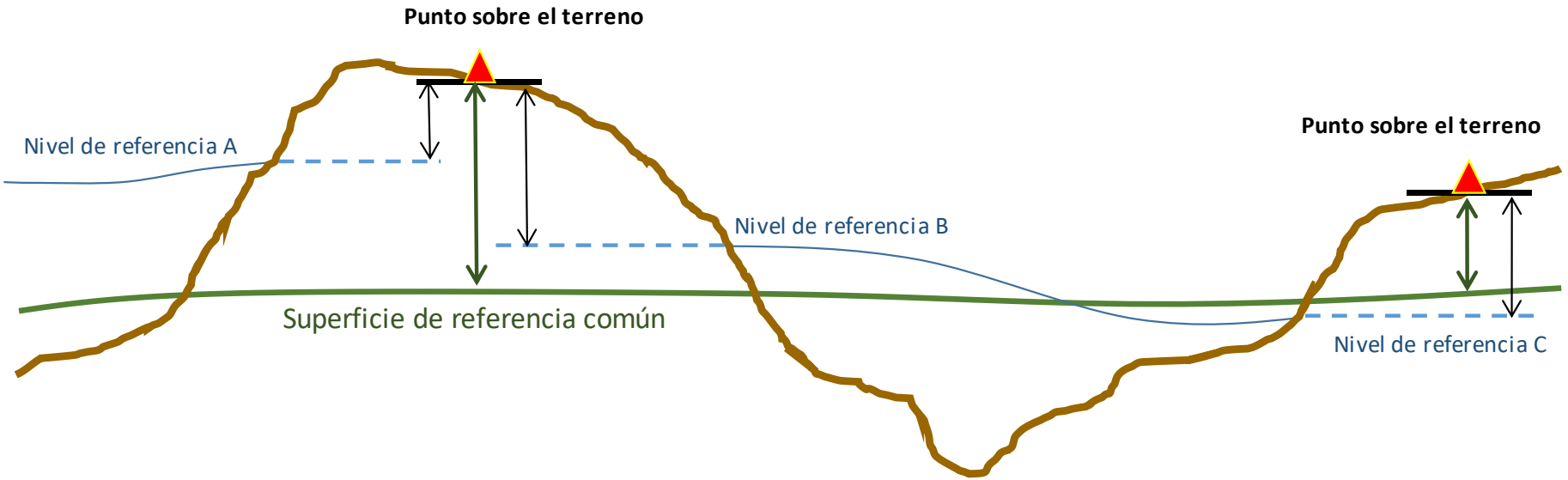
IHRS:

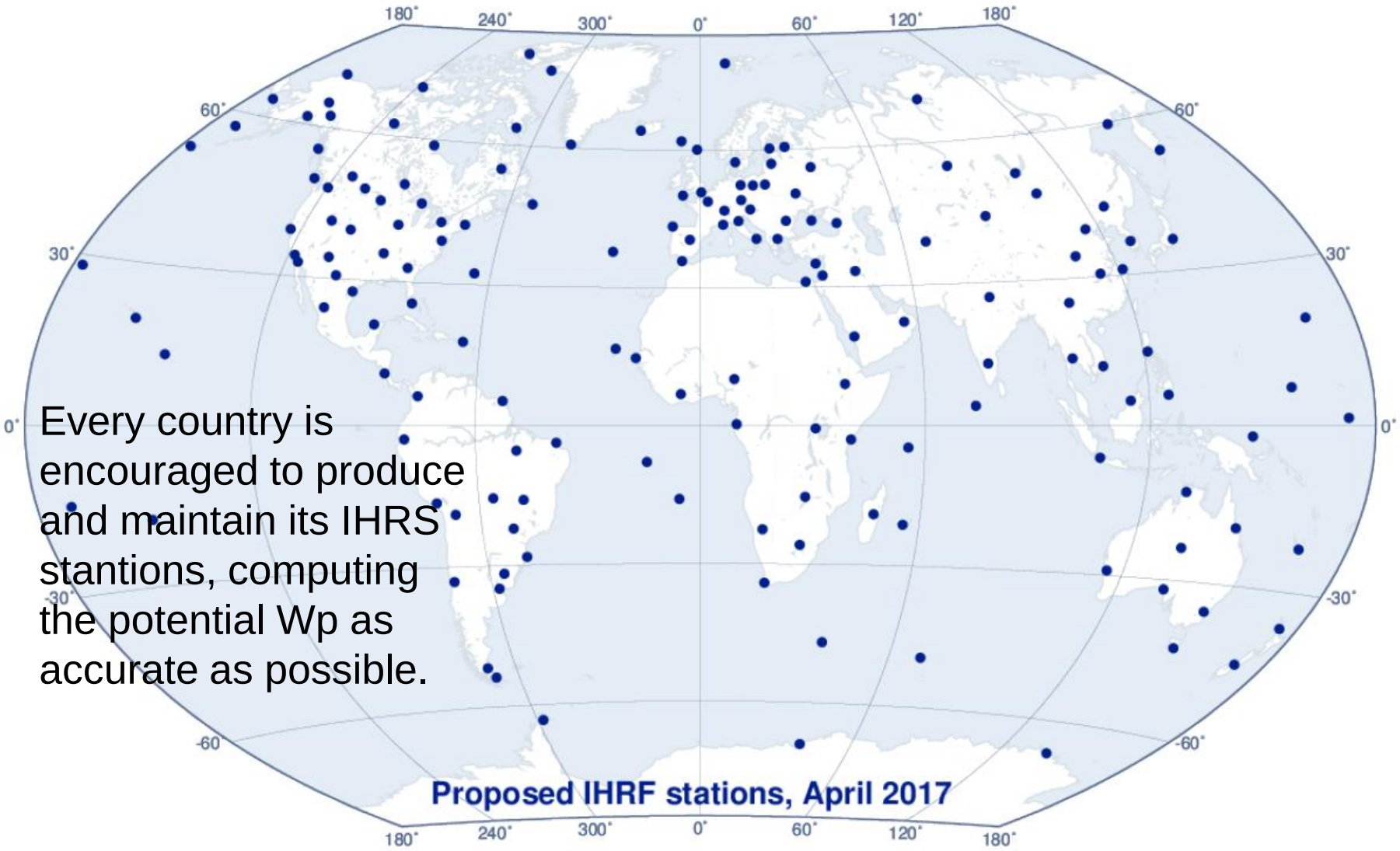
- The vertical reference is an equipotential surface with a fixed Wo value.
- A mean tide system should be used.
- Heights are determined by differences of gravity potetial.
- The standard
  Wo = 62 636 853.4 $m^2s^{-2}$



## IHRS

The reference level will allow the unification of height systems.





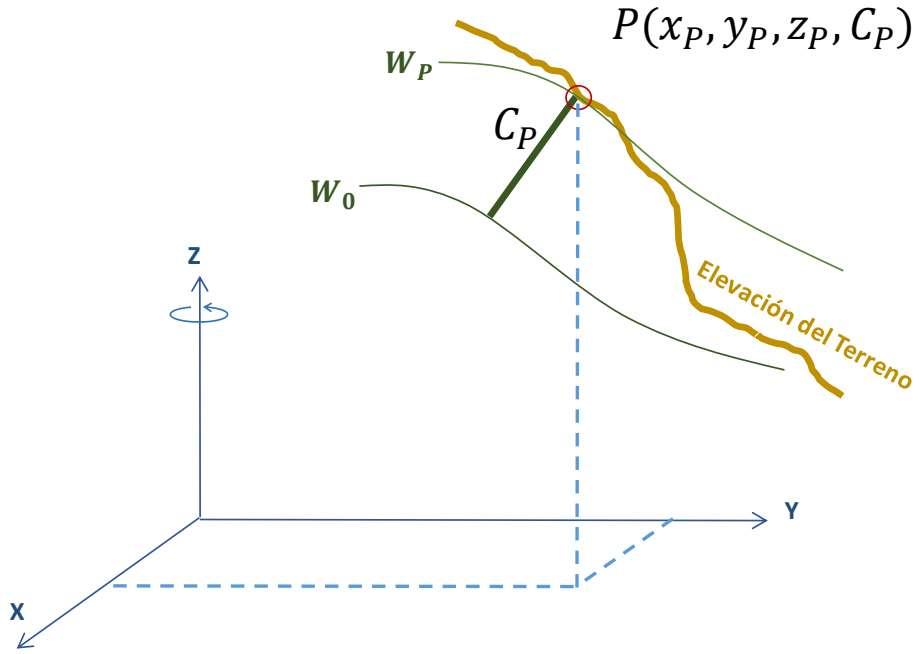

Every country is encouraged to produce and maintain its IHRS stantions, computing the potential Wp as accurate as possible.

For a point B, the geopotential number and height are:

$$C_B = W_0 - W_B = \int_0^B g\,\delta n \cong \sum_0^B g\,dn$$

$$H_B = \frac{W_0 - W_B}{\hat{g}} = \frac{C_B}{\hat{g}}$$

Every estimate of position and potential should be accompanied by the respective time variation.



In practice,

A) The Wp value can be extracted from a global geopotential model, but this is less recommended.

B) Derive Wp from existing national geoid or quasigeoid model.

$$W_P = W_{P,satellite-only} + W_{P,high-resolution}$$

C) Enhance the high resolution gravity field modeling, combining satellite and terrestrial data.

$$W_P = U_P + \gamma\,\zeta_P + \left(W_0 - U_0\right)$$

# Conclusions

- Every local or national VRF contain distortions that have to be modeled and declared.
- Distortions in VRF based on gravimetric geoids/cuasigeoids tend to be random and smaller as technology advances.
- Heights can be treated as a dynamic quantity to find coherent results among surveys at different epoch.
- The world trend is to determine heights on a gravimetric reference that supports the epoch variation.