Clock networks for future height systems

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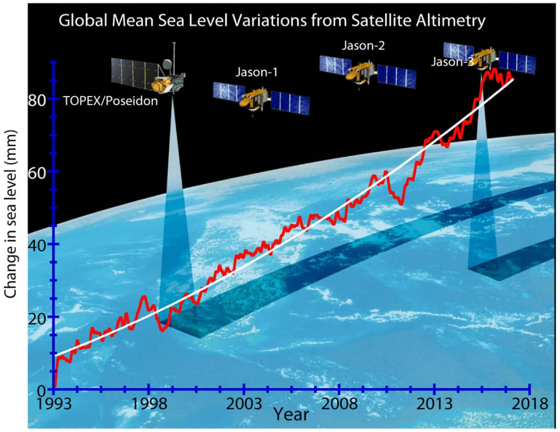
Outline

- Introduction
- Heights and the International Height Reference System (IHRS)
- Clock networks for the realization of IHRS
- Clock networks for height system unification
- Conclusions

Introduction

The precise height information is necessary for:

- global sea level rise;
- tunnel or bridge that connect different countries;
- floods and droughts;
- natural disasters, e.g., earthquake, tsunami, and sedimentation.



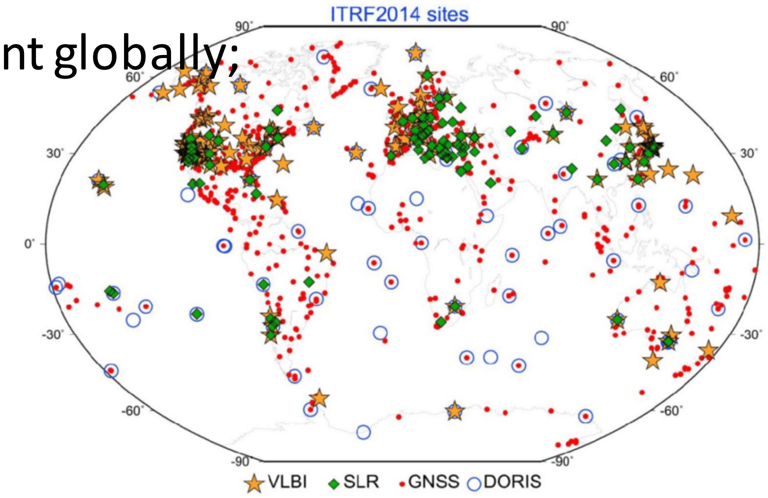
Introduction

The geodetic reference frame is required with:

- one order of accuracy higher than the magnitude of the effects;
- consistency and reliability worldwide;
- long-term stability (the same accuracy at any time).

The geodetic reference frame can be split into:

- terrestrial reference frame:
  - geometric coordinates consistent globally;
  - accuracy at **mm to cm** level.
- height reference frame;
- …;



Introduction

The problems for the existing height systems:

- more than **100** realizations worldwide;
- discrepancies of **dm to m** level (different vertical datums);
- different types of physical heights (missing standardization);
- **1 - 2 orders** of accuracy less than ITRF.

To realize an **international height reference system (IHRS)** which is **highly-accurate, consistent and stable** in a **global** scale is now one of the main goals of the International Association of Geodesy (IAG).

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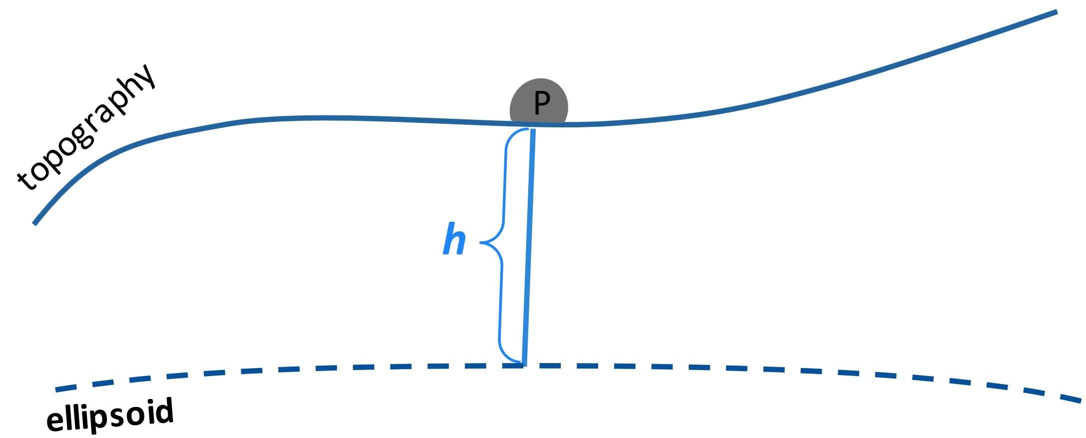
Heights

Height: vertical distance from the point to a reference surface.

Different types of height:

- ellipsoidal height *h*;

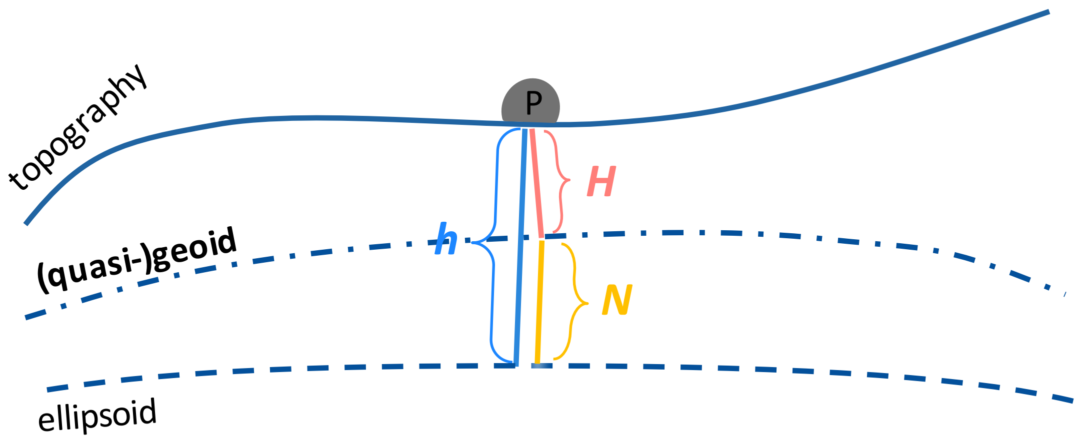


Heights

Height: vertical distance from the point to a reference surface.

Different types of height:

- ellipsoidal height *h*;
- orthometric or normal height *H*;



Heights

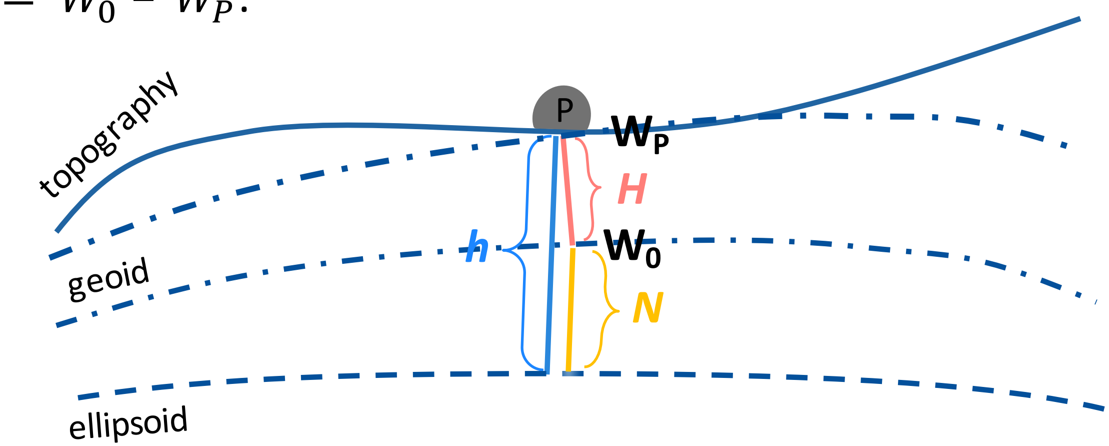
Height: vertical distance from the point to a reference surface.

Different types of height:

- ellipsoidal height *h*;
- orthometric or normal height *H*;
- geopotential number $C = W_0 - W_P$.

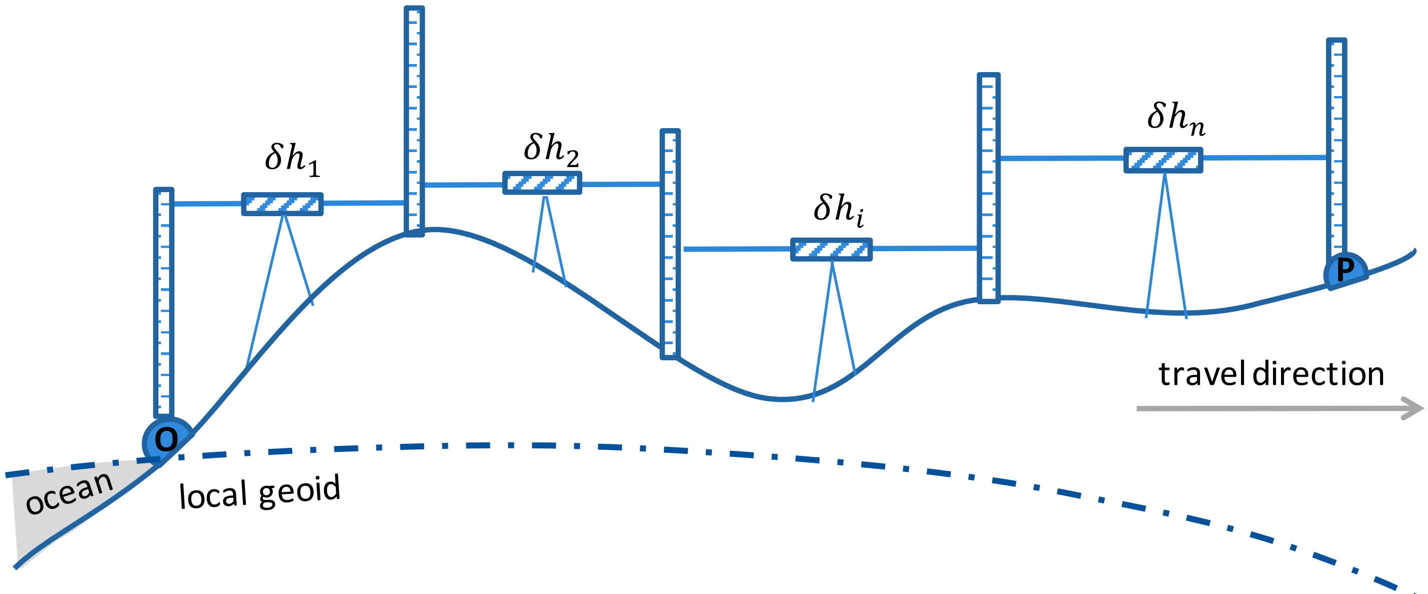
Relationships:

- $H = h - N$
- $H = \frac{C}{\{\bar{g}, \bar{\gamma}\}}$



Ways to determine physical heights

- Geodetic levelling: $H_P = H_O + \delta h_1 + \delta h_2 + \cdots + \delta h_n$



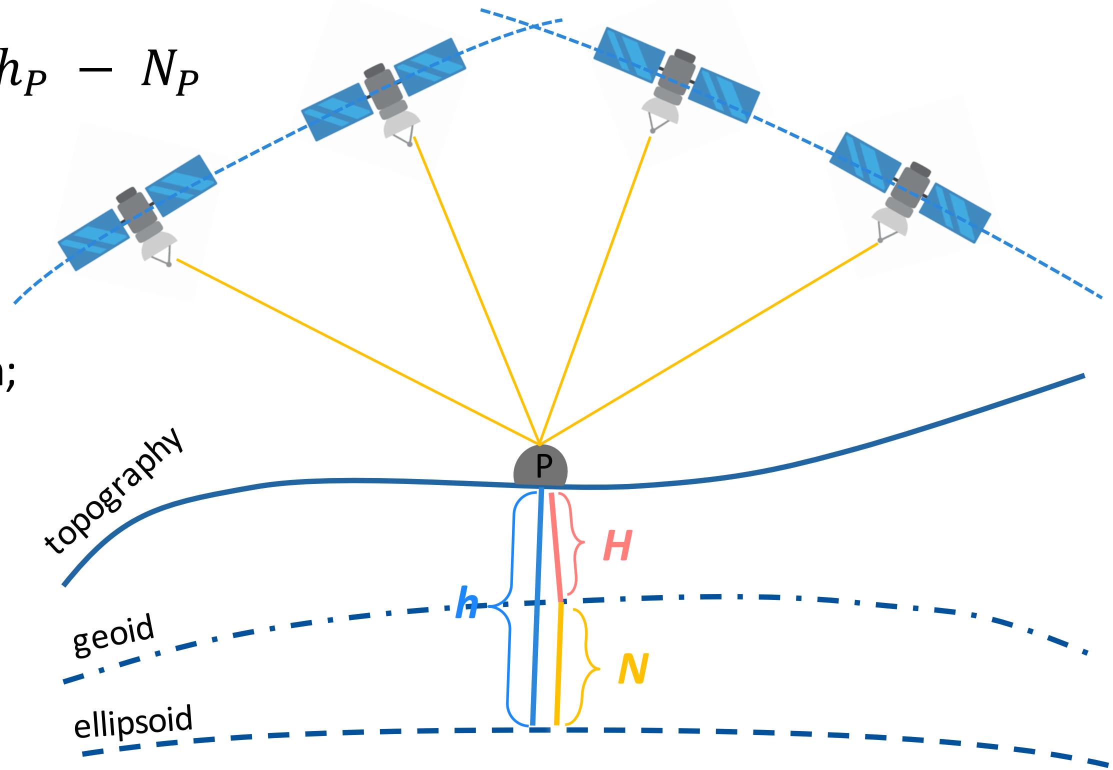
Error sources

- random errors: mm - cm;
- offsets of datum: dm;
- accumulated errors: 1-3 cm/100 km.

- time, money and labor consuming;
- error accumulated over long distances;
- benchmark destroyed by natural disasters;
- offsets between different local height systems.

Ways to determine physical heights

- Geodetic levelling: $H_P = H_O + \delta h_1 + \delta h_2 + \cdots + \delta h_n$
- GNSS + geoid: $H_P = h_P - N_P$



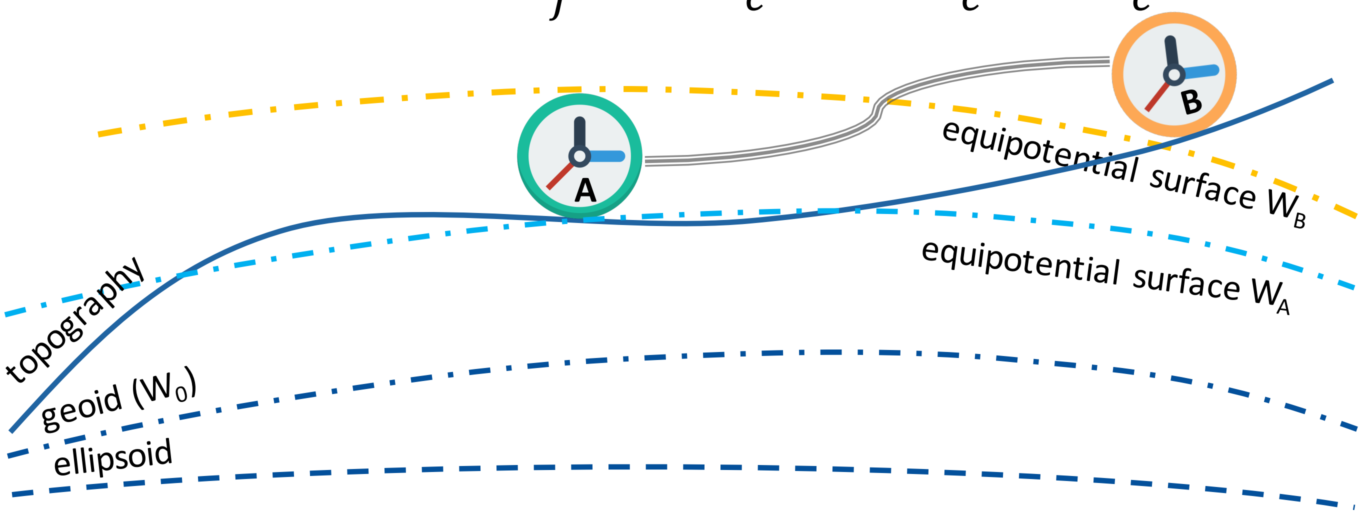
Error sources

- ellipsoid height (h): 1-3 cm;
- geoid height (N):
  - regional: 2-5 cm;
  - global: dm.

- efficient, economical and high accuracy over long distances;
- fewer framework points are required;
- challenge in modelling a high-accuracy and high-resolution geoid.

Ways to determine physical heights

- Geodetic levelling: $H_P = H_O + \delta h_1 + \delta h_2 + \cdots + \delta h_n$
- GNSS + geoid: $H_P = h_P - N_P$
- Chronometric levelling: $\frac{\Delta f}{f} = \frac{W_A - W_B}{c^2} = \frac{\Delta W}{c^2} = \frac{-\Delta C}{c^2}$



Error sources

$\frac{\Delta f}{f}$ (10^{-18}) ----> ΔW (0.1 m^2/s^2)

----> h (1.0 cm)

- efficient and high accuracy over large distances;
- direct measurement on potential difference resp. height differences.

International Height Reference System

IAG Resolution No.1, 2015 define the IHRS as:

- **vertical coordinates are geopotential numbers C_P;**
- the position P is given by the coordinate vector $\boldsymbol{X}_P$ in the ITRF;
- …

The IHRF is established with:

- a global network of reference stations:
  - a core network (perdurable, long-term stability);
  - regional and national densifications (local accessibility).
- high-precise primary coordinates $(\boldsymbol{X}_P, \dot{\boldsymbol{X}}_P, W_P, \dot{W}_P)$ of these reference stations.

Estimation of W_P

Three approaches to determine W_P or C_P:

1. Levelling + gravimetry: $W_P = W_0 - C_P$, $C_P = \int g dh$;
2. GBVP: $W_P = U_P + T_P, T_P$ (determination of geoid);
3. Global Gravity Model: $W_P = f(X, C_{nm}, S_{nm})$.

Drawbacks:

1. Levelling + gravimetry: local datums, different gravity reductions, systematic levelling errors, etc.;
2. GBVP: different standards, restricted accessibility to gravity data, etc.;
3. GGM: limited spatial resolution, inconsistency between approaches.

These methods show their **limits in realizing the IHRS**, i.e., the estimation of W_P for reference points.

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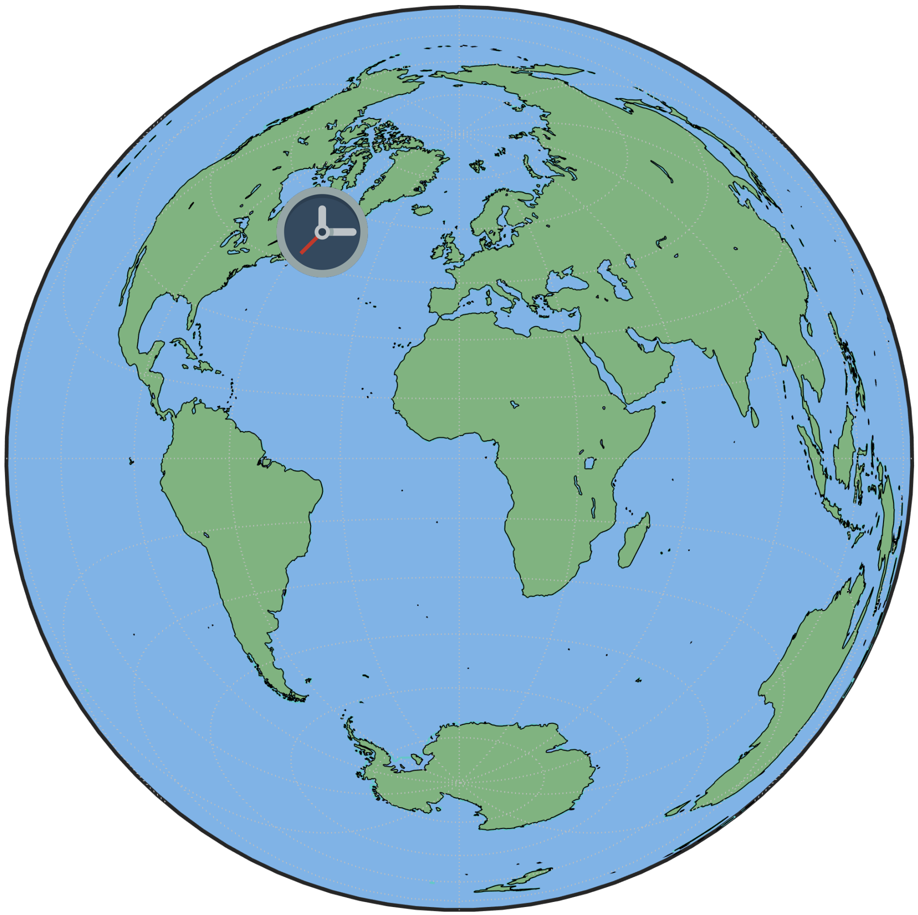
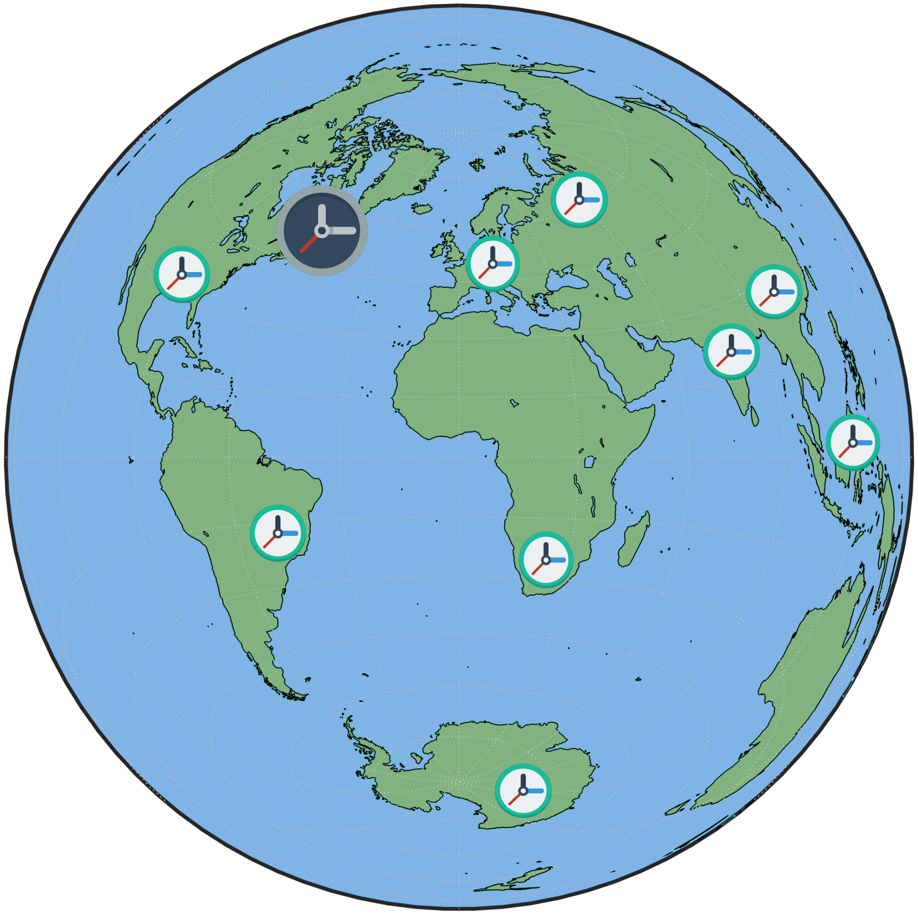
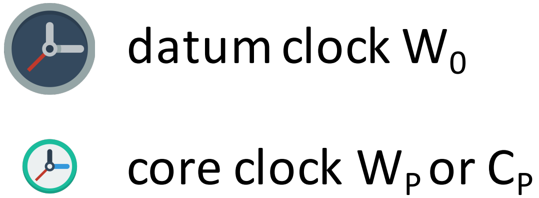
Clock networks for IHRS



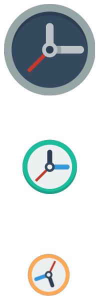
datum clock W_0

Clock networks for IHRS

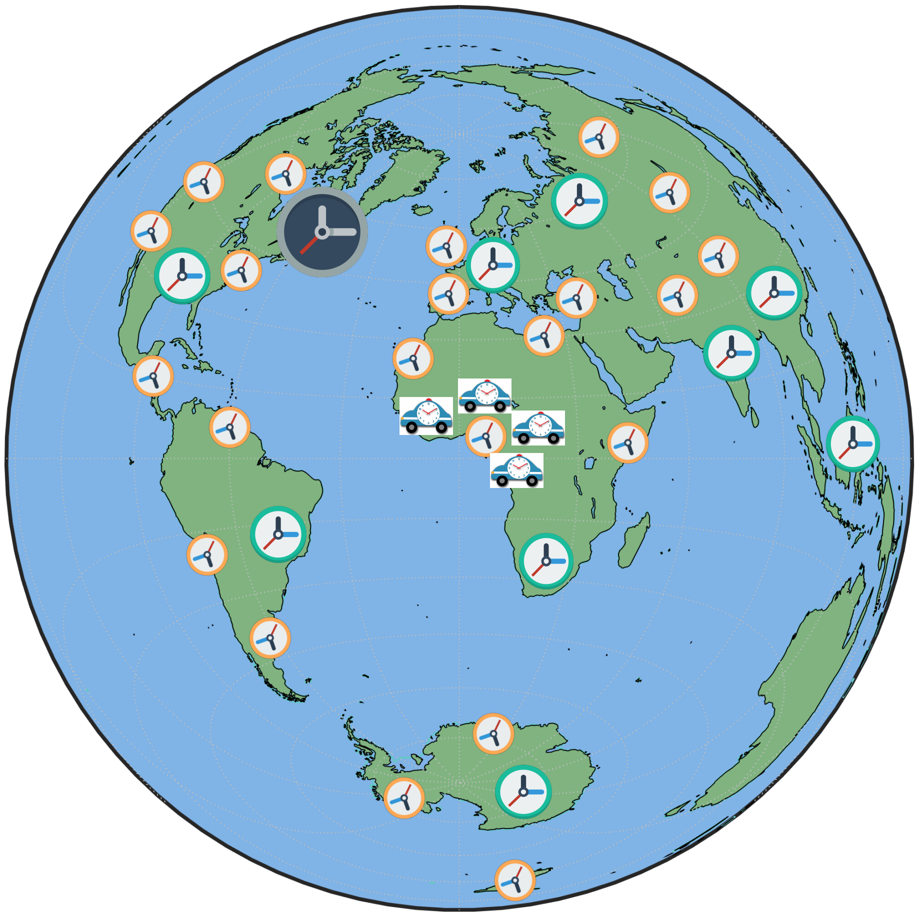




Clock networks for IHRS



Clock networks for IHRS



- datum clock W_0
- core clock W_P or C_P
- national clock W_P or C_P
- transportable clock

Clock networks for IHRS

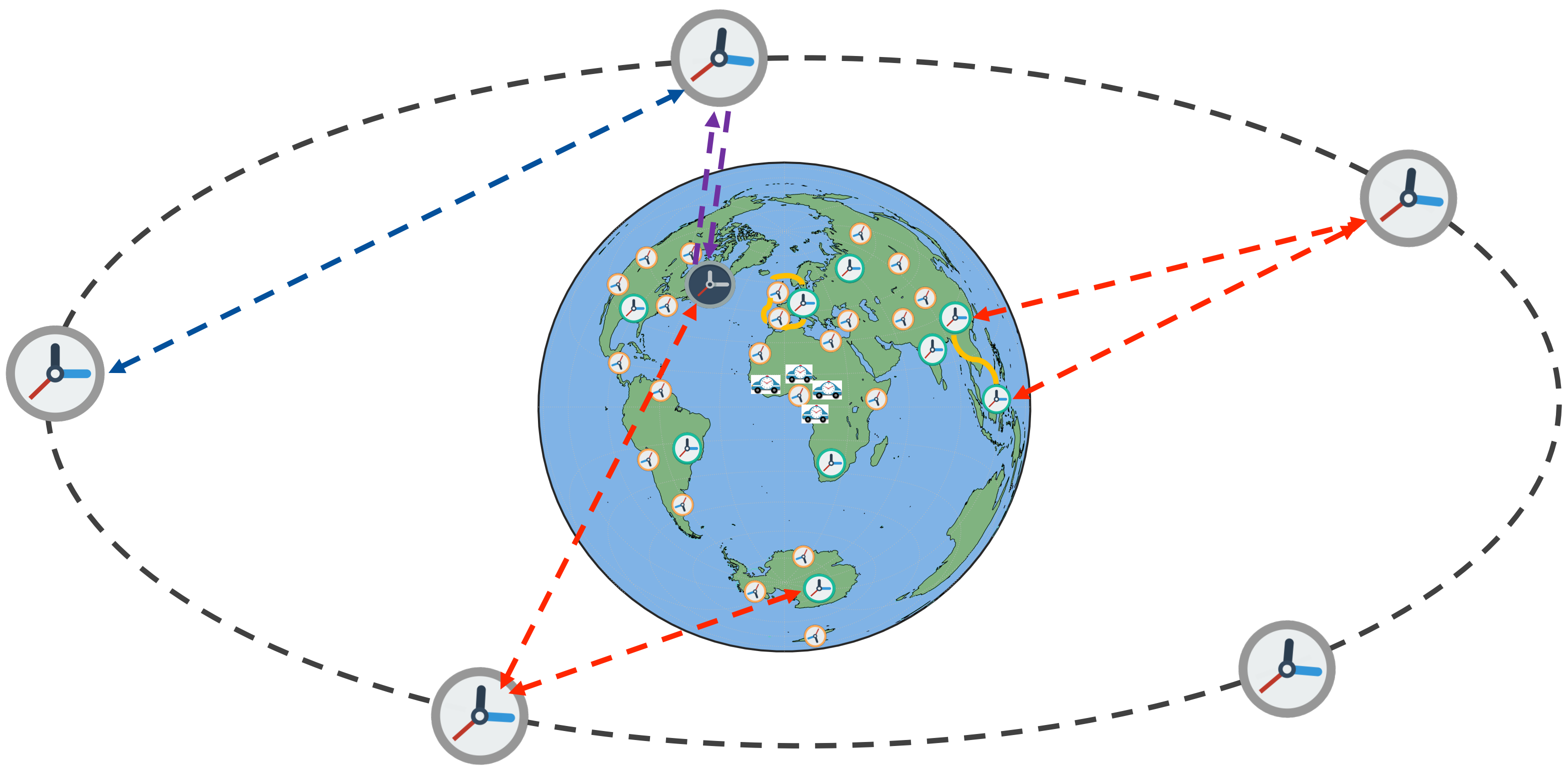
spaced clock W_S

datum clock W_0

core clock W_P or C_P

national clock W_P or C_P

transportable clock

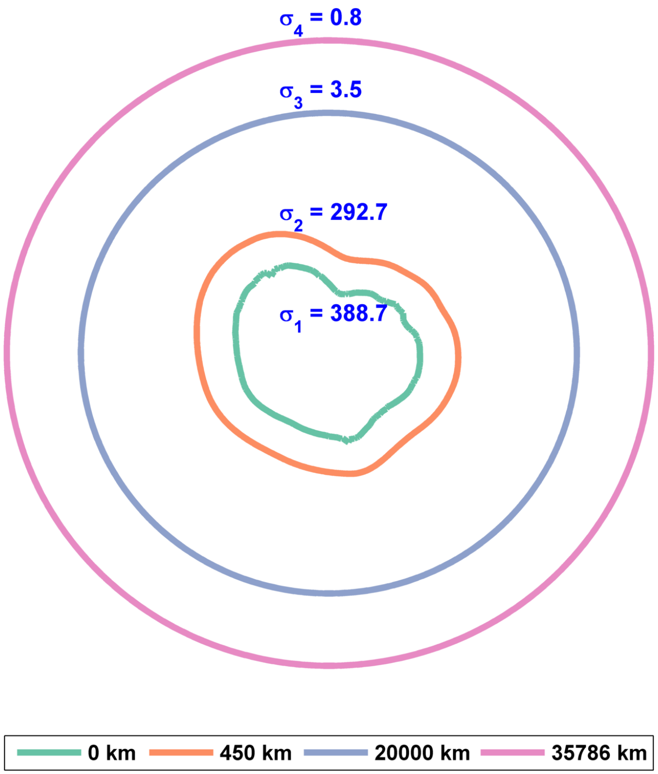


Clocks in space

The gravity potential field at different altitude:

- Earth surface: 0 km
- LEO: 450 km;
- MEO: 20000 km;
- Geostationary orbit: 35786 km.

The gravity potential field is more regular in a higher orbit, e.g., the geostationary orbit. Such a orbit might be a good choice for the space-based clocks.



Gravity potential above the equator

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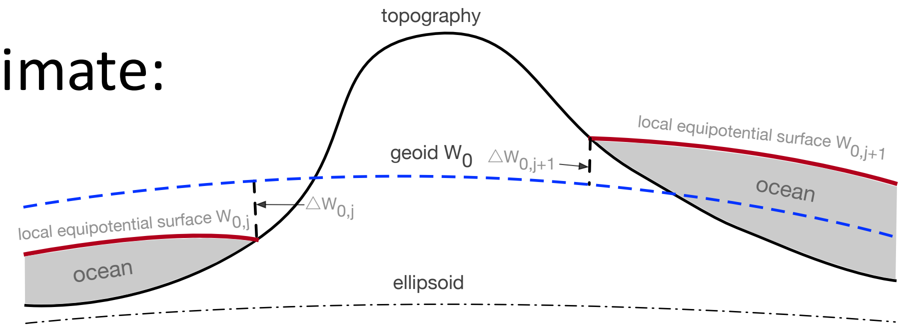
Height system unification

To realize the IHRS, one approach is to unify local height systems.

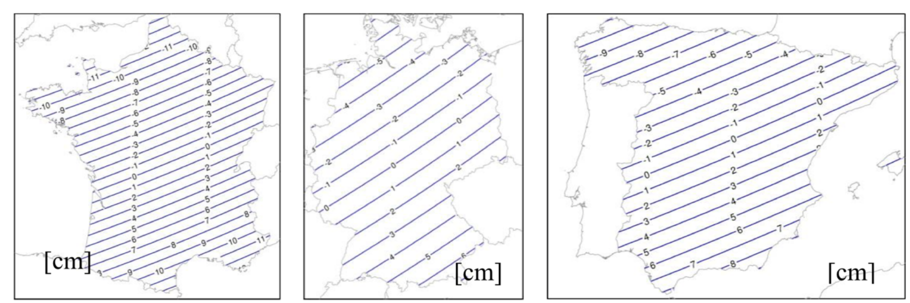
For the unification, we have to estimate:

- offsets between height datums;
- tilts along levelling lines.



Existing approaches for the unification:

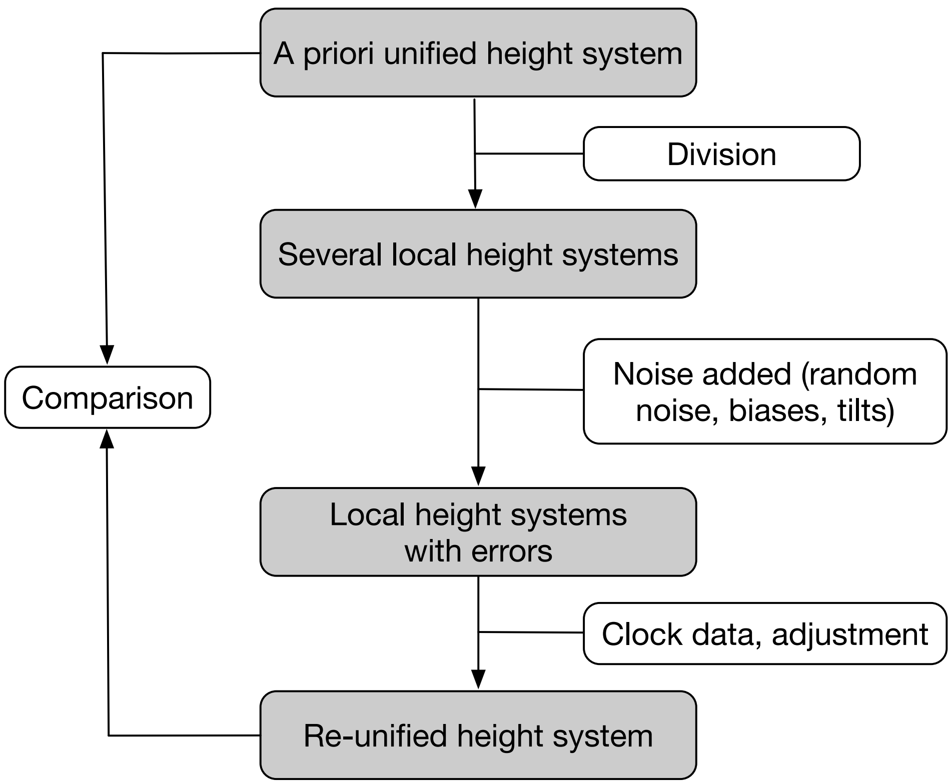
- Levelling + gravimetry;
- Oceanographic modelling;
- Modified GBVP.



France Germany Spain

Height system unification

We proposed to use clock networks for the height system unification, with the closed-loop simulator as:



Questions to be answered:

- how well can clock networks unify local height systems;
- how many clocks are required;
- how should the clocks be distributed;
- what is the effect of clocks' accuracy?

Height system unification

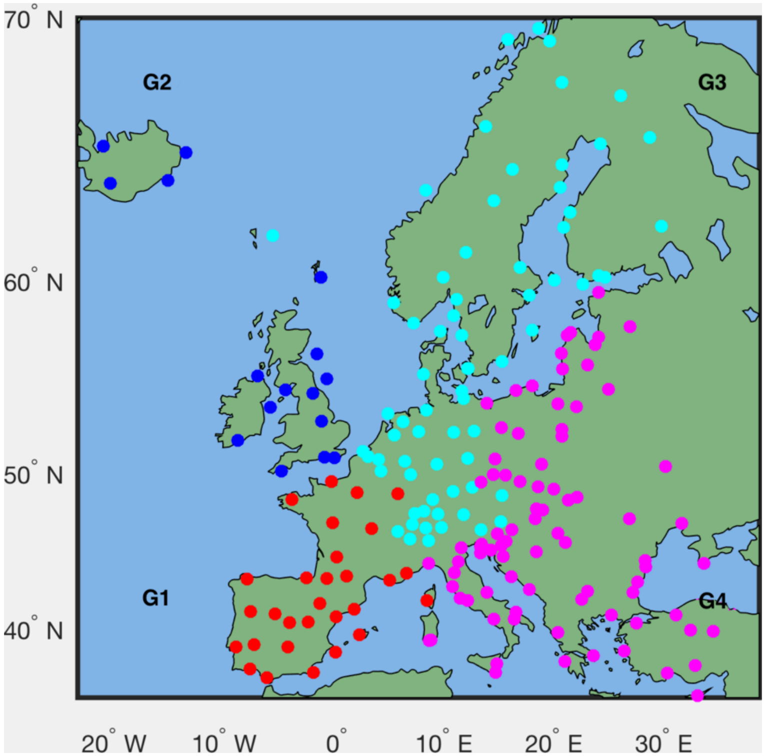
The a priori height system: EUVN/2000

Division:

- **G1**: Marseille (France)
- **G2**: Newlyn (UK);
- **G3**: Amsterdam (Nethelands);
- **G4**: Genova (Italy).

Number of points per group

	G1	G2	G3	G4	total
#	29	16	73	84	**202**



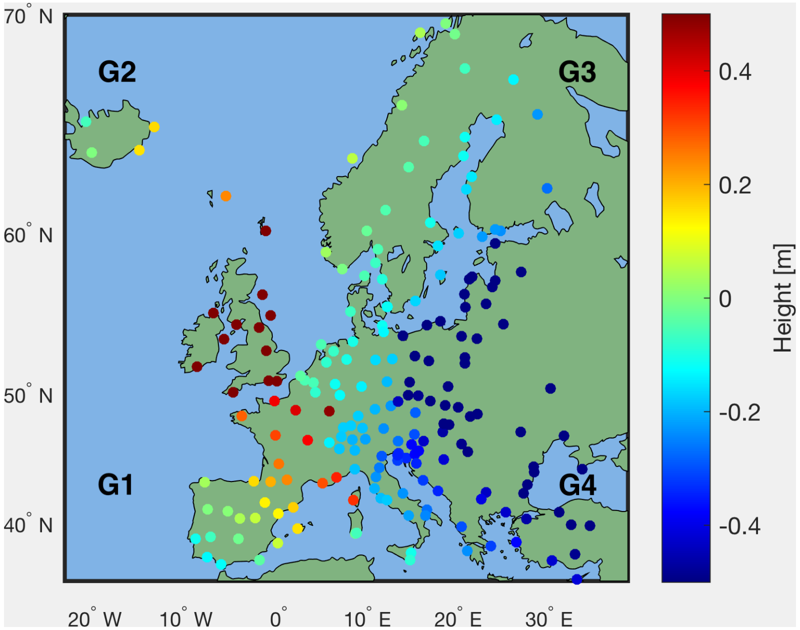
Height system unification

The introduced errors:

- levelling heights:
  - random errors: 1.0 cm;
  - offsets;
  - tilts;
- clocks: random errors (1.0×10^{-18})

Introduced offsets (unit: cm) and tilts (unit: cm/100km)

	G1	G2	G3	G4
offsets	-18.0	25.0	0	8.0
tilt in lat.	3.0	-2.0	1.5	-3.0
tilt in lon.	2.0	3.0	-1.5	-2.0

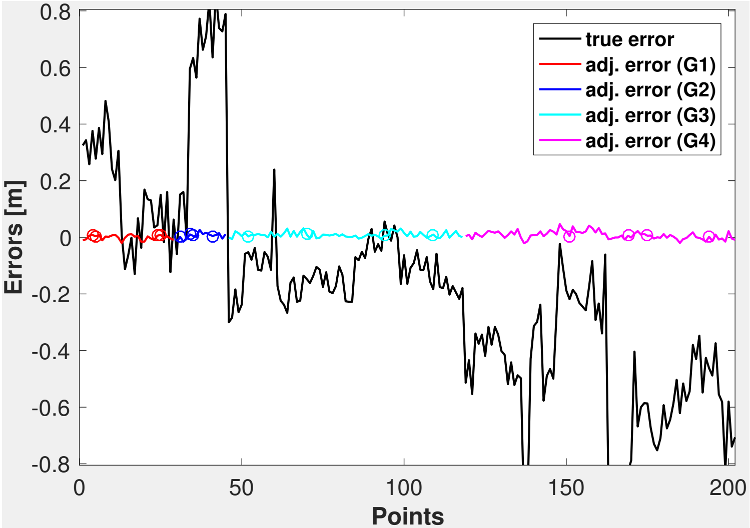


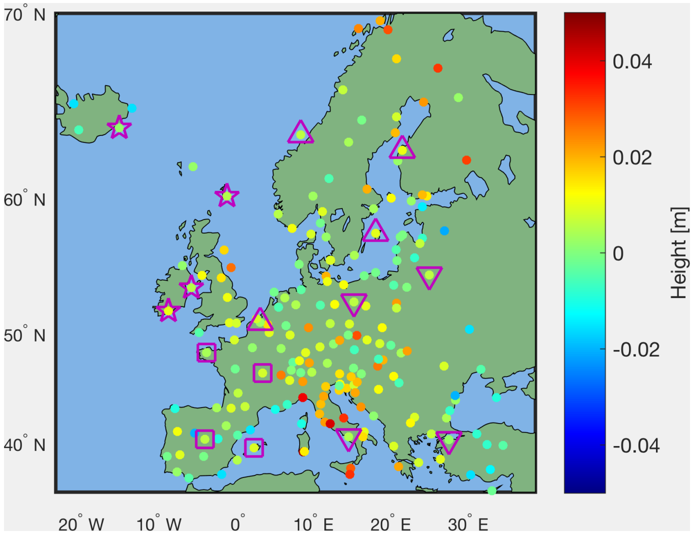
Height system unification

Four identical clocks are used in each local height system.

RMS of errors, unit in cm

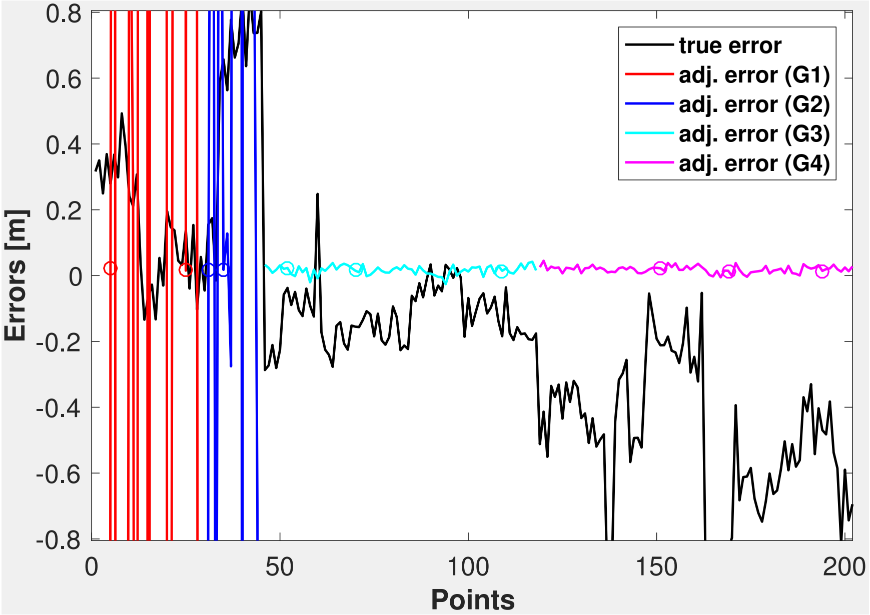
	G1	G2	G3	G4
true errors	22.81	62.29	15.36	53.65
adjusted errors	0.84	1.19	1.29	1.58

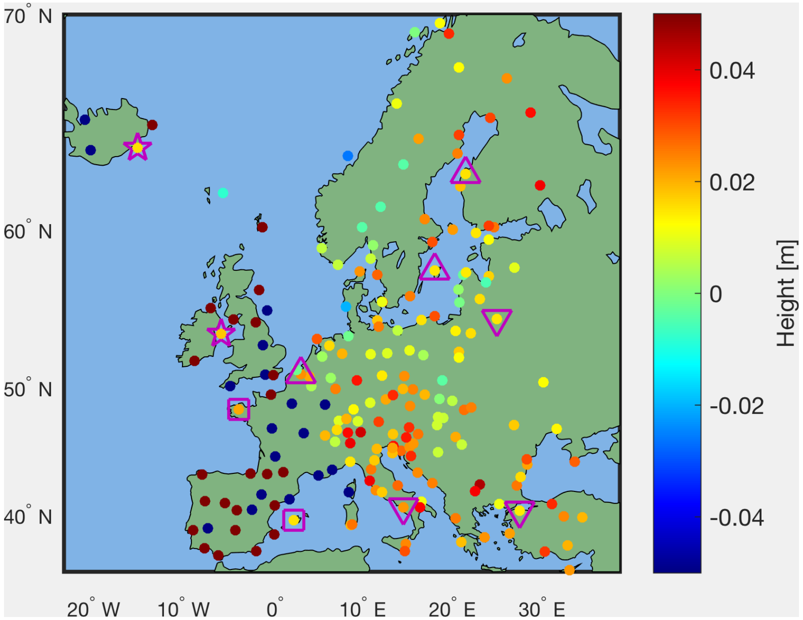




Height system unification

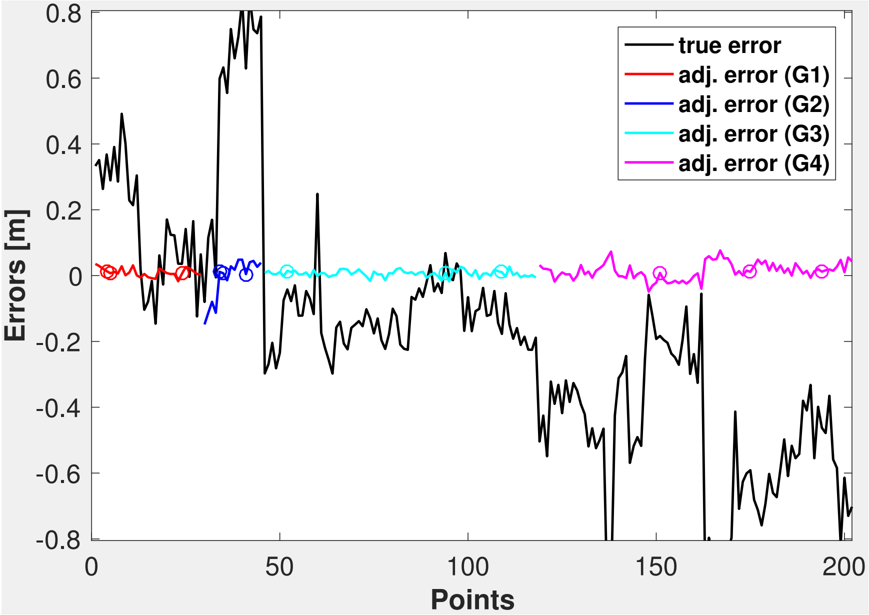
The number of clocks: **(2, 2, 3, 3)**

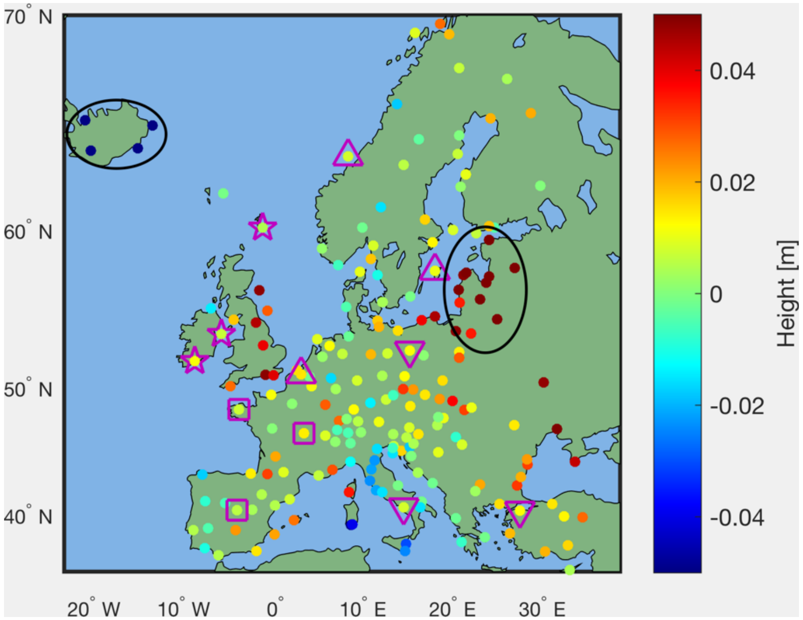




Height system unification

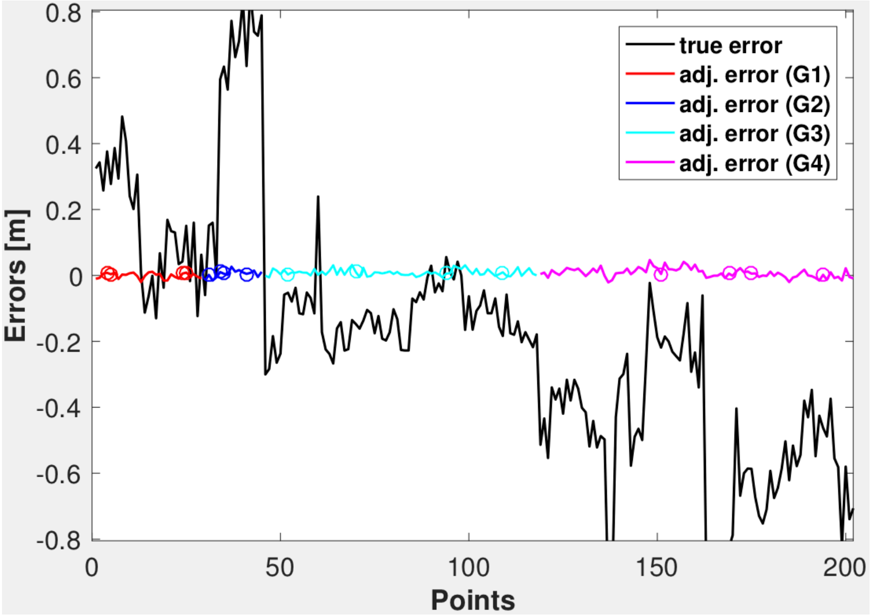
The number of clocks: **(3, 3, 3, 3)**

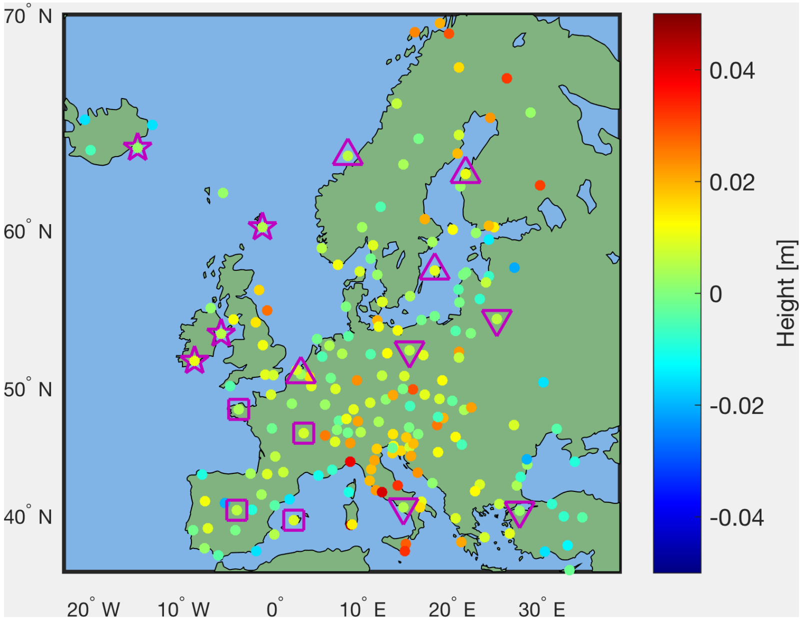




Height system unification

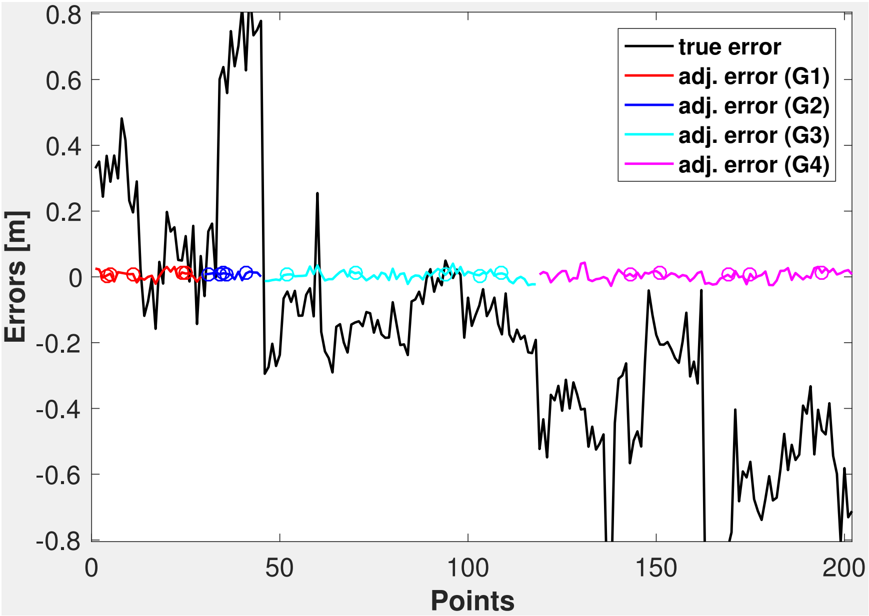
The number of clocks: **(4, 4, 4, 4)**

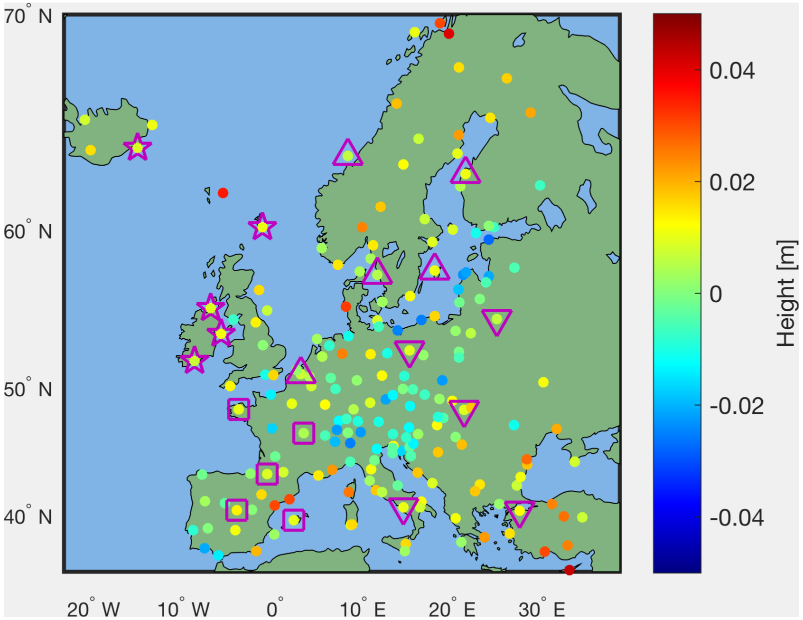




Height system unification

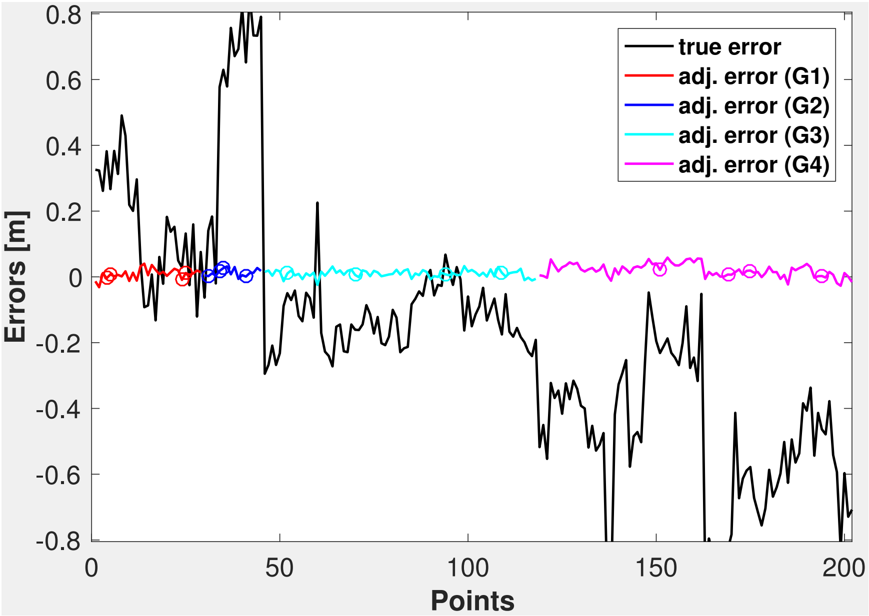
The number of clocks: **(5, 5, 5, 5)**

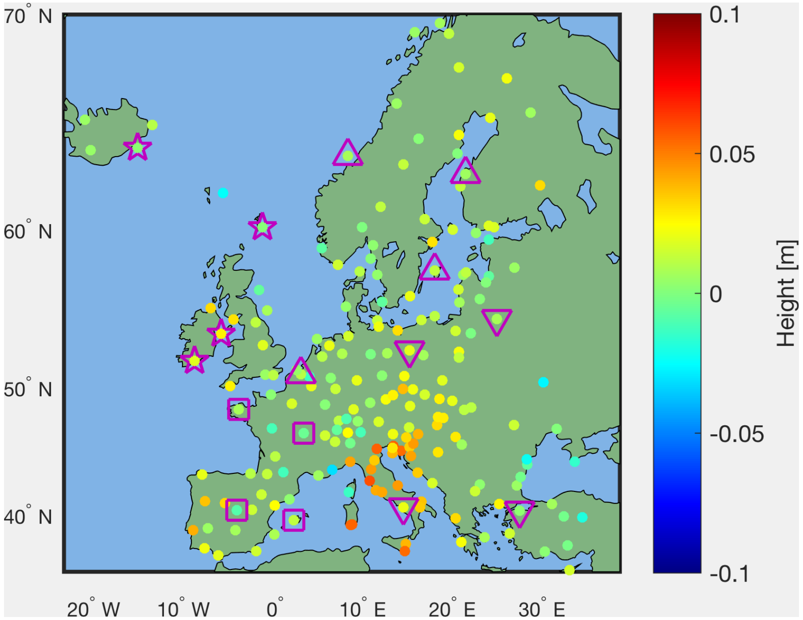




Height system unification

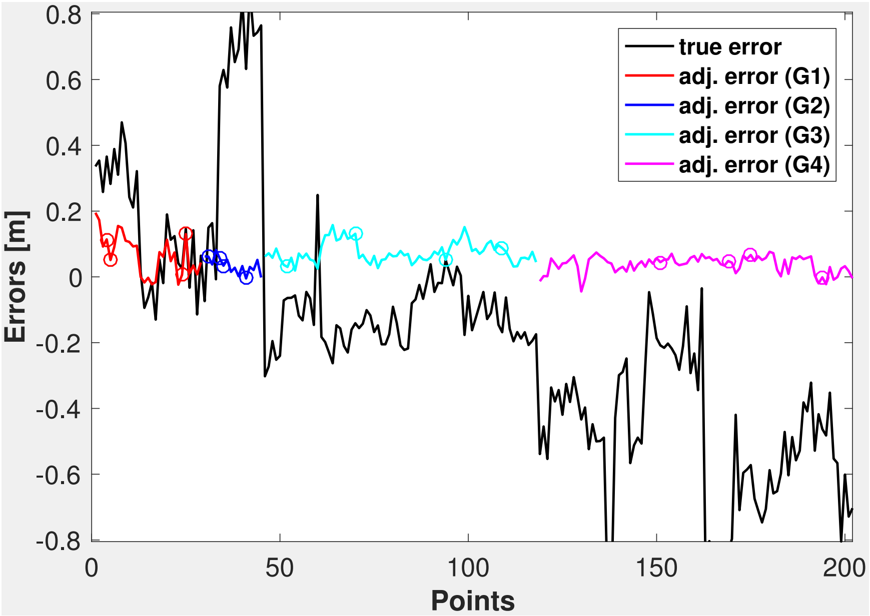
Clock's accuracy: 5.0×10^{-18}

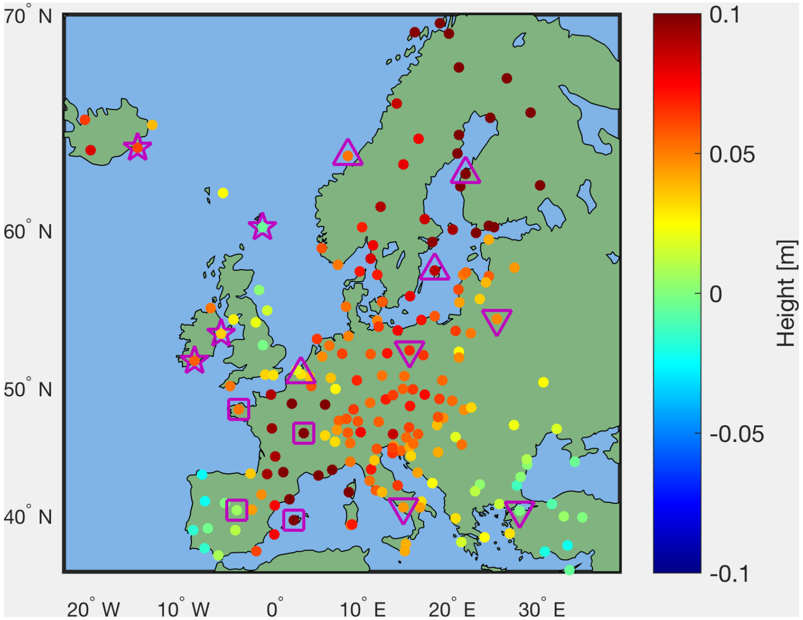




Height system unification

Clock's accuracy: 20.0×10^{-18}

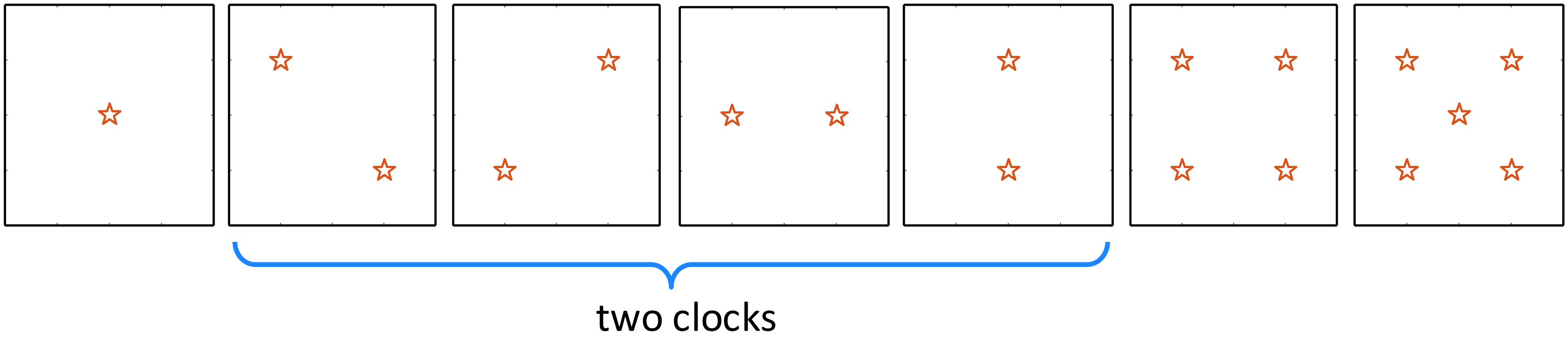




Height system unification

Distribution of clocks:

- offsets and tilts along the latitudinal direction;
- number of clocks: (2, 2, 3, 2);



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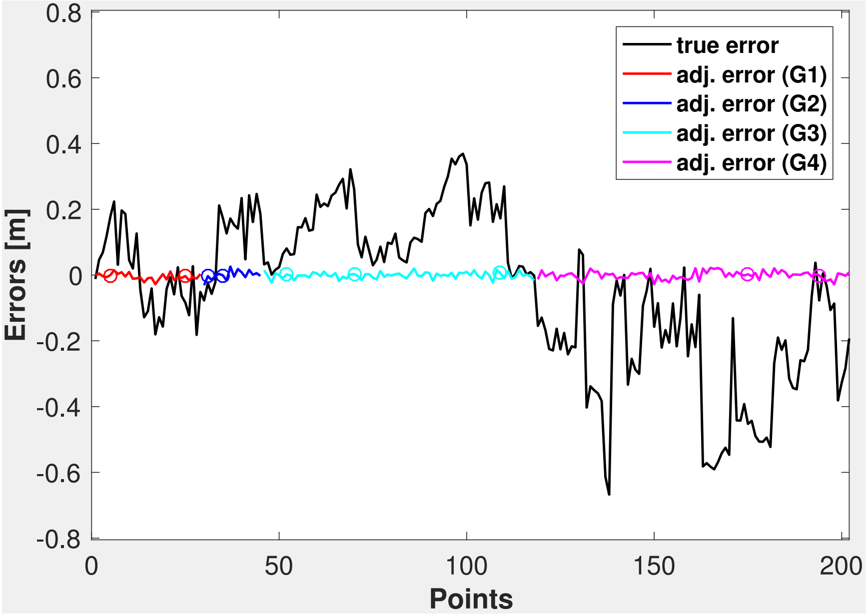
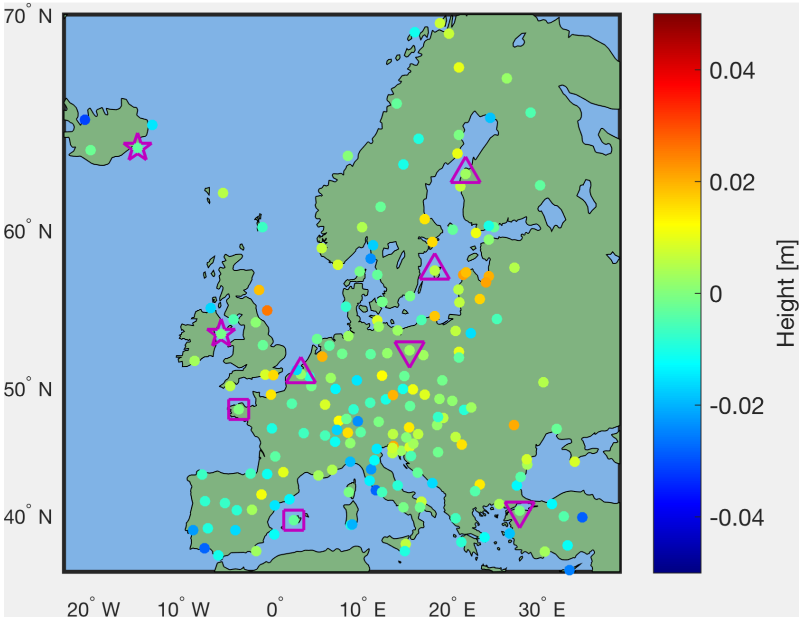


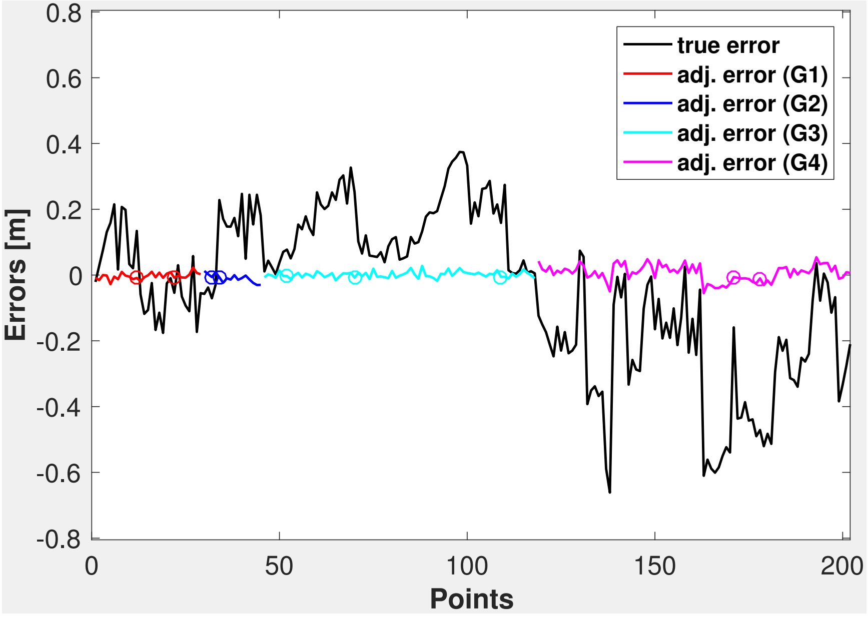


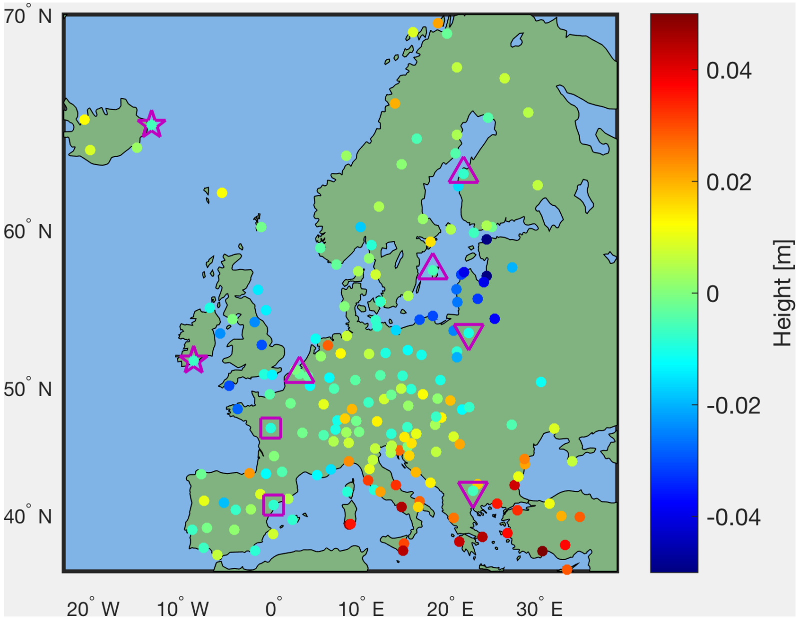
diagonal distribution

Height system unification

Distribution of clocks:

- offsets and tilts along the latitudinal direction;
- number of clocks: (2, 2, 3, 2);



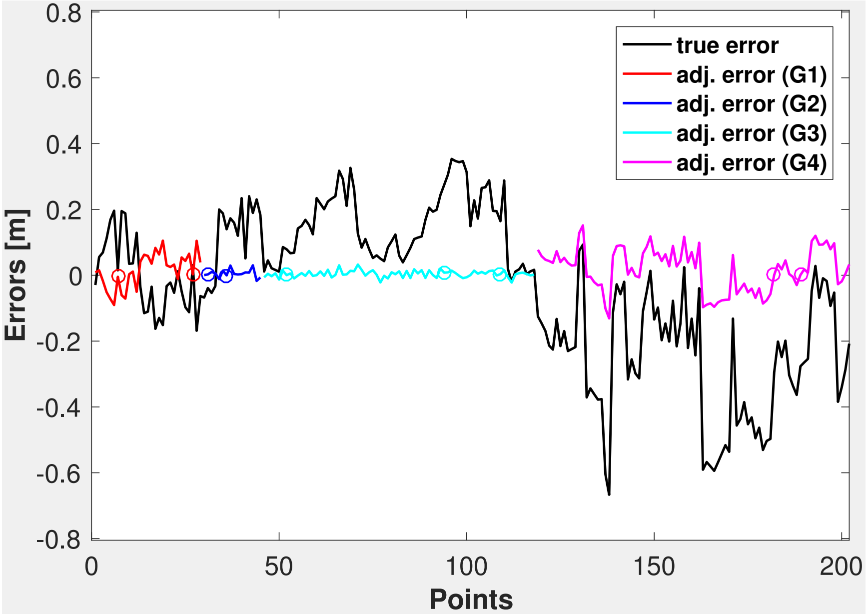


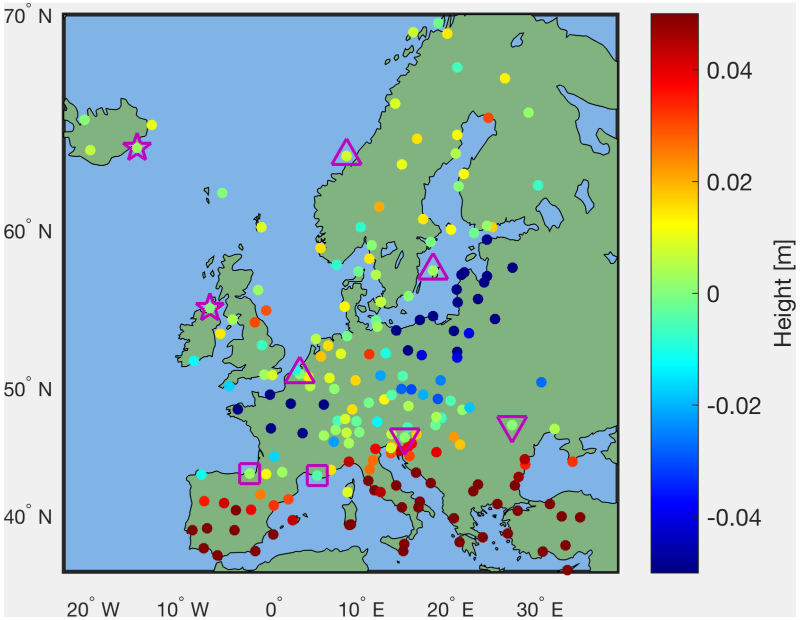
latitudinal distribution

Height system unification

Distribution of clocks:

- offsets and tilts along the latitudinal direction;
- number of clocks: (2, 2, 3, 2);





longitudinal distribution

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Conclusions

- A hybrid clock network might be well suit to realize a consistent, accurate and stable IHRS in the future:
  - datum, core and national clocks serve as the backbone of the IHRF;
  - transportable clocks can be used for the densification;
  - space clocks enable the links between clocks or used as space reference.
- The clock network can potentially be used to connect different regional height systems:
  - estimate offsets between height systems and tilts over levelling lines;
  - a few clocks in each region are sufficient;
  - clocks should be properly distributed so that the tilts can be detected;
  - clocks nowadays lack of accuracies for the unification, but they still show potential for unification at dm level.

Thanks for your attention!