Requirements for geodetic reference frames in global change research

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Outline

1. Introduction: Objectives of modern geodesy
2. Geodetic observations, models, parameters
3. Definition of geodetic reference systems
4. Requirements for reference frames in global change research
5. Realization of adequate geodetic reference frames
6. Use of reference frames in practice and future developments

1. Objectives of geodesy

"Geodesy is the science of the measurement and mapping of the Earth surface" **(Helmert 1880)**

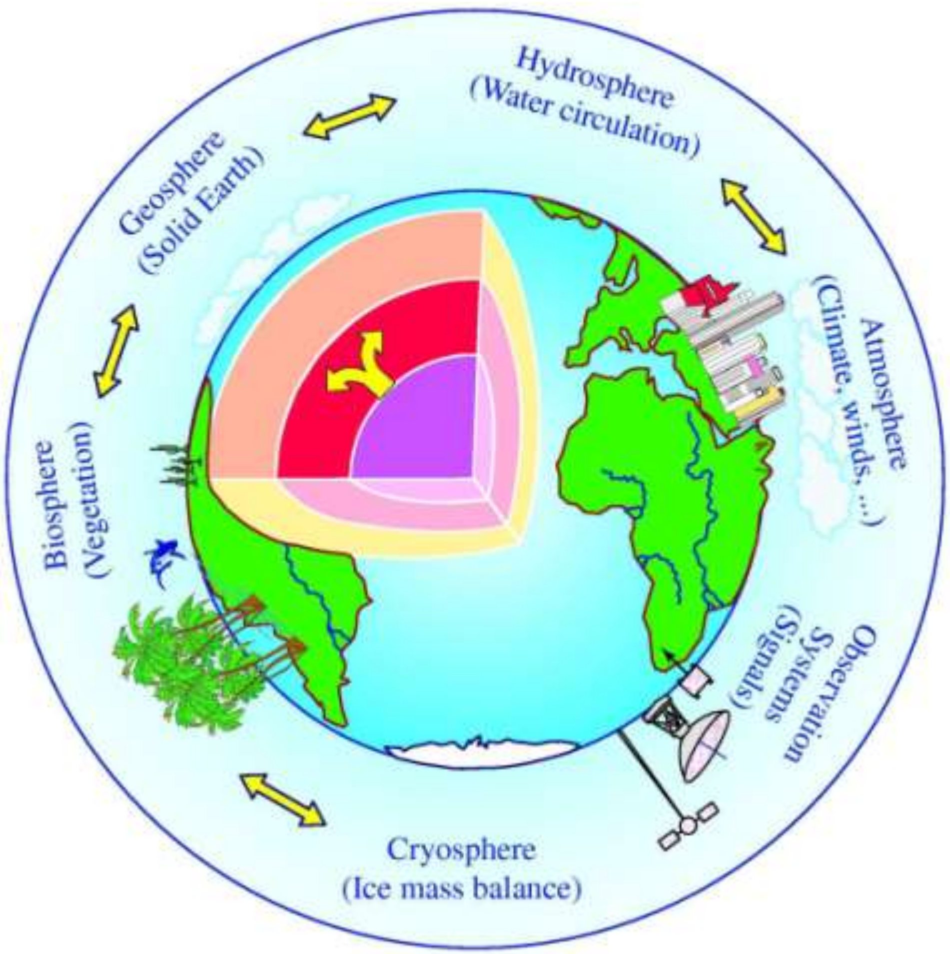
In fulfilling this objective, geodesy experienced the fact that the geometry and physics of the Earth surface are changing with time. The capability arose from the technical developments of

- applications of space techniques (astrometry and satellites),
- enormous achievements in data processing (computers),
- increasing accuracy of measurements (from [m] to [mm]).

As a consequence, we can no longer use stationary and static approaches (like Helmert), but we must apply kinematic and dynamic tools including all environmental factors affecting the measurements: solid Earth, fluid Earth and gaseous Earth.

This leads to the extension from *Earth surface* to *Earth system*.

1. Objectives of modern geodesy: Earth System research



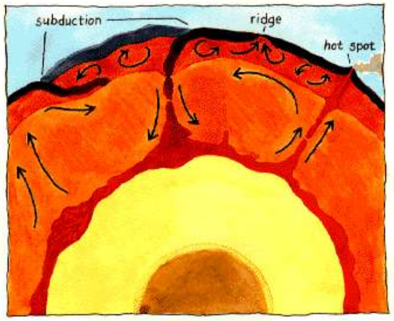
Components of the System Earth observable by geodetic techniques

Geodesy is capable of providing information on physical processes between the elements (components) of the Earth's system by observing

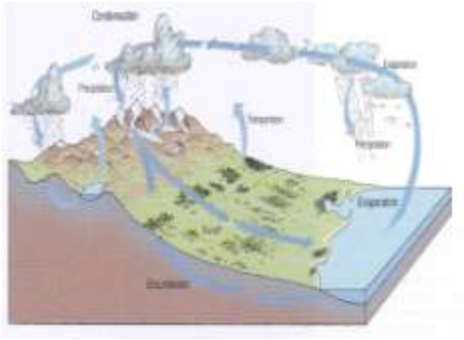
- deformation of the **solid Earth** (point positioning, surface scanning);
- **water circulation** in oceans, ice, atmosphere, solid Earth (satellite altimetry, atmosphere sounding, gravity field determination);
- **mass exchange** between the atmosphere, hydrosphere, geo-sphere, biosphere, cryosphere (Earth rotation and gravity field).

1. Objectives of modern geodesy: Earth System research

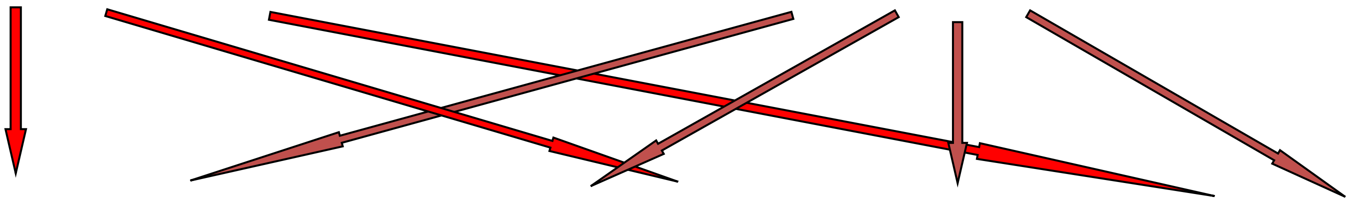
Mass transport in the solid, fluid and gaseous Earth, and geodesy



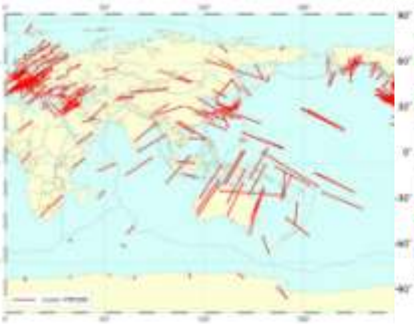
Convection
Subduction
Earthquakes
Volcanoes
Isostasy

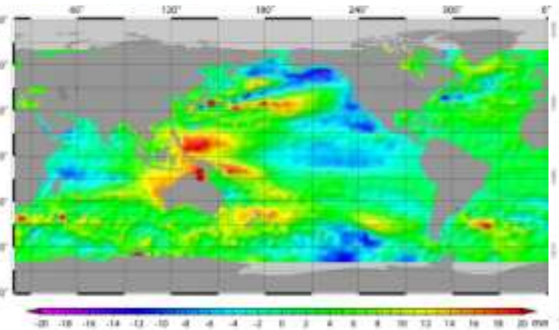


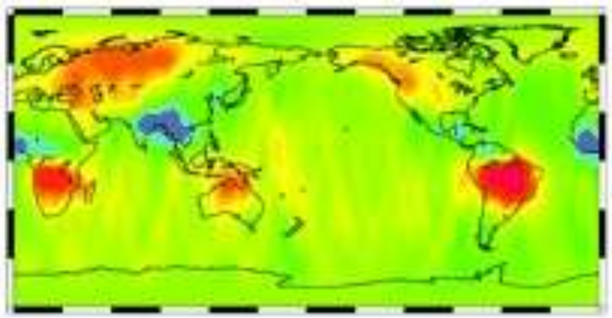
Precipitation
Evaporation
Storage, runoff
Currents
Deglaciation



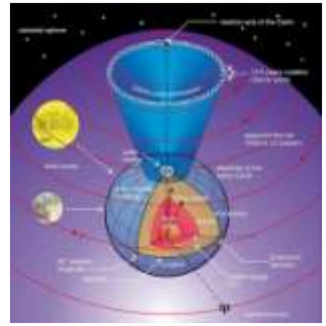
point motions | **sea surface change** | **polar motion, LOD** | **gravity variations**

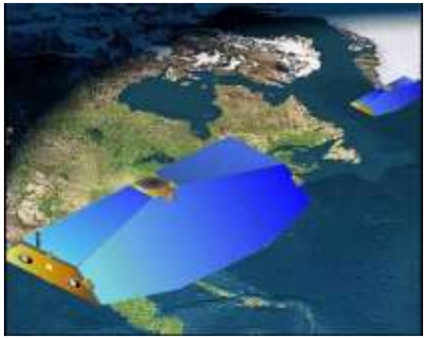






1. Objectives of modern geodesy: Earth System research





Geometry (positioning)

Earth rotation

Gravity field

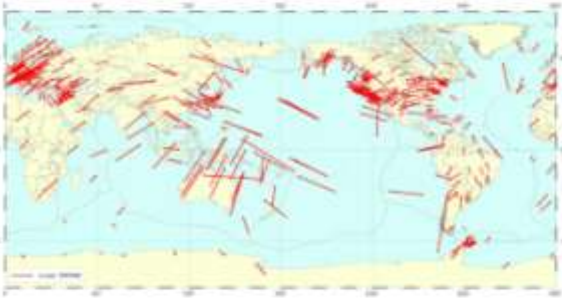
combine parameters

separate effects

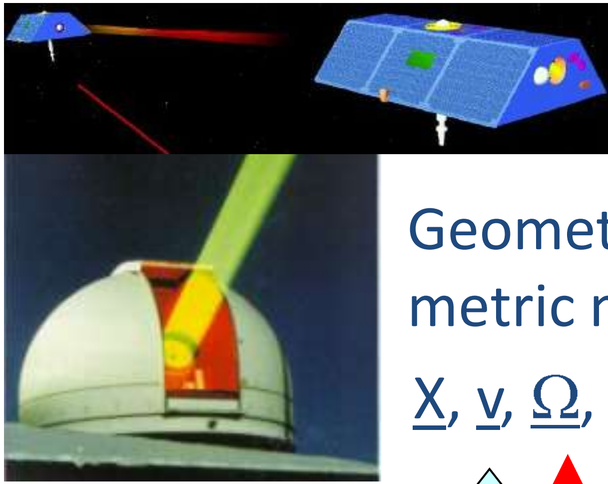
Solid Earth

Atmosphere

Hydrosphere



"Geodesy is the science of the measurement and the analysis of phenomena and effects of physical processes in the System Earth".



observation

Geometric, gravi-metric measuring

$\underline{X}$, $\underline{v}$, $\underline{\Omega}$, $\underline{C}_{n,m}$, $\underline{g}$

Reality

Rotation

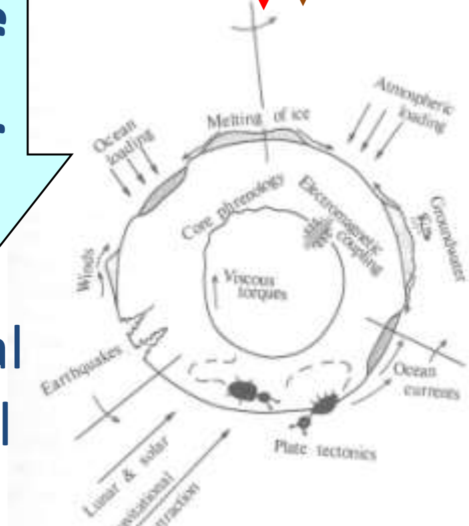
simplification

estimation

measures depend on the reality, parameters on models

$\partial\Omega/\partial t \neq \partial C_{2i}/\partial t$

Physical model

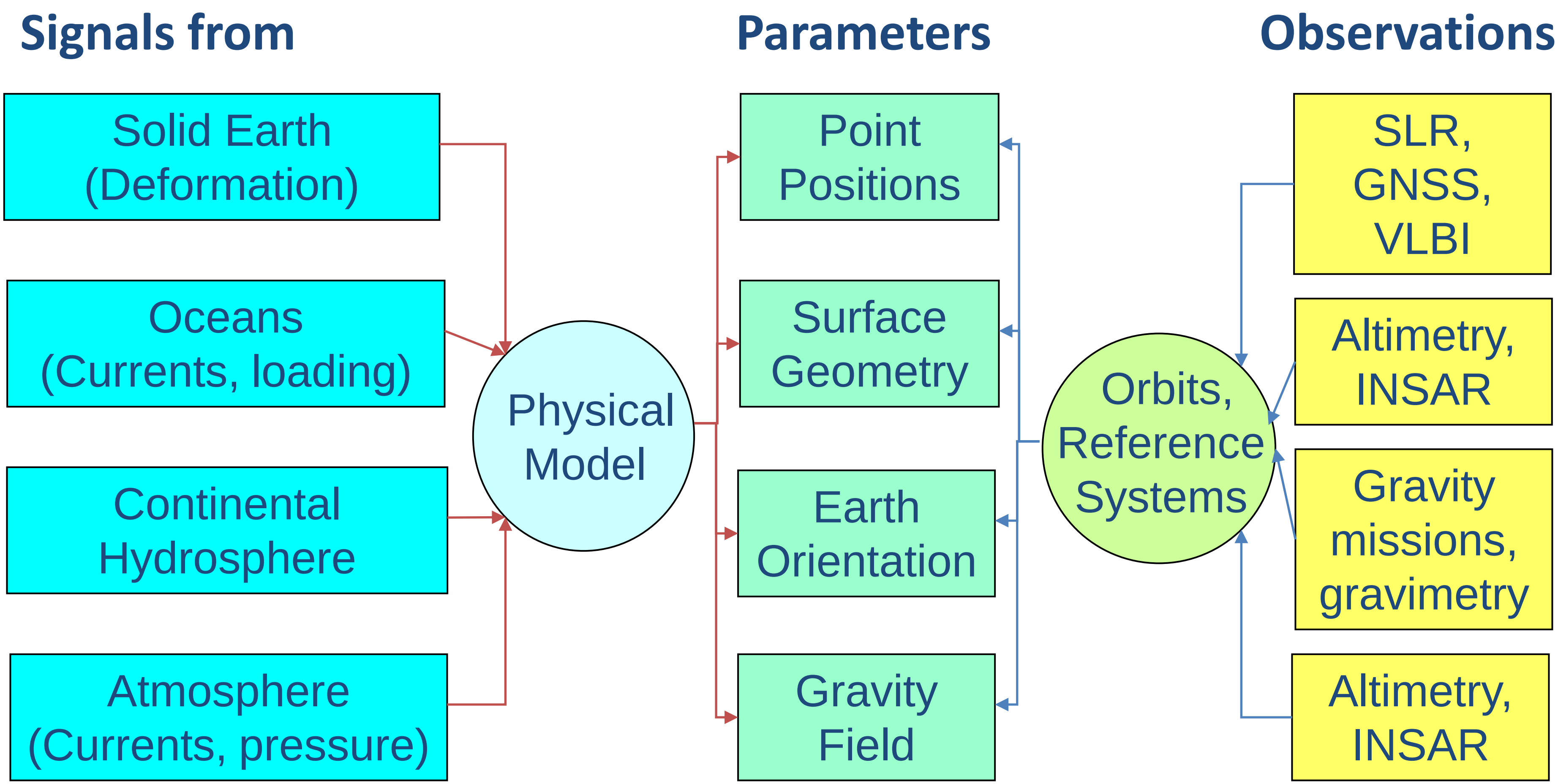


Parameterization

Mathematical approach

$\underline{X}$, $\underline{v}$, $\underline{\Omega}$, $\underline{C}_{n,m}$, $\underline{g}$ = f(mod)

2. Geodetic observations, models, parameters



Different signals, identically modelled provide parameters to be observed by different techniques using **consistent** satellite orbits and reference systems.

Examples of processes affecting parameters

Process	acts as	and influences
Core/mantle convection	- plate driving force - mass displacement - angular momentum	- point position - gravity field - Earth rotation
Ocean currents	- loading force - angular momentum - mass displacement	- point position - Earth rotation - gravity field
Precipitation	- angular momentum - groundwater storage - water flow-off	- Earth rotation - gravity field - sea surface
Atmospheric currents	- loading forces - pressure - angular momentum	- point position - Earth surface - Earth rotation

Examples of parameters affected by processes

Parameter	is affected by	of processes in
Point position	- tectonic motion - loading effects	- solid geosphere - hydrosphere, atmosphere
Surfaces	- deformation - water flow-off - air pressure	- solid geosphere - hydrosphere - atmosphere
Earth rotation	- winds, air pressure - ocean currents - deformation	- atmosphere - hydrosphere - solid geosphere
Gravity field	- geodynamics - ground water - deformation	- geosphere - hydrosphere - solid geosphere

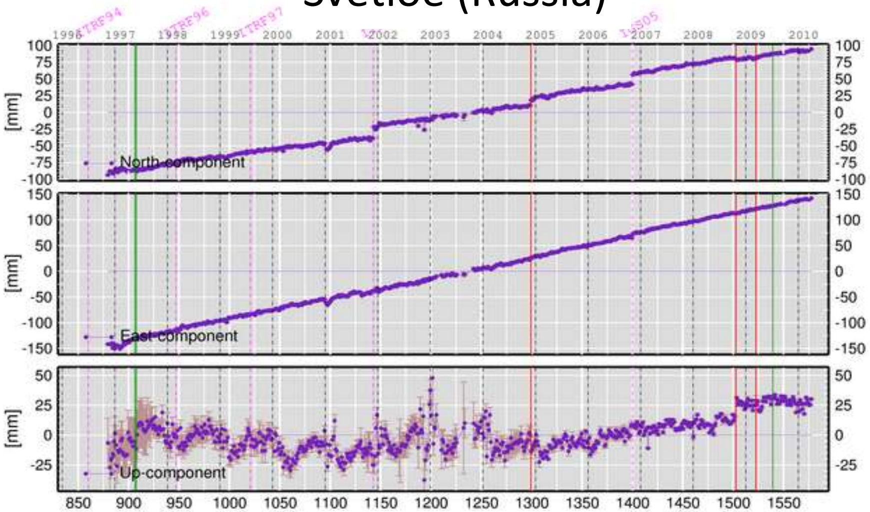
Examples of non appropriate modelling

Parameter	(mis-)modelled by	is affected by
Point position	- simple kinematic reference frame (constant velocities)	- non-linear (seasonal) variations
	- global loading models	- regional rheology
Ocean surface	- dynamic satellite methods using stationary gravity	- gravity variations
	- positioning techniques	- non-linear station motions
Earth rotation	- Earth system mass models	- missing mass balance
	- positioning / satellite orbits	- tracking station motions
Gravity field	- terrestrial gravity	- reference frame IGSN
		- height system errors

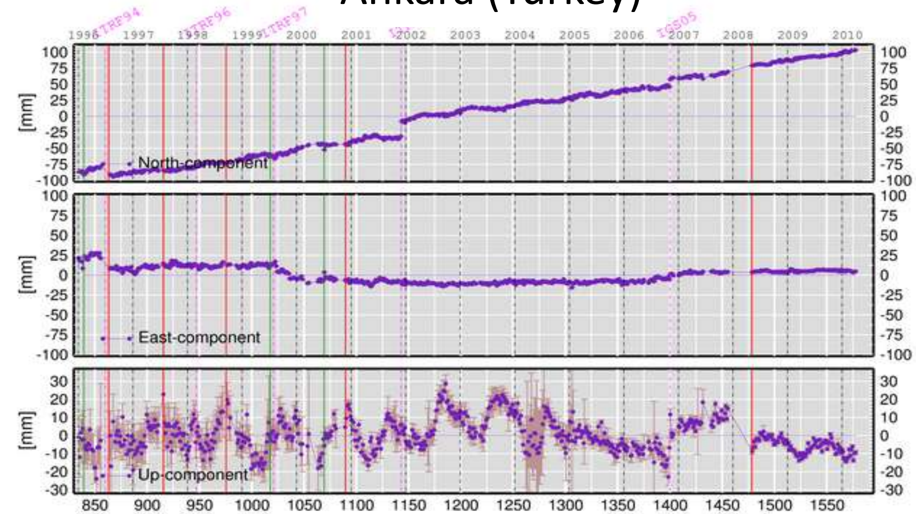
2. Geodetic observations, models, parameters

Non-linear behaviour: true motions and reference frame variations

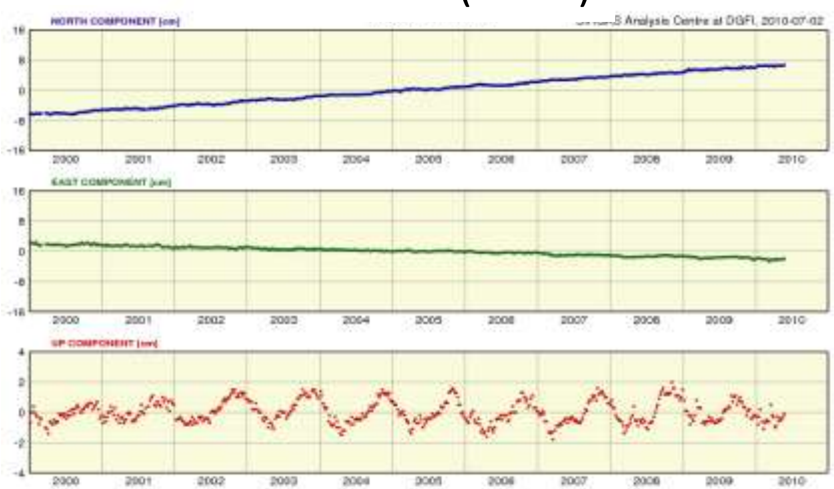
Svetloe (Russia)



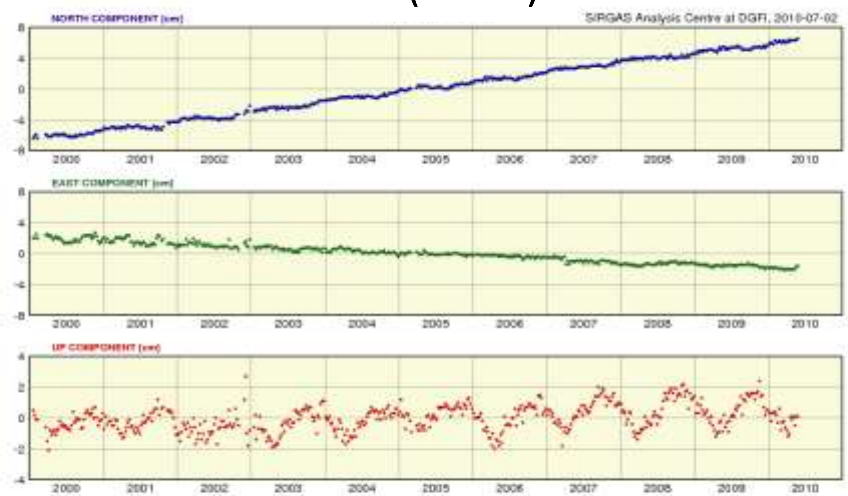
Ankara (Turkey)



Brasilia (Brazil)



Cuiaba (Brazil)



3. Definition of geodetic reference systems

A geodetic reference system must define in an unequivocal way

- all parameters necessary for the determination and representation of geodetic quantities (geometric, gravimetric);
- fundamental physical constants for appropriate computations;
- coordinate systems for Earth and space parameters (origin, orientation, scale unit);
- physical models for reduction of well-determined disturbances (only those must be reduced which are known with better accuracy than the geodetic observations);
- conventional models for reduction of undesirable effects in the geodetic observations for which the parameters shall be estimated in the adjustment procedure;
- any other conventions affecting the parameters to be estimated.

Necessary constants and conventions

- Geocentric gravitational constant (GM)
- Speed of light (c)
- Time system (TCG)
- Tide system (zero tide)
- Relativity models
- Terrestrial reference system (origin, orientation, scale)
- Kinematic reference system (consistent with Earth rotation)
- Inertial (celestial) reference system (origin, nutation)
- Gravimetric reference system (absolute gravity)
- Reference sea surface (W_0)
- Reference gravity model (global, regional)
- Reduction models (ionosphere, troposphere, topography)
- Satellite orbit reduction models (tides, radiation, pressure, …)

Definition of the International Terrestrial Reference System (ITRS)

The ITRS is defined primarily as a geocentric, metric system, i.e.,

- The origin is physically fixed in the Earth centre of mass (geocentre);
- The orientation is conventionally fixed in the pole position 1984,0;
- The scale is given by the metre convention;
- The kinematic system is fixed by the zero-rotation of the Earth crust.

Definition of the European Reference System (ETRS)

The ETRS is defined as a system moving with the Eurasian plate, i.e.,

- it is originally not consistent with the reference system of satellite orbits, which are given in ITRS. It has to be transformed!

Definition of the Latin American Reference System (SIRGAS)

SIRGAS is defined identical with, as a densification of the ITRS, i.e.,

- its coordinates refer to a reference epoch with constant velocities.

Frequent misunderstandings in geodetic reference systems

Origin (geocentre): Positioning techniques cannot determine the geocentre, but they need a well-defined origin (X_0, Y_0, Z_0) fixed independently, e.g. by the gravity field (C_{11},S_{11},C_{10} = 0) used in satellite orbit determination.

Orientation: Positioning techniques do not determine the Earth rotation but reference frame rotations (ω_X, ω_Y, ω_Z).

Tensor of inertia: C_{20},C_{21},S_{21},C_{22},S_{22} derived from dynamic satellite methods are affected by motions of reference tracking stations.

Kinematic reference: Station velocities from positioning techniques are correlated with Earth rotation parameters.

Consequences

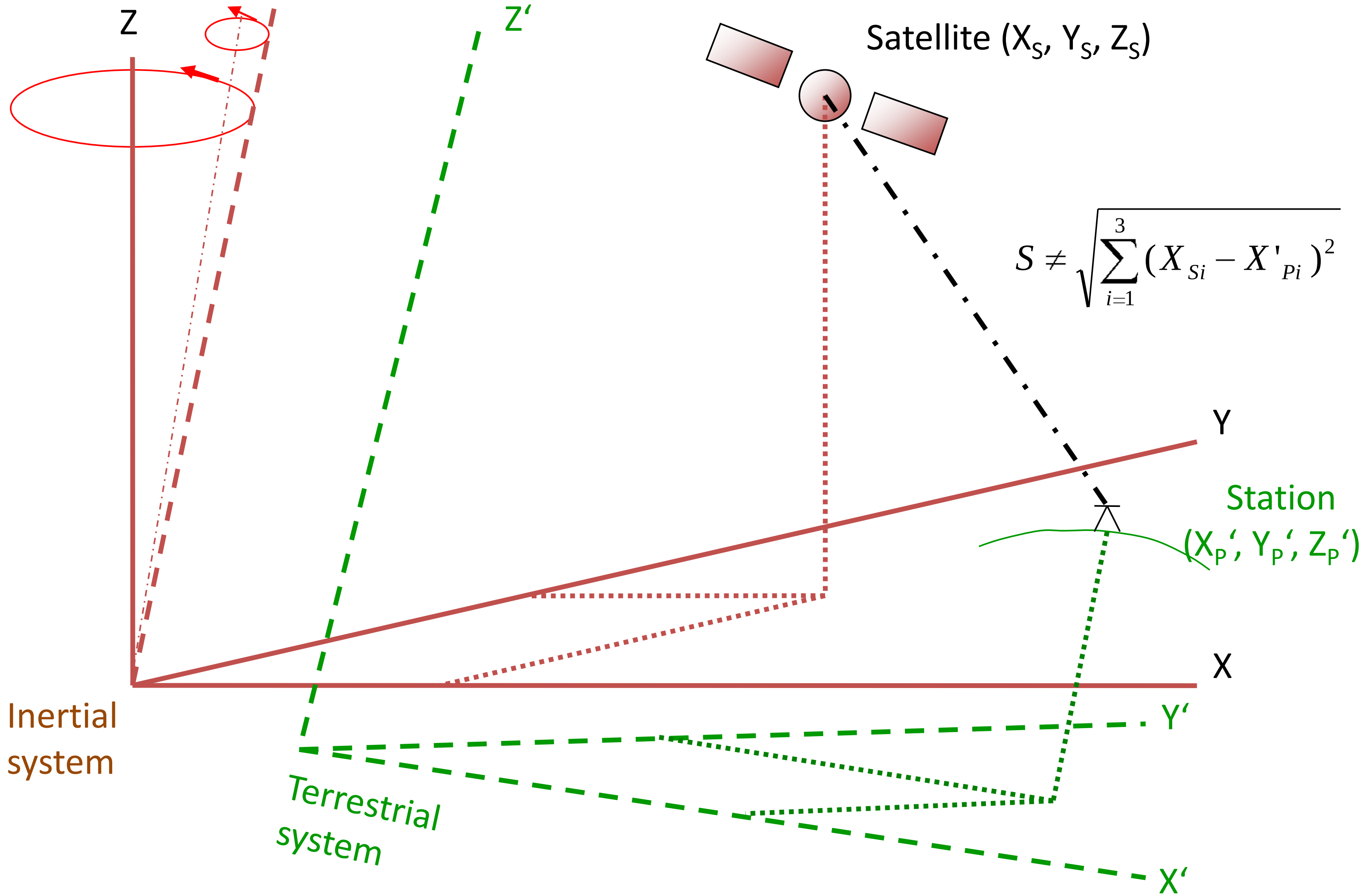
Reference systems have to be realized using geometric (positions, rotations) and gravimetric data consistently in a joint procedure.

Example inconsistencies of geometry – gravity reference system

Inconsistency	Geometry	Gravity
Reference frame	ITRF (identical WGS)	Variable
Definition of origin	Centre of network $\underline{X}_0$	Centre of mass $\underline{C}_{1i} = 0$
... of orientation	Rotation axis: $\underline{X}_P$, UT1	Axis of inertia $\underline{C}_{2i}$
... of scale	Speed of light: c	Geocentric const GM
Models for tides	Tide free	Zero tide
... for deformation	Geometric only	Dynamic (masses)
Loading effects	Ocean loading reduced Atmosphere loading in general not reduced	Ocean loading not re. Atmosphere masses reduced in satellites

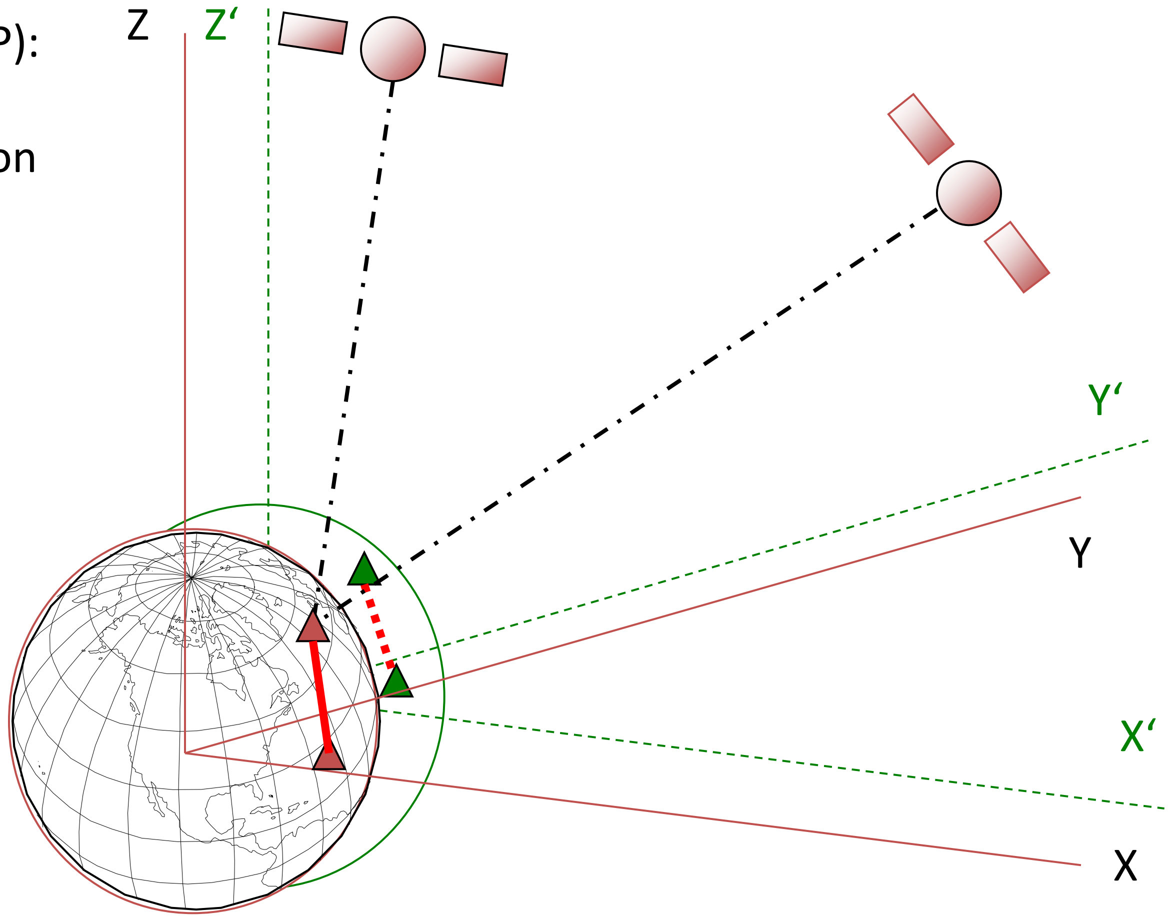
→ Reference systems for geometry and gravity are not identical

Basic requirement: Identical for orbits and station coordinates



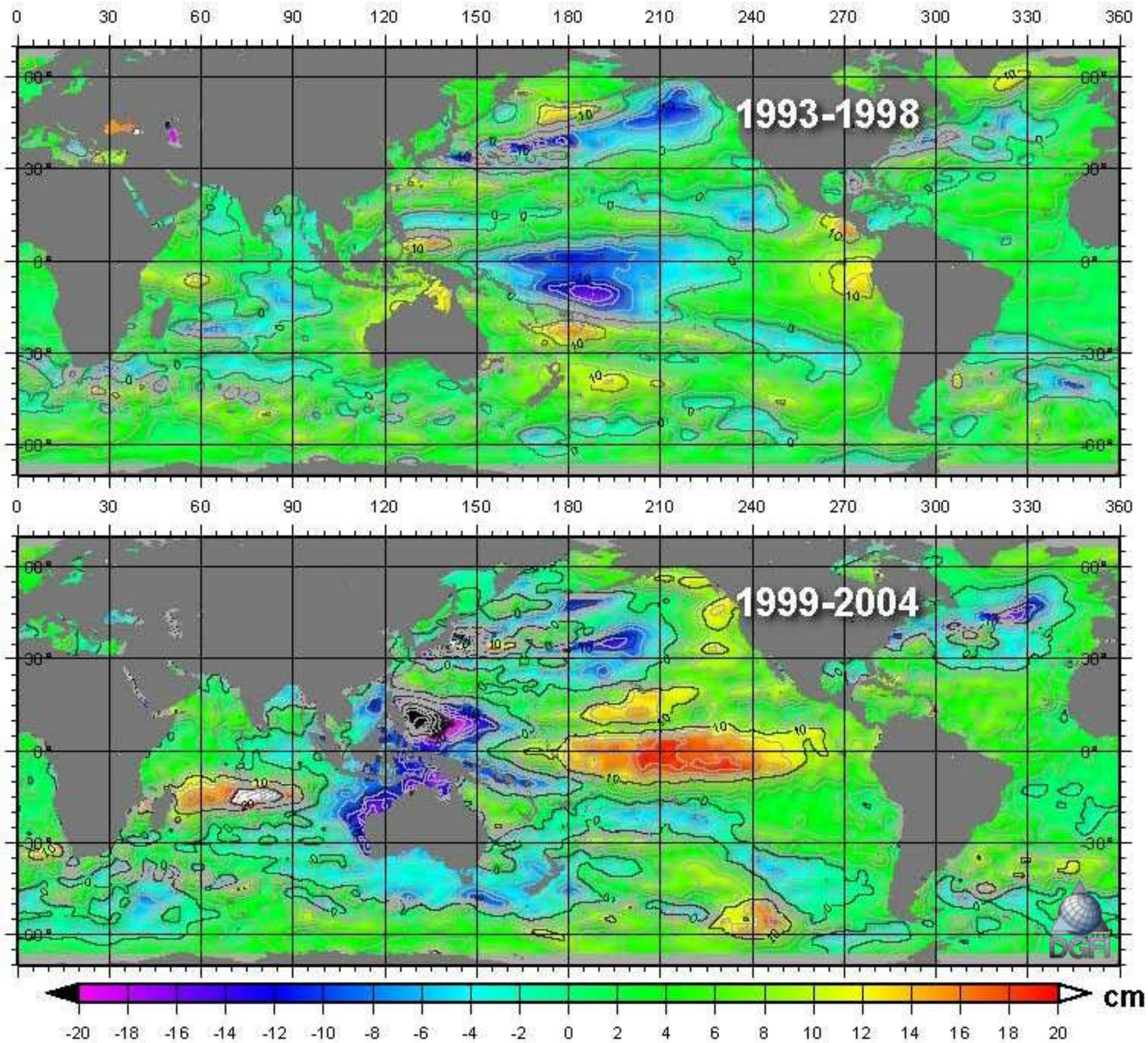
Errors when using different reference systems

1. Absolute positioning (PPP): System differences enter completely into the station coordinates.



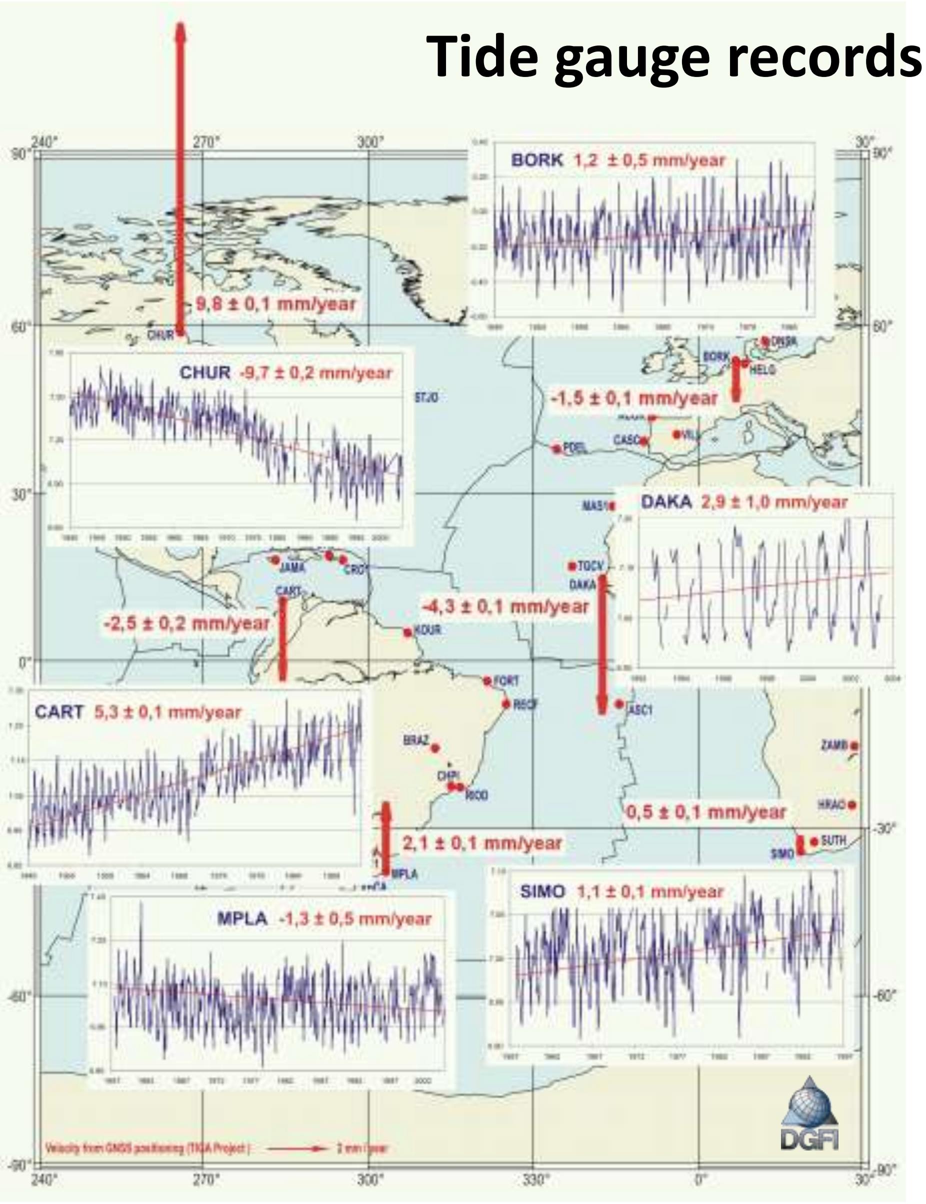
2. Relative positioning (differential):

A scale factor of ~ 2 ... 3 · 10^{-7} per metre diference enters into all baselines (0,25 mm/km; i.e. for moving Eurasian plate since 1989: 0,4 m ≈ 0,1 mm/km)



Most demanding requirement is for monitoring sea level changes

There is no equal rise in all regions, but there are large geographical differences of sea level rise and fall.

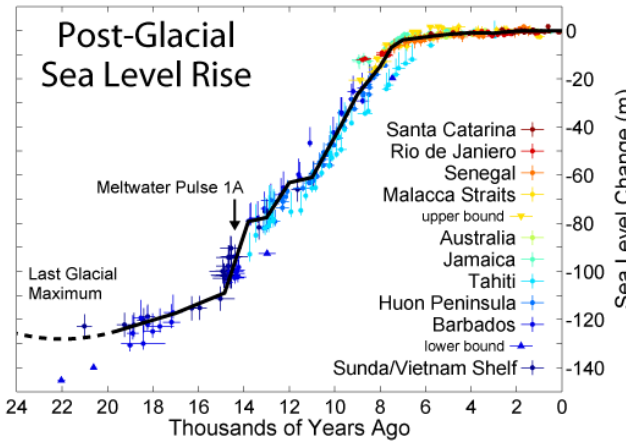


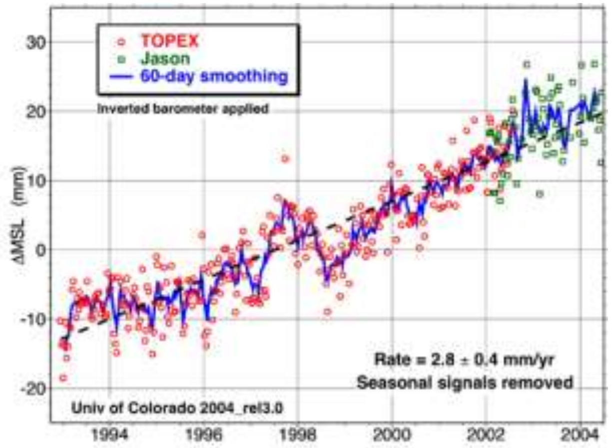
Tide gauge records provide the sum of sea level changes and vertical motions of the tide gauge: Precise GNSS monitoring of heights in long-term stable reference frame is required.

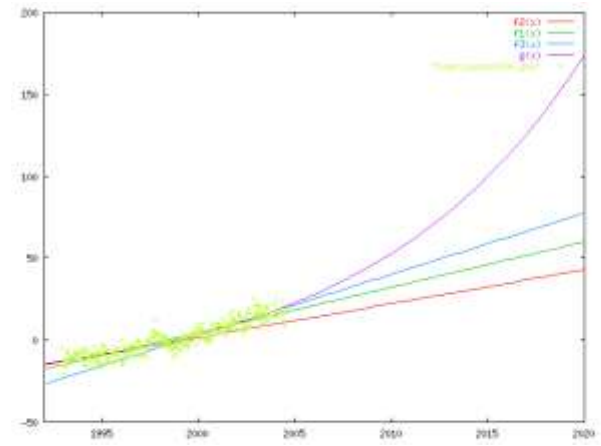
Examples [mm/a]:

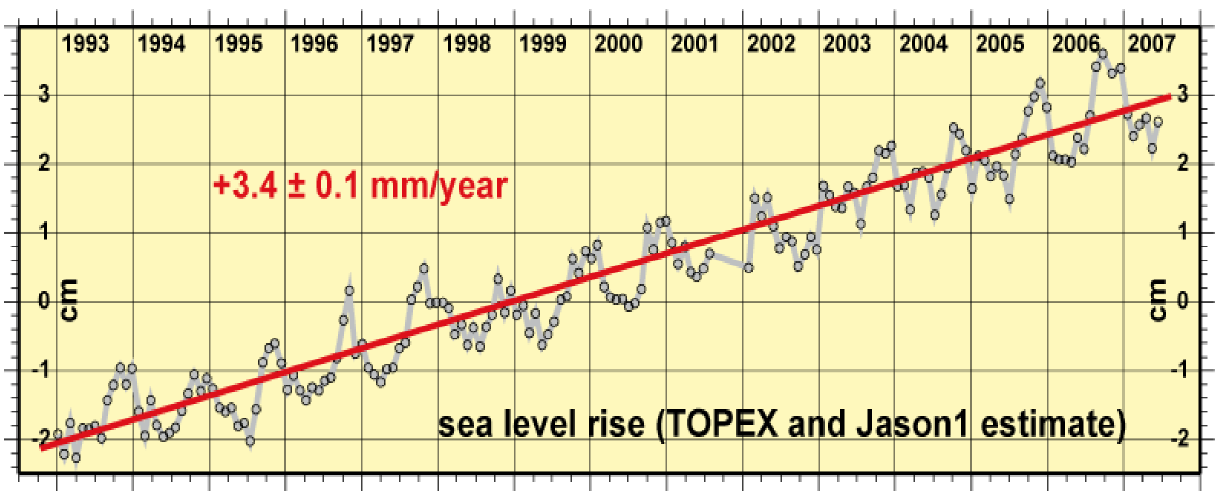
Station	Tide Gauge	GPS	Sum
CHUR	-9,7 ± 0,2	9,8	0,1
BORK	1,2 ± 0,5	-1,5	-0,3
DAKA	2,9 ± 1,0	-4,3	-1,4
CART	5,3 ± 0,1	-2,5	2,8
MPLA	-1,3 ± 0,5	2,1	0,8
SIMO	1,1 ± 0,1	0,5	1,6
a/v	-3,2 ± 6,2		0,6

Historical, present-day and forecasted sea level change









Sea level change is primarily caused by holocene deglaciation. To see anthropogenic acceleration, we need ± 0,1 mm/a precision.

5. Realization of reference frames

Requirement: Long-term stable, consistent for geometry and gravity

- Origin = geocentre

= Earth centre of mass

$$X_0 = \iiint X \, dm / M$$
$$Y_0 = \iiint Y \, dm / M$$
$$Z_0 = \iiint Z \, dm / M$$

Spherical harmonics of the Earth gravity field:

$$C_{11} = \iiint X \, dm / a M$$
$$S_{11} = \iiint Y \, dm / a M$$
$$C_{10} = \iiint Z \, dm / a M$$

Using a gravity field model with $C_{11} = S_{11} = C_{10} = 0$ in satellite orbit determination fixes the origin always and unequivocally in the geo-centre, there is no degree of freedom for the position of the origin.

The geocentric ephemeris are transferred to terrestrial coordinates by distance measurements (e.g., SLR). Range differences (GNSS) eliminate the relation to the geo-centre to a great extend.

Coordinate transformation between reference stations superposes a constraint, i.e., the origin of the reference system is re-defined from the centre of mass to the centre of the reference frame.

5. Realization of reference frames

Requirement: Long-term stable, consistent for geometry and gravity

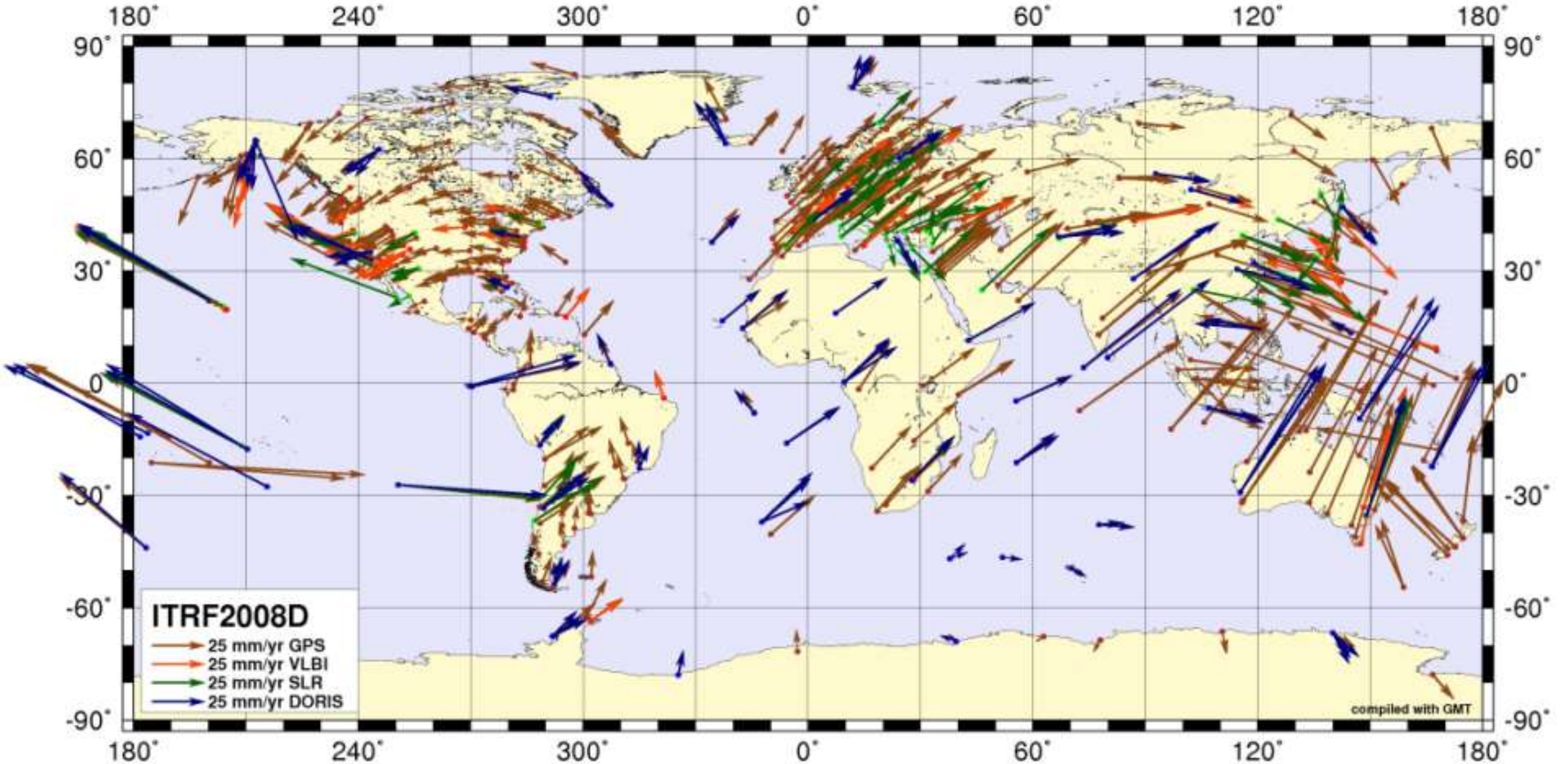
- The orientation is fixed conventionally at an epoch (BIH 1984), **not** physically by the axes of maximum inertia (= 2nd degree and order spherical harmonics) because these are determined too weak.
- The time evolution of orientation is defined by the condition of no rotation of the Earth crust. This must be realized by a present-day plate kinematic and deformation model (**not** by a geological model like NNR NUVEL-1A, because geological ≠ present day motions).
- The consistency with Earth rotation parameters (EOP) has to be guaranteed by common adjustment of station positions, velocities, EOP, and the plate and deformation model.
- These requirements are fulfilled in the International Terrestrial Reference Frame 2008 computation at DGFI (ITRF2008D).

5. Realization of ITRF2008

ITRF2008 input data

Tecnique	Service Analysis Ctr.	Data time series	Interval
GPS	IGS AC NRC Ottawa	Weekly solutions (with LOD)	1997 - 2008
SLR	ILRS CC ASI Matera	Weekly solutions (with LOD)	1983 - 2008
VLBI	IVS CC GIUB Bonn	24 h sessions, free normal equations	1980 - 2008
DORIS	IDS CC CLS Toulouse	Weekly solutions (with LOD)	1993 - 2008
Total	~1500 occupations ~ 920 points 578 stations	~4500 Solutions with daily EOP (UT1 from VLBI only)	1980 - 2008

ITRF2008 velocities



Different velocities in the same site for different time periods!

Comparison of ITRF2008 computations at DGFI and IGN

Computation methodology:

DGFI: Accumulation of datum free (weekly) normal equations,

IGN: Helmert-transformation of (weekly) solutions,

Both: Common adjustment of positions, velocities, and EOP;
Origin given by SLR data, scale by SLR and VLBI;

DGFI: Orientation time evolution from present-day model (APKIM)

IGN: Orientation time evolution from geological model (NUVEL-1A)

Comparison IGN vs. DGFI positions ([mm]) and velocities [mm/a])

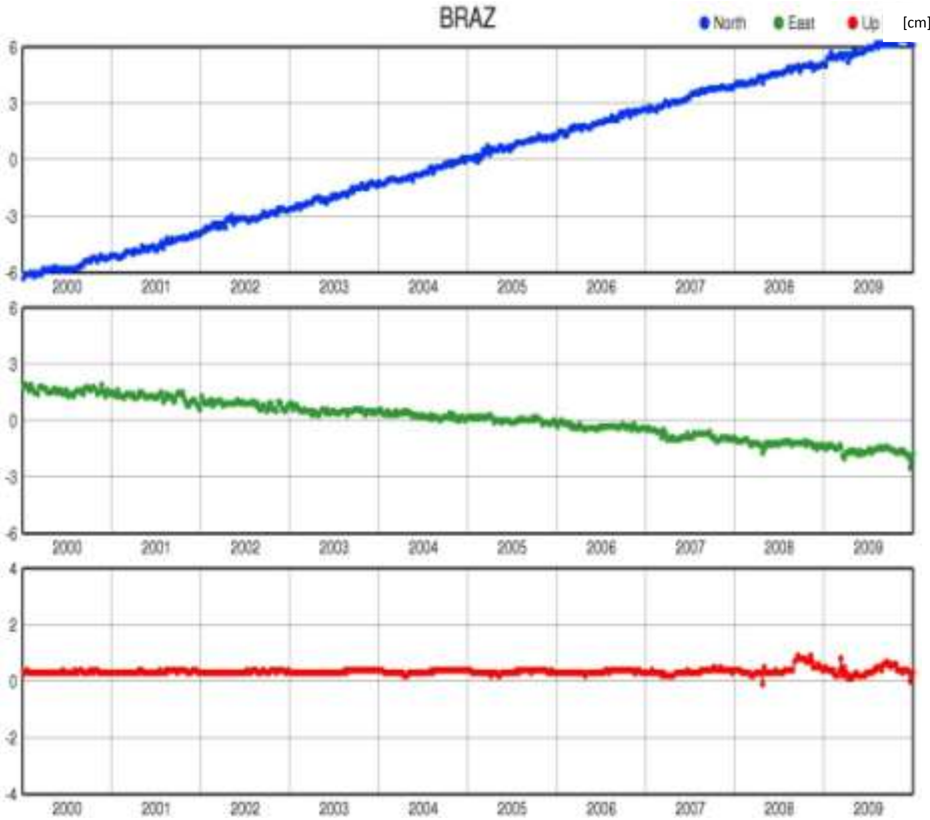
	ΔT(X)	ΔT(Y)	ΔT(Z)	ΔR(X)	ΔR(Y)	ΔR(Z)	ΔScale	RMS
SLR	-0,1/-0,2	0,0/-0,5	-0,3/ 0,1	0,5/ 0,3	-1,0/0,4	1,8/ 0,4	-2,0/ 0,1	2,0/ 0,8
VLBI	-1,8/ 0,4	1,3/ 0,4	-0,9/-0,1	0,1/ 0,0	-1,3/0,0	5,3/-0,1	2,1/-0,1	0,4/ 0,1
GPS	-1,1/ 0,1	0,1/-0,1	-4,9/ 0,0	0,4/ 0,0	-1,3/0,1	0,1/ 0,0	2,9/ 0,0	1,3/ 0,2
DORIS	1,3/ -0,1	0,1/ 0,4	-3,0/ 0,8	0,0/ 0,0	-2,7/0,0	-3,3/ 0,0	3,2/-0,1	3,2/ 1,0

6. Use of reference frames in practice

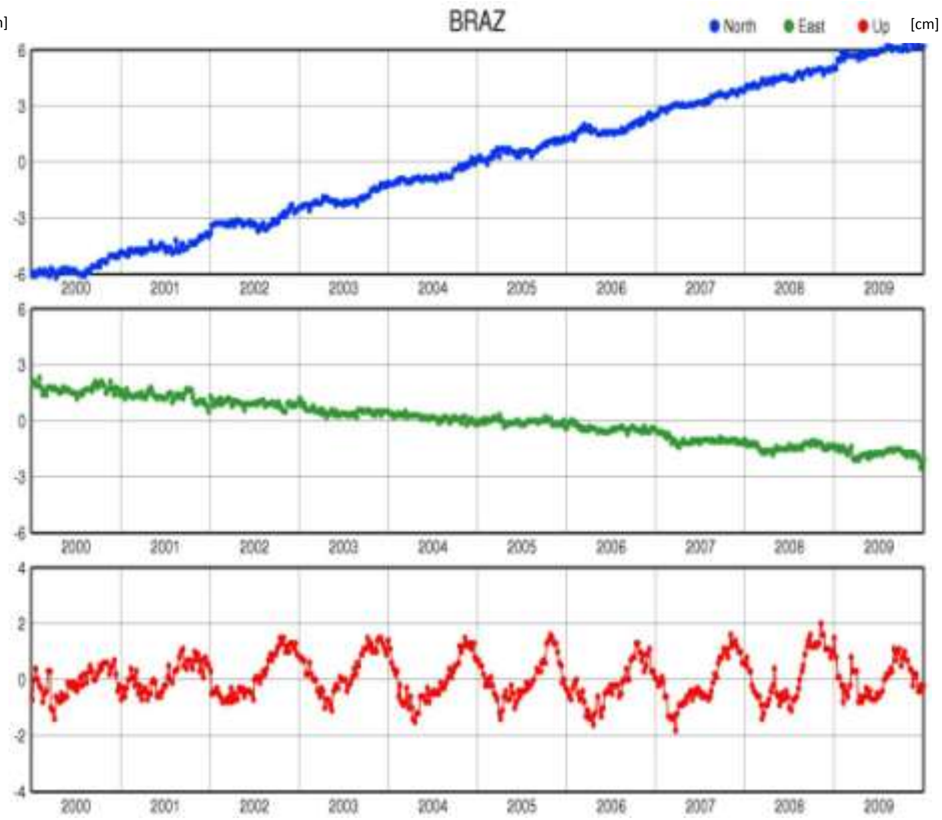
- The ITRF is a good basis for most global applications. The accuracy of station positions and velocities is sufficient for most practical use. It is not sufficient for the highest requirements of global change research ($\sigma v < 0.1$ mm/a), which has to be improved.
- For regional applications, the accessibility is not sufficient from the ITRF. Regional densifications are necessary. Densification of ITRF has to be done in a proper way. A problem is the transformation from the ITRF reference epoch (2005.0) to the actual observation epoch.
- When using constant station velocities from the ITRF, one neglects seasonal variations, i.e. we get different positions in different time.
- When applying similarity transformations (Helmert, NNT/NNR) one changes the datum of the frame (geocentre → centre of network) and damages the long-term stability.

Example of station position time series with epoch datum using constant velocities and weekly IGS coordinates, respectively.

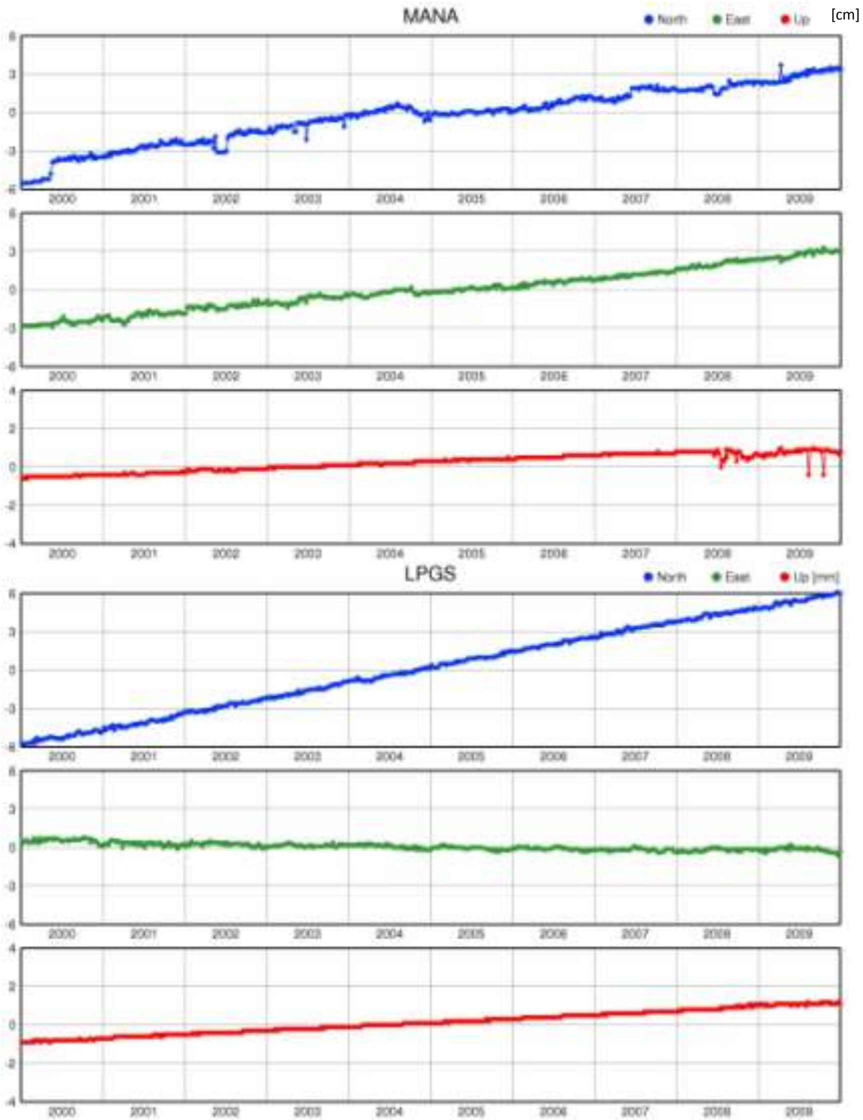
Datum from constant velocities



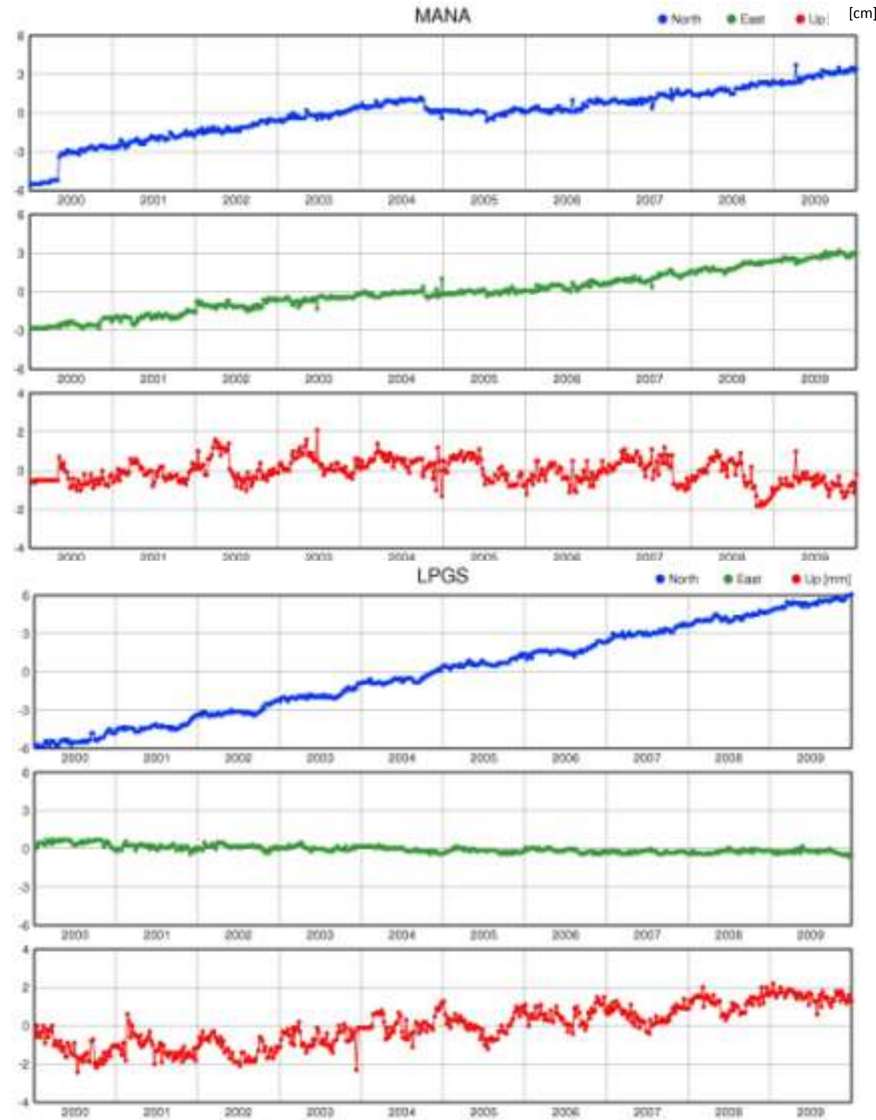
Datum from weekly IGS solutions



Datum from constant velocities



Datum from weekly IGS solutions



7. Conclusion

- Reference systems are the basic requirement for all geodetic parameters (positions, Earth rotation, gravity field) and Earth system representations (solid, fluid and gaseous processes). They have to be estimated and interpreted simultaneously.
- The ITRF is the best reference frame to be used in all these applications in global scale and regional densifications. It has to be improved in the future for advanced global change research.
- Station positions, Earth rotation and gravity field parameters have to be estimated simultaneously.
- The reference frame has to be used in its original form in global applications. Regional use has to refer to this global reference as a consistent densification, not by network transformation.

Thank you for your attention!