Terrestrial Reference Frames

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EGU and IVS Training School on VLBI for Geodesy and Astrometry
March 2-5, 2013, Aalto University, Espoo, Finland

DGFI

Outline

- Global terrestrial reference frames
- The Terrestrial and the Celestial Reference Frame
- Regional reference frames
- Applications of reference frames
- References

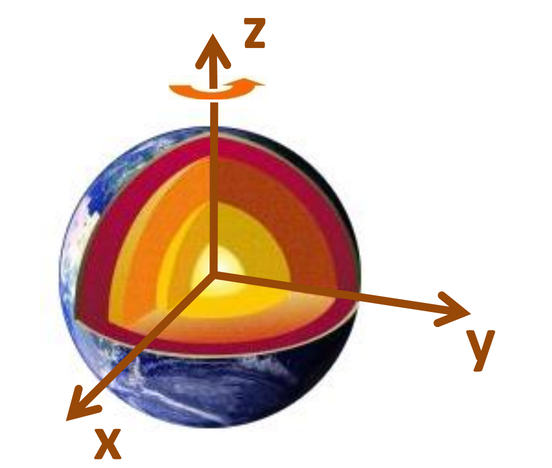
Global terrestrial reference frames

- The International Terrestrial Reference System (ITRS)
- The ITRS realization DTRF2008 computed by DGFI
- The research topic: epoch reference frame

International Terrestrial Reference System

Definition

- Origin: Centre of mass of the Earth
- Unit length: Meter (SI)
- z axis: mean Earth rotation axis
- x and y axis in equatorial plane
- X axis intersects Greenwich meridian



http://www.globale-evolution.de

Realization

- By positions and velocities of global distributed observing stations of the geodetic space techniques
  - Global Navigation Satellite Systems (GNSS (GPS, GLONASS))
  - Very Long Baseline Interferometry (VLBI)
  - Satellite Laser Ranging (SLR)
  - Satellite based Doppler measurement system (DORIS)

→ International Terrestrial Reference Frame (ITRF)

International Terrestrial Reference Frame

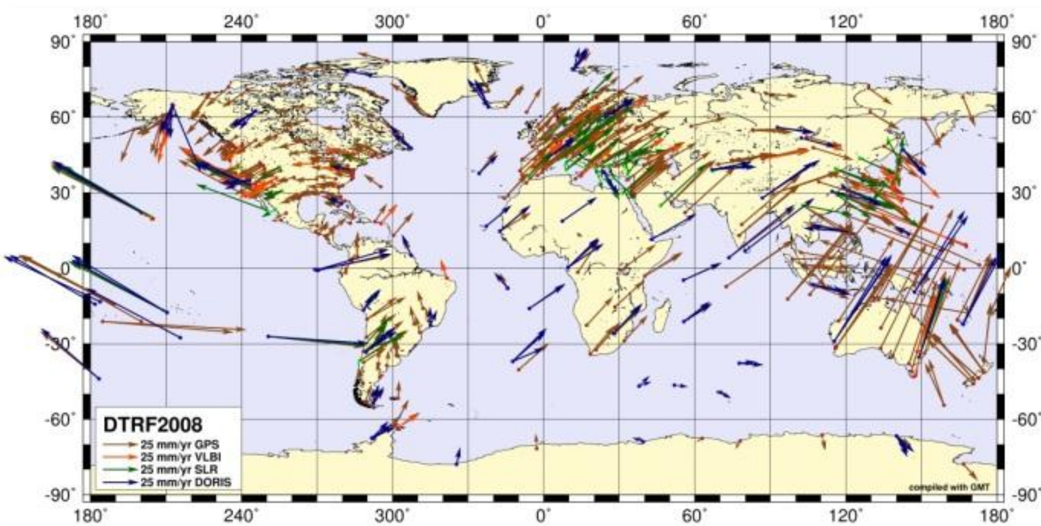
… is the basis for

the determination of the Earth‘s figure and its orientation in space

- Referencing of processes at the Earth and in its near environment (Geo referencing)
  - Geophysical processes (plate tectonics, Earthquakes, ocean dynamics …)
  - Determination of satellite orbits
- Positioning, Navigation

→ It is a fundamental component of the Global Geodetic Observing System (GGOS)

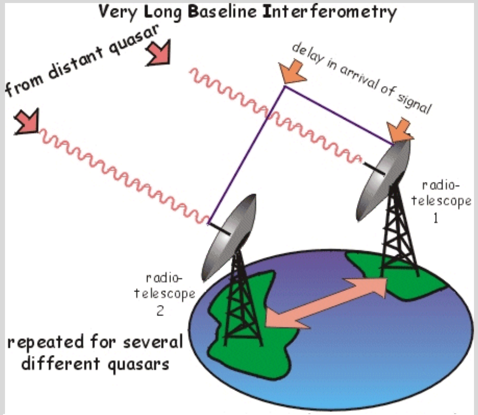
- Examples for applications will be given at the end of the lecture



Realization computed at DGFI: DTRF2008

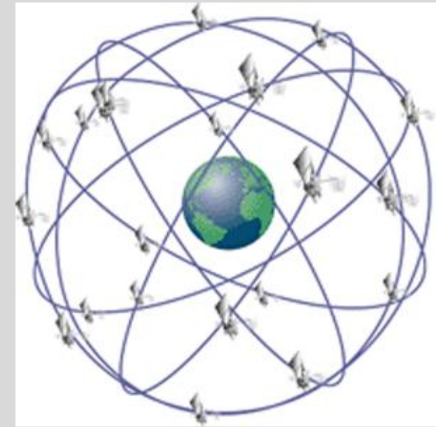
Geodetic space observation techniques

Very Long Baseline Interferometry (VLBI)

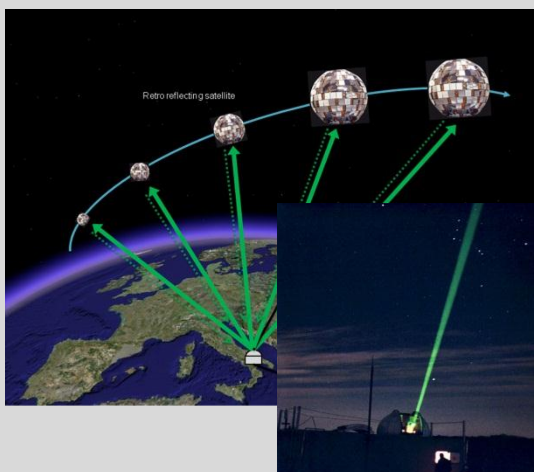


http://www.jammisciencescreen.com

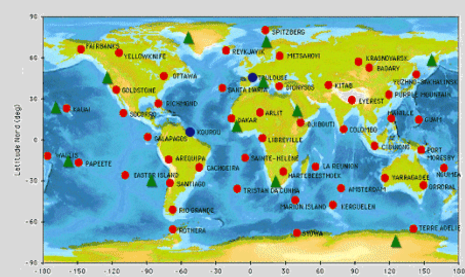
Global Navigation Satellite Systems (GNSS)



Satellite Laser Ranging (SLR)



Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)



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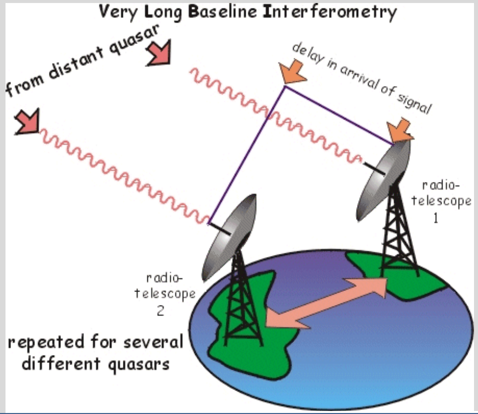
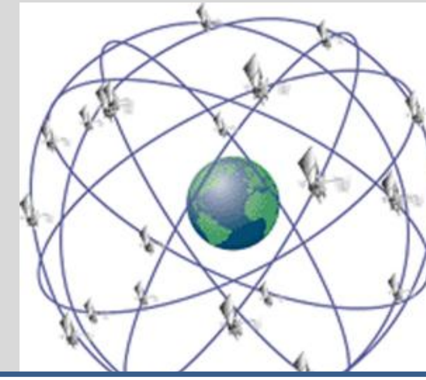
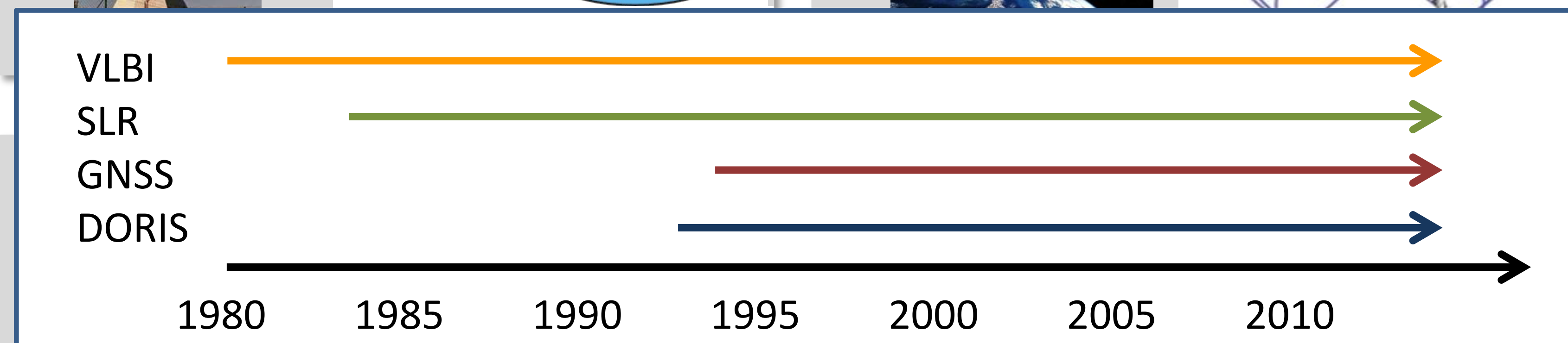
Geodetic space observation techniques

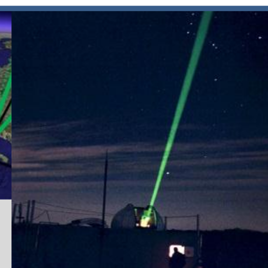
Very Long Baseline Interferometry (VLBI)

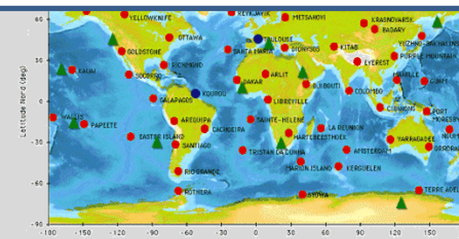


Global Navigation Satellite Systems (GNSS)









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Observation techniques: pros,cons

VLBI:

pro: the only observation techniques, which observes extragalactic objects and hence allows for the determination of all **Earth Orientation Parameters (EOP)**. The **scale** is determined with high accuracy.

con: few stations with suboptimal global distribution → poor accuracy of temporal highly resolved parameters (e.g. EOP)

SLR:

pro: low orbiting (high sensitivity), spherical satellites (good modeling) allow for the determination of the **center of mass of the Earth** with high accuracy. The **scale** is also determined with high accuracy.

con: few stations with suboptimal global distribution → poor accuracy of temporal highly resolved parameters (e.g. EOP)

Observation techniques: pros,cons

GNSS:

pro: a large number of stations and observations lead to a high precision of the determined parameters.

con: forces on the satellites difficult to model → systematic effects in the realized centre of mass

DORIS:

pro: a lot of stations with a good global distribution

con: low accuracy of observation (centimetres)

Combination of the techniques

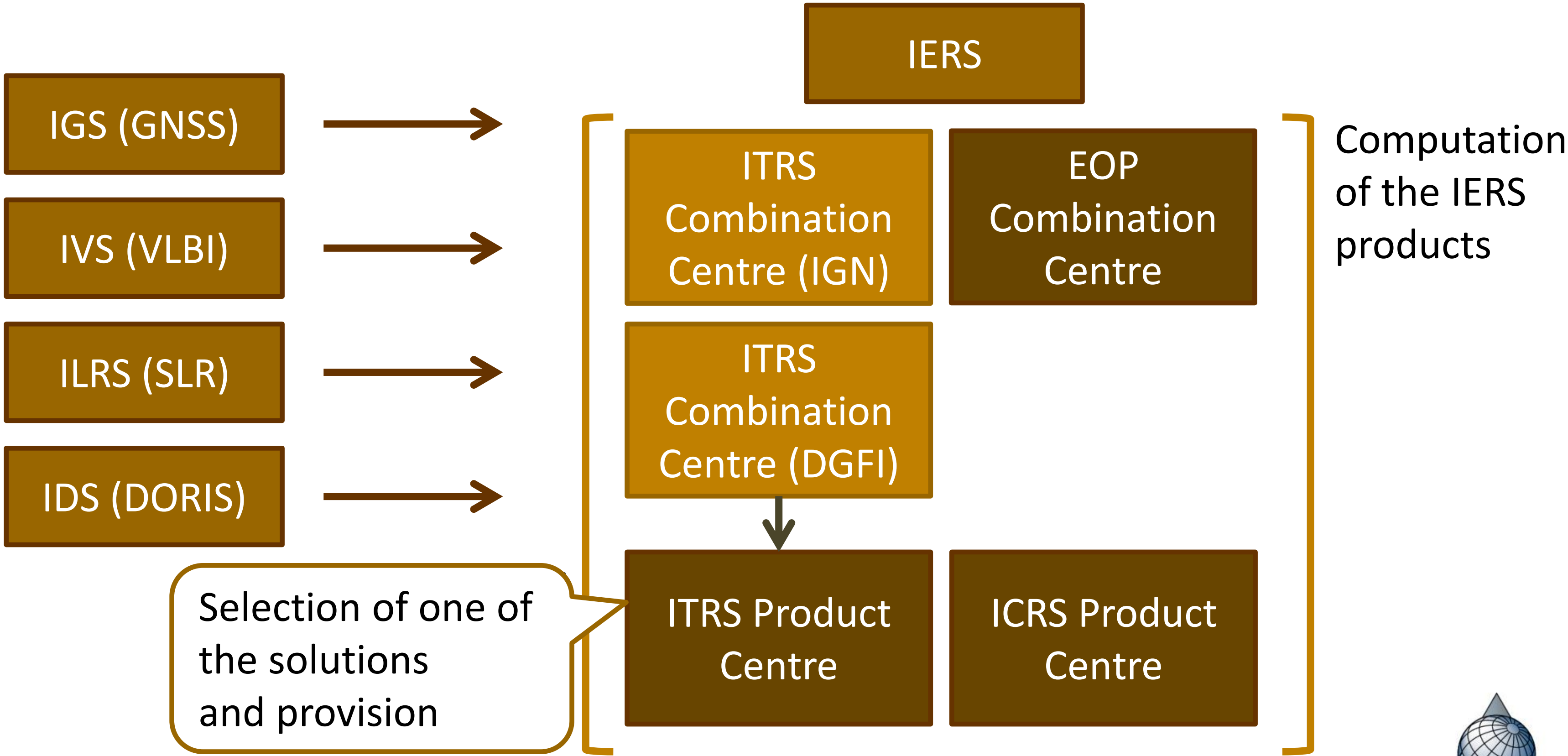
- **Means?** Determination of geodetic parameters from the observations of all techniques in one adjustment
- **Why?** Strengths of the several techniques can be exploited, weaknesses are balanced; high redundancy
- **How?** At DGFI by addition of normal equation systems (Gauß-Markov-Model) of the different observation techniques

Realisiation of the ITRS – Structur of the relevant IAG-Services

IAG: International Association of Geodesy

Technique Services

International Earth Rotation and Reference Systems Service



Input data for DTRF2008

Processing within Technique Services

- An international service is responsible for the analysis of the observations of each observing technique and the generation of the products
- Observations are processed by the Analysis Centres of the service …
- The results are combined by the Combination Centre (weekly or session-wise) (Result: one data set per technique)
- The processing is done using common standards (DTRF2008: Conventions IERS2003; current: IERS2010, plus technique-specific models)

Input data for ITRF2008 and DTRF2008

Technique	Service	Time span	Resolution	Typ
GNSS	IGS	1997-2008	weekly	solution
VLBI	IVS	1980-2008	session	NEQ
SLR	ILRS	1983-2008	forthnightly, weekly	solution
DORIS	IDS	1993-2008	weekly	solution

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Geodetic parameters…

… derived from the observations of the four observation techniques and relevant for the ITRF

	Earth Orientation Parameters (EOP)					Indirect parameters: datum parameters	
	Station coordi-nates	Terrest-rial pole	ΔUT1	Length of day (LOD)	Nutation para-meters	Origin	Scale
VLBI	x	x	x	x	x		x
SLR	x	x		x		x	x
GNSS	x	x		x			
DORIS	x	x		x			

Technique-specific parameters are consistently estimated but reduced, e.g. orbit and clock parameters, atmospheric parameters, ambiguities, range biases, … .

Geodetic parameters…

… derived from the observations of the four observation techniques and relevant for the ITRF

	Earth Orientation Parameters (EOP)					Indirect parameters: datum parameters	
	Station coordi-nates	Terrest-rial pole	ΔUT1	Length of day (LOD)	Nutation para-meters	Origin	Scale
VLBI	x	x	x	x	x		x
SLR	x	x		x		x	x
GNSS	x	x		x			
DORIS	x	x		x			

Only VLBI can determine ΔUT1 and Nutation parameters in an absolute sense! → VLBI is the only technique which contributes to the realizations of ITRS and the Int. Celestial Reference System ICRS (Session 3.5) and provide the transformation parameters between ITRF and ICRF.

Geodetic parameters…

… derived from the observations of the four observation techniques and relevant for the ITRF

	Earth Orientation Parameters (EOP)					Indirect parameters: datum parameters	
	Station coordi-nates	Terrest-rial pole	ΔUT1	Length of day (LOD)	Nutation para-meters	Origin	Scale
VLBI	x	x	x	x	x		x
SLR	x	x		x		x	x
GNSS	x	x		x			
DORIS	x	x		x			

- Station coordinates and EOP benefit from a combination
- Origin and scale of ITRF are given by techniques which are able to realize these parameters with high accuracy

→ Combination leads to higher accuracy and reliability of the products

Observation equation (linear)

- The expected values of the observations $\boldsymbol{b}$ are written as a linear combination of known coefficients and unknown parameters $\boldsymbol{p}$

- The relations between observations and parameters are defined by physical or mathematical laws

$$\boldsymbol{A}\boldsymbol{x} = \boldsymbol{b} + \boldsymbol{v}$$

$$\boldsymbol{x} = \boldsymbol{p} - \boldsymbol{p}_0$$

$\boldsymbol{A}$	$n\ x\ u$	coefficients matrix
$\boldsymbol{b}$	$n\ x\ 1$	observation vector
$\boldsymbol{x}$	$u\ x\ 1$	vector of unknowns
$\boldsymbol{p}$	$u\ x\ 1$	parameter vector
$\boldsymbol{p}_0$	$u\ x\ 1$	vector of a priori values of $\boldsymbol{p}$
$\boldsymbol{v}$	$n\ x\ 1$	vector of observation errors

Observation equation (linear)

$$\boldsymbol{Ax} = \boldsymbol{b} + \boldsymbol{v}$$

$$\boldsymbol{x} = \boldsymbol{p} - \boldsymbol{p_0}$$

$\boldsymbol{A}$	$n\ x\ u$	coefficients matrix
$\boldsymbol{b}$	$n\ x\ 1$	observation vector
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$\boldsymbol{v}$	$n\ x\ 1$	vector of observation errors

Assumption: variance-covariance matrix $\boldsymbol{C_{bb}}$ of observations is known, except of a variance factor σ^2

$$\boldsymbol{C_{bb}} = \sigma^2 \boldsymbol{P_{bb}}^{-1}$$

$\boldsymbol{P_{bb}}$ $n\ x\ n$ weighting matrix of observations

$$E(\boldsymbol{v}) = \boldsymbol{0}$$

$\hat{\boldsymbol{x}}$ is estimated by applying the condition: $\hat{\boldsymbol{v}}^T \boldsymbol{P_{bb}} \hat{\boldsymbol{v}} \doteq$ Min.

Least squares adjustment: the Gauß-Markov-Model Basics

Observation equation (linear)

deterministic part of GMM

$\boldsymbol{Ax} = \boldsymbol{b} + \boldsymbol{v}$	$\boldsymbol{A}$	$n\ x\ u$	coefficients matrix
	$\boldsymbol{b}$	$n\ x\ 1$	observation vector
	$\boldsymbol{x}$	$u\ x\ 1$	vector of unknowns
$\boldsymbol{x} = \boldsymbol{p} - \boldsymbol{p_0}$	$\boldsymbol{p}$	$u\ x\ 1$	parameter vector
	$\boldsymbol{p_0}$	$u\ x\ 1$	vector of a priori values of $\boldsymbol{p}$
	$\boldsymbol{v}$	$n\ x\ 1$	vector of observation errors

Assumption: variance-covariance matrix $\boldsymbol{C_{bb}}$ of observations is known, except of a variance factor σ^2

stochastic part of GMM

$\boldsymbol{C}_{\boldsymbol{bb}} = \sigma^2 \boldsymbol{P}_{\boldsymbol{bb}}{}^{-1}$	$\boldsymbol{P}_{\boldsymbol{bb}}$	$n\ x\ n$	weighting matrix of observations

$E(\boldsymbol{v}) = \boldsymbol{0}$

$\hat{\boldsymbol{x}}$ is estimated by applying the condition: $\hat{\boldsymbol{v}}^T \boldsymbol{P}_{\boldsymbol{bb}} \hat{\boldsymbol{v}} \doteq \text{Min.}$

Normal equation

$$(\boldsymbol{A}^T\boldsymbol{P}\boldsymbol{A})\hat{\boldsymbol{x}} = \boldsymbol{A}^T\boldsymbol{P}\boldsymbol{b}$$

with $\boldsymbol{N} = \boldsymbol{A}^T\boldsymbol{P}\boldsymbol{A}$ and

$\boldsymbol{y} = \boldsymbol{A}^T\boldsymbol{P}\boldsymbol{b}$

$$\boldsymbol{N}\,\hat{\boldsymbol{x}} = \boldsymbol{y}$$

Solution

$$\hat{\boldsymbol{x}} = \boldsymbol{N}^{-1}\boldsymbol{y}$$

deterministic part

$$\sigma^2 = (\hat{\boldsymbol{v}}^T\boldsymbol{P}\hat{\boldsymbol{v}})/(\boldsymbol{n} - \boldsymbol{u})$$

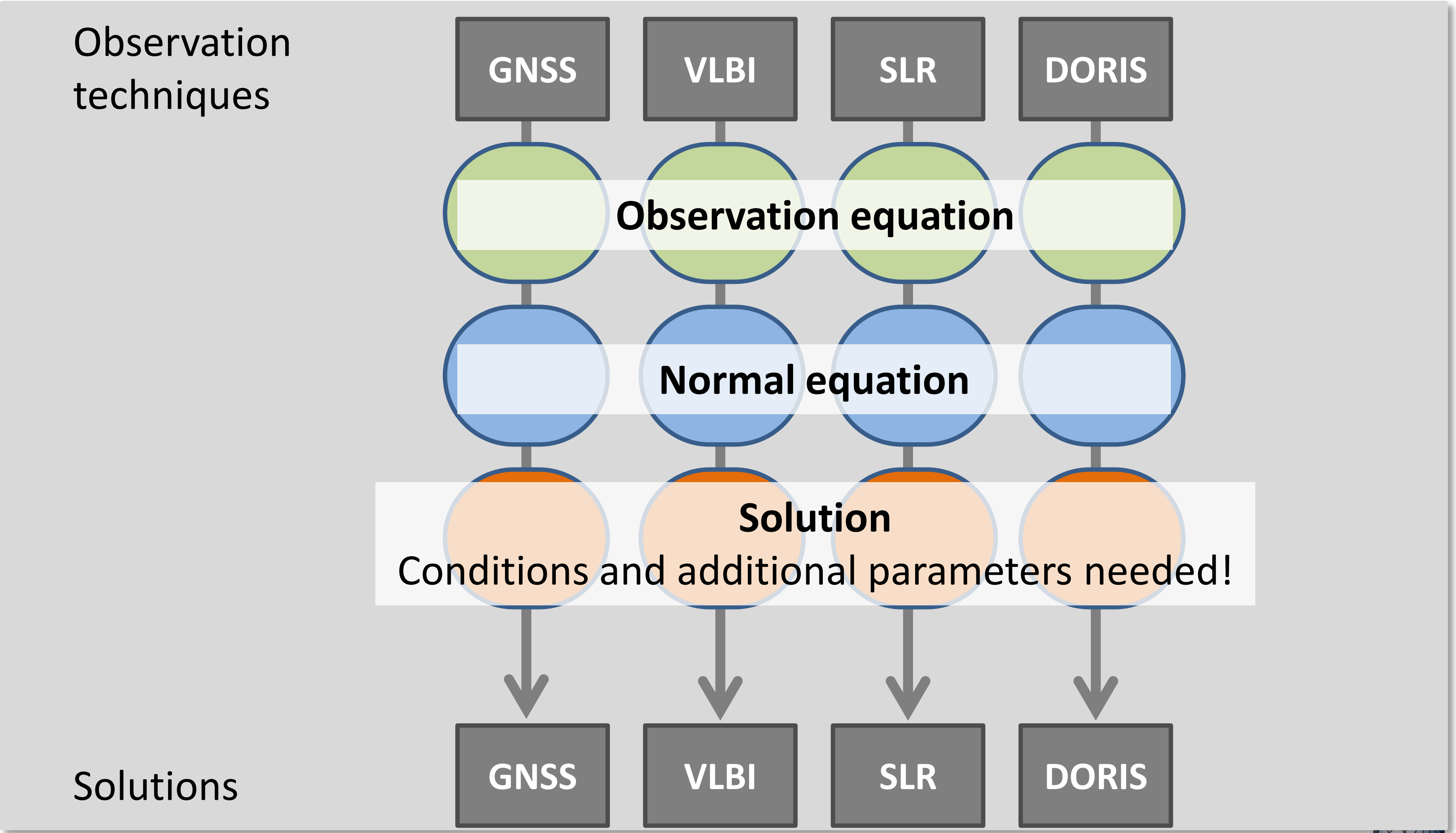
$$\boldsymbol{C}_{\hat{\boldsymbol{x}}\hat{\boldsymbol{x}}} = \sigma^2\boldsymbol{N}^{-1}$$

stochastic part

wherein $\boldsymbol{C}_{\hat{\boldsymbol{x}}\hat{\boldsymbol{x}}}$ is the variance-covariance matrix of the estimated unknowns $\hat{\boldsymbol{x}}$

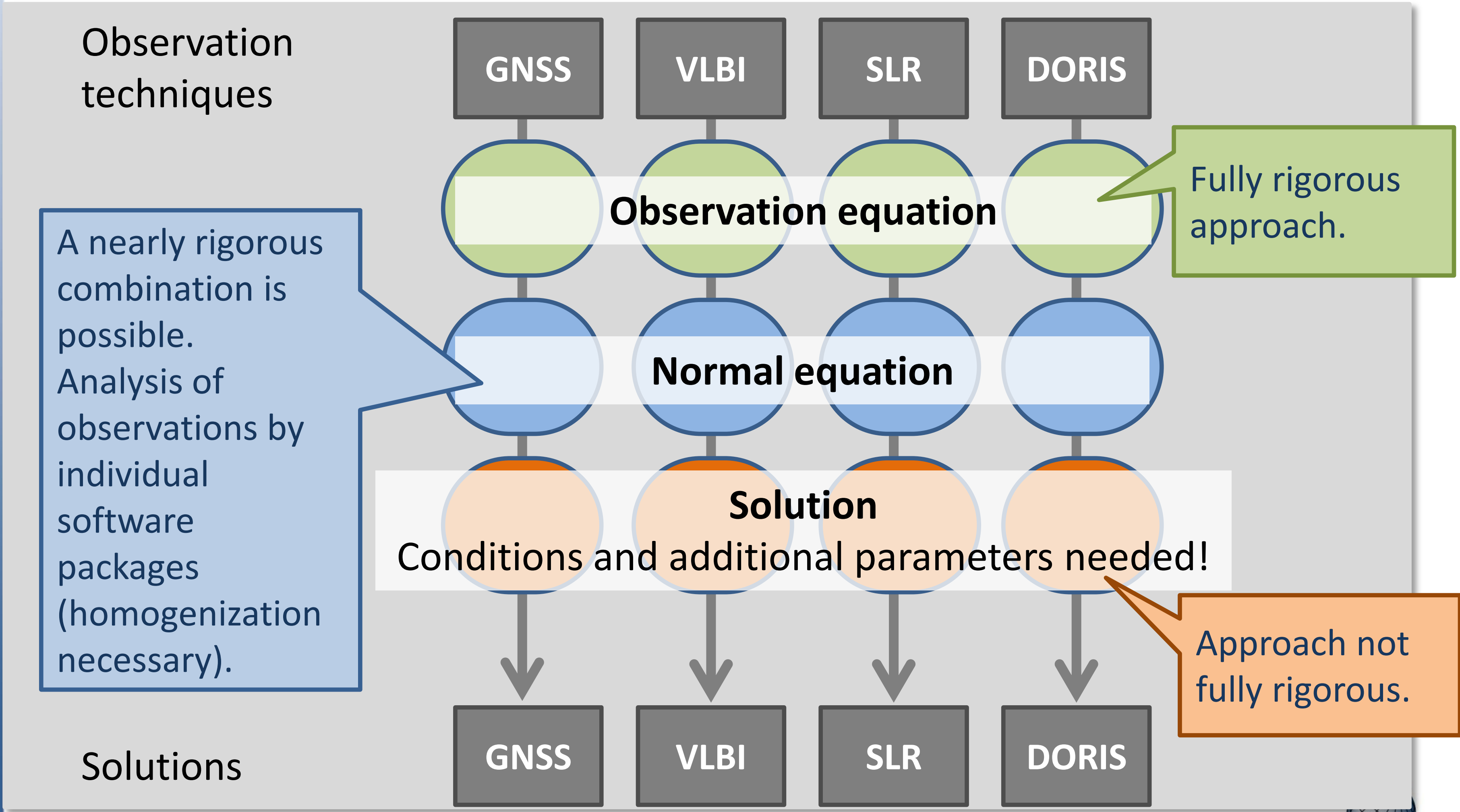
Conceivable combination approaches

Combination is possible at the three levels of Gauß-Markov-Model



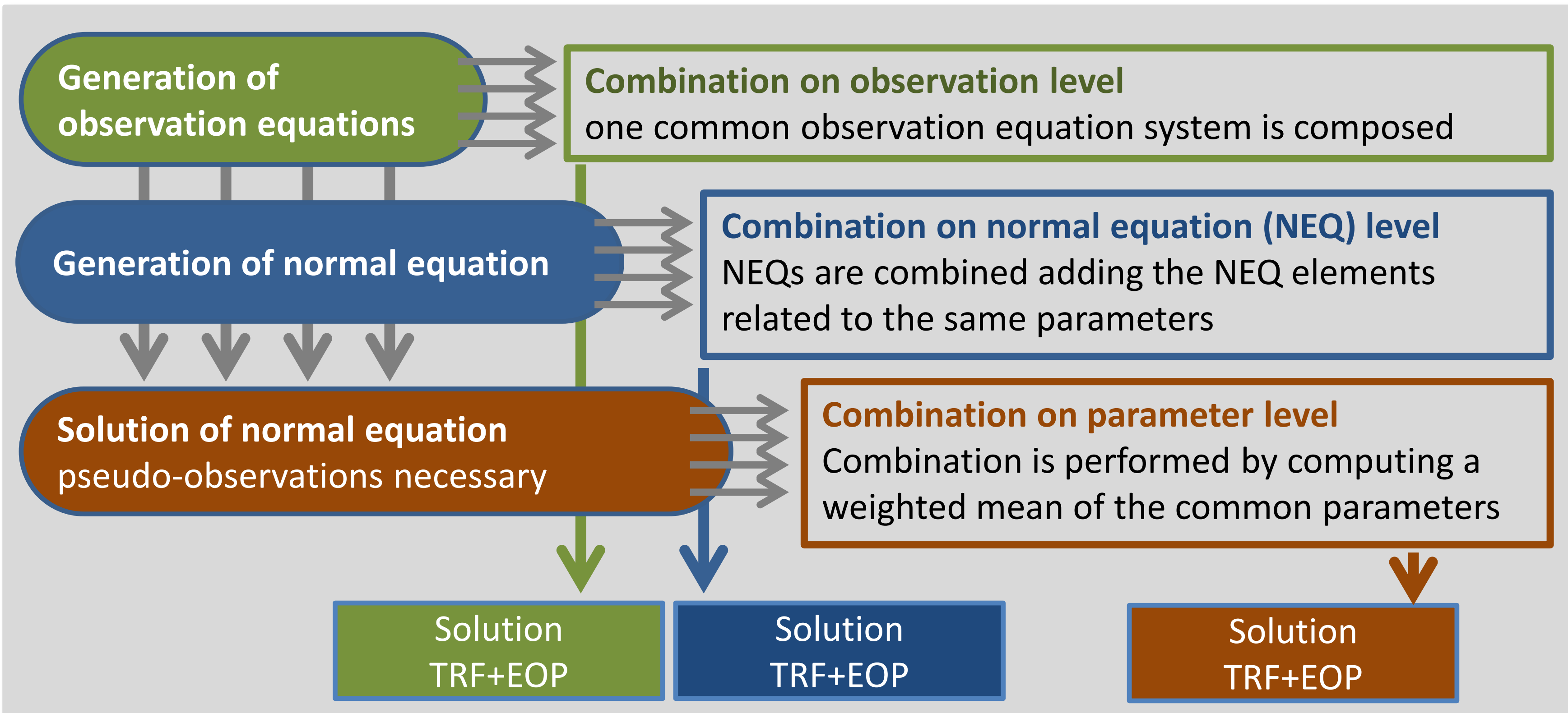
Conceivable combination approaches

Combination is possible at the three levels of Gauß-Markov-Model



Conceivable combination approaches

Prerequisite: different observation techniques provide common parameters



Conceivable combination approaches

Application of combination approaches in TRF computation

Combination at observation level:

Different groups work on software packages able to process and combine all four techniques starting from observation level → not yet fully tested and applied for ITRS realization applications (introduced shortly on the next slides)

Combination at normal equation level:

ITRS realization DTRF2008 of DGFI (explained in detail later)

Combination at parameter (solution) level:

Computation of ITRS realization ITRF2008 and previous ITRF solutions of IGN (see the next slides)

Combination at the observation level

Observation equation

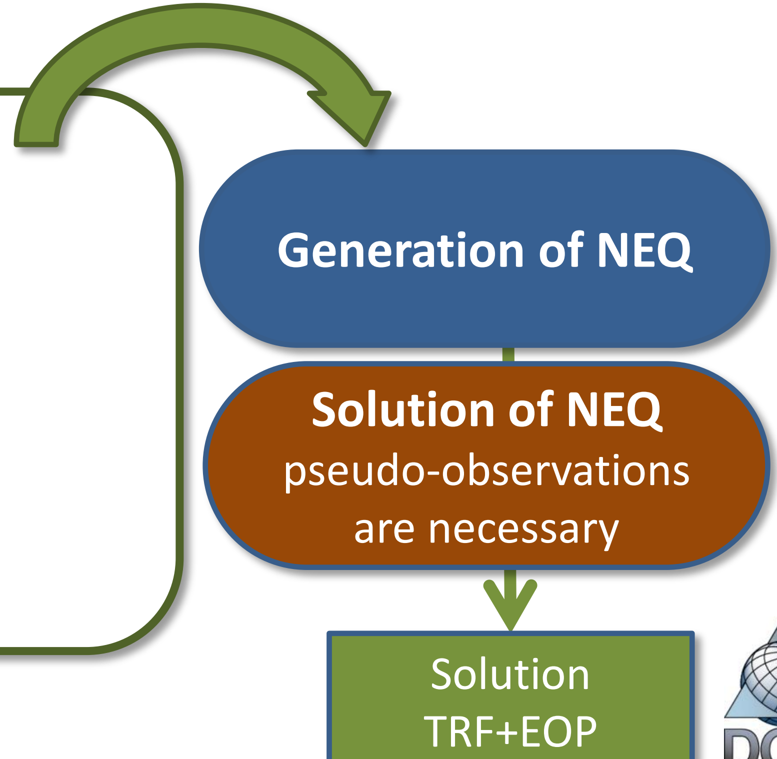
$$A_k x_k = b_k + v_k$$
$$C_{b_k b_k} = \sigma^2 P_k^{-1}$$

k = 1, …, m observation techniques

Combination on **observation level**

$$\begin{bmatrix} A_1 \\ \dots \\ A_m \end{bmatrix} x = \begin{bmatrix} b_1 \\ \dots \\ b_m \end{bmatrix} + \begin{bmatrix} v_1 \\ \dots \\ v_m \end{bmatrix}$$

$$C_{bb} = \sigma^2 \begin{bmatrix} P_1^{-1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & P_m^{-1} \end{bmatrix}$$



Combination at the observation level

- Advantages compared to combination of normal equations:
  - A homogeneous analysis of the different observation types by applying the same models and parameterizations is performed innately and must not be organized for different software packages.
  - The pre-processing, i.e. the outlier detection and the weighting of individual observations, is done on the basis of all observations not technique-wise. However, it can be assumed that the impact on the combined solution is quite small.

- The approach is not applied for ITRS realization yet.

Combination of parameters (IGN approach)

Parameter (solution) level

Observation equation for the combination on parameter level

$$\mathbf{I}\,\boldsymbol{x}_k = \hat{\boldsymbol{x}} + \boldsymbol{v}_k$$

$$\boldsymbol{C}_{\hat{x}_k\hat{x}_k} = \sigma^2 (\boldsymbol{N}_k + \boldsymbol{D}_k)^{-1}$$

$\boldsymbol{k}$ = 1, ..., m obs. techn.
$\boldsymbol{D}$: NEQ matrix of pseudo observations

→ observations are the solved parameters of input solutions

Combination on **parameter level**

$$\boldsymbol{I}\begin{bmatrix}\boldsymbol{x}_1\\ \dots \\ \boldsymbol{x}_m\end{bmatrix} = [\hat{\boldsymbol{x}}] + \begin{bmatrix}\boldsymbol{v}_1\\ \dots \\ \boldsymbol{v}_m\end{bmatrix}$$

$$\boldsymbol{C}_{xx} = \sigma^2 \begin{bmatrix}(\boldsymbol{N}_1+\boldsymbol{D}_1)^{-1} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \ddots & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & (\boldsymbol{N}_m+\boldsymbol{D}_m)^{-1}\end{bmatrix}$$

→ Solution TRF+EOP

Combination of parameters (IGN approach)

- In order to realize the geodetic datum while generating the input solutions, pseudo-observations are applied ($\hat{\boldsymbol{x}}_k = \boldsymbol{D}^{-1}\boldsymbol{d}$). → The resulting variance-covariance matrix used as weighting matrix in the combination depend on the used conditions.

$$\hat{\boldsymbol{x}}_k = (\boldsymbol{N} + \boldsymbol{D})^{-1}(\boldsymbol{y} + \boldsymbol{d})$$
$$\boldsymbol{C}_{\hat{x}_k\hat{x}_k} = \sigma^2(\boldsymbol{N}_k + \boldsymbol{D}_k)^{-1}$$

- Usually applied conditions are
  - No-Net-Translation (NNT) and No-Net-Rotation (NNR) conditions which do not allow a translation and a rotation of the solved station network w.r.t. the a priori coordinates.
  - Loose constraints: a slightly constraining of all station coordinates to their a priori values.

Combination of parameters (IGN approach)

- In the combination, singularity of the individual input solutions w.r.t. datum parameters is rebuild by setting up parameters of a Helmert transformation (3 translations, 3 rotations, scale) → necessary, because datum realization has to be redone homogeneously for the ITRF solution.

  E.g. for technique k the observation equation (see previous slide) is extended by the equation of Helmert transformation:

$$\hat{\boldsymbol{x}} = \boldsymbol{x}_k + \boldsymbol{T}_k + D_k \boldsymbol{x}_k + \boldsymbol{R}_k \boldsymbol{x}_k$$

T: Translation matrix
R: Rotation matrix
D: Scale factor

A set of good and global distributed stations is used to determine the transformation parameters.

Combination of parameters (IGN approach)

- This approach is not fully rigorous mainly because:
  - The weights of the input parameters are not independent from the datum realization of the input solutions. In particular in case of applied loose constraints, the variances are not reliable.
  - The Helmert transformation parameters and thus the solution strongly depend on the selected set of stations used for the transformation.

References for the IGN approach, e.g.:

Altamimi et al. 2011

IERS Conventions 2010

CGE DGFI

Combination of normal equations (DGFI approach)

Observation and Normal equation

Observation equation

↓

Normal equation

$$\boldsymbol{A_k x_k = b_k + v_k}$$

$$\boldsymbol{C_{b_k b_k}} = \sigma^2 \boldsymbol{P_k}^{-1}$$

$$\boldsymbol{N_k \hat{x}_k = y_k}$$

k = 1, …, m techniques

with: $\boldsymbol{N = A^T P A}$ and

$$\boldsymbol{y = A^T P b}$$

Combination at the normal equation level

$$\boldsymbol{N} = \frac{1}{\sigma_1^{\ 2}} \boldsymbol{N_1} + \dots + \frac{1}{\sigma_m^{\ 2}} \boldsymbol{N_m}$$

$$\boldsymbol{y} = \frac{1}{\sigma_1^{\ 2}} \boldsymbol{y_1} + \dots + \frac{1}{\sigma_m^{\ 2}} \boldsymbol{y_m}$$

$\boldsymbol{N}_{u \times u}$, $\boldsymbol{y}_{u \times 1}$

$$b^T P b = \frac{1}{\sigma_1^{\ 2}} b_1^{\ T} P_1 b_1 \ + \ \dots \ + \ \frac{1}{\sigma_m^{\ 2}} b_m^{\ T} P_m b_m$$

Solution of NEQ

↓

TRF + EOP

Solution of combined normal equation (DGFI)

Parameter (deterministic part)

$$\hat{\boldsymbol{x}} = \boldsymbol{N}^{-1}\boldsymbol{y}$$

Variance-covariance matrix of the parameters $\boldsymbol{C}_{\hat{x}\hat{x}}$ (stochastic part)

$$\sigma^2 = (\hat{\boldsymbol{v}}^T \boldsymbol{P} \hat{\boldsymbol{v}})/(\boldsymbol{n} - \boldsymbol{u})$$

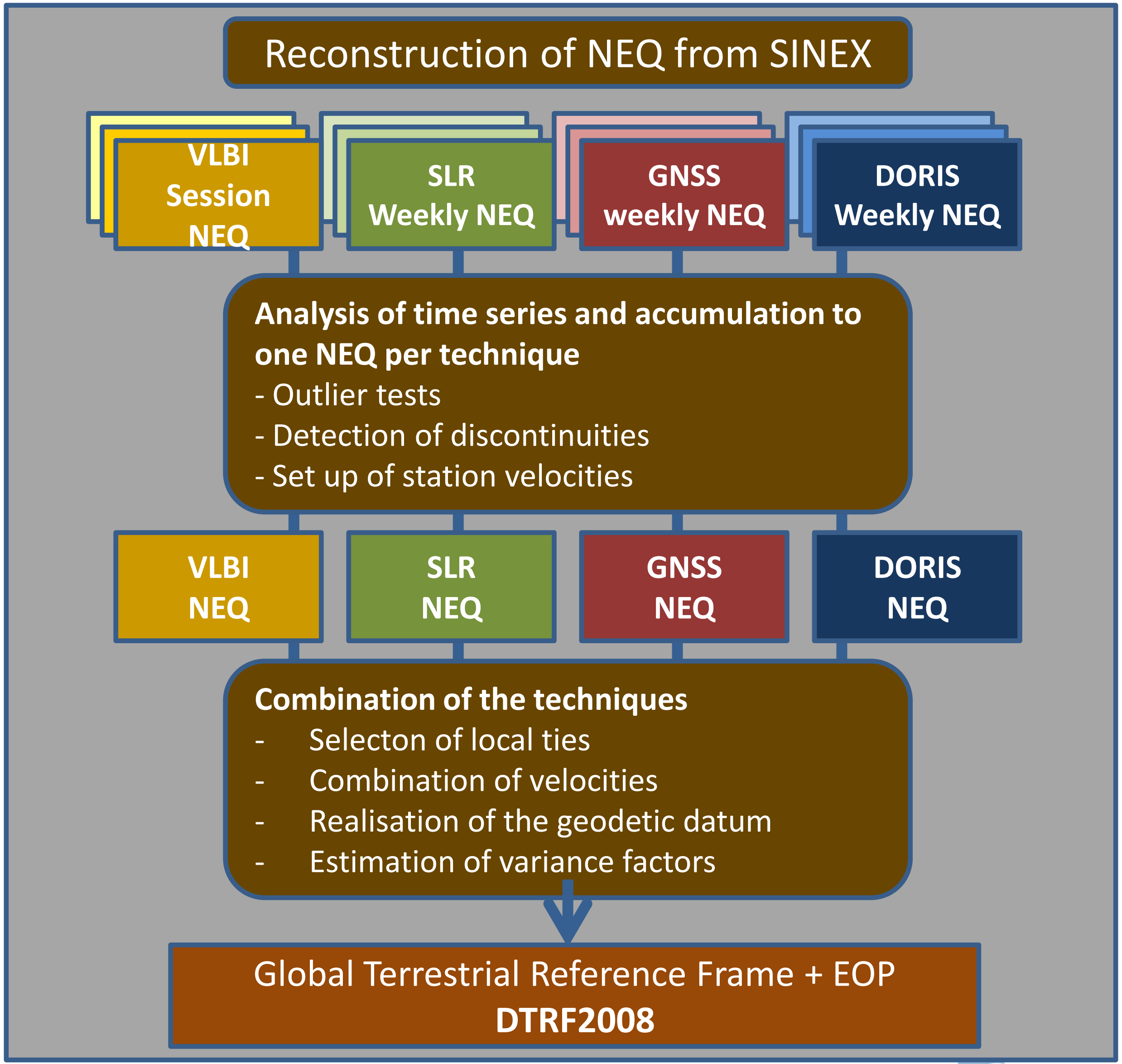
with $\hat{\boldsymbol{v}}^T \boldsymbol{P} \hat{\boldsymbol{v}} = \hat{\boldsymbol{b}}^T \boldsymbol{P} \hat{\boldsymbol{b}} - \boldsymbol{y}^T \hat{\boldsymbol{x}}$

$$\boldsymbol{C}_{\hat{x}\hat{x}} = \sigma^2 \boldsymbol{N}^{-1}$$

Note: Input data are normal equations, which are constraint free w.r.t. those geodetic datum parameters they are not sensitive for! But constraints necessary in order to stabilize certain groups of weak parameters (e.g. clock or troposphere parameters) are included.

Computation of DGFI solution DTRF2008

Strategy

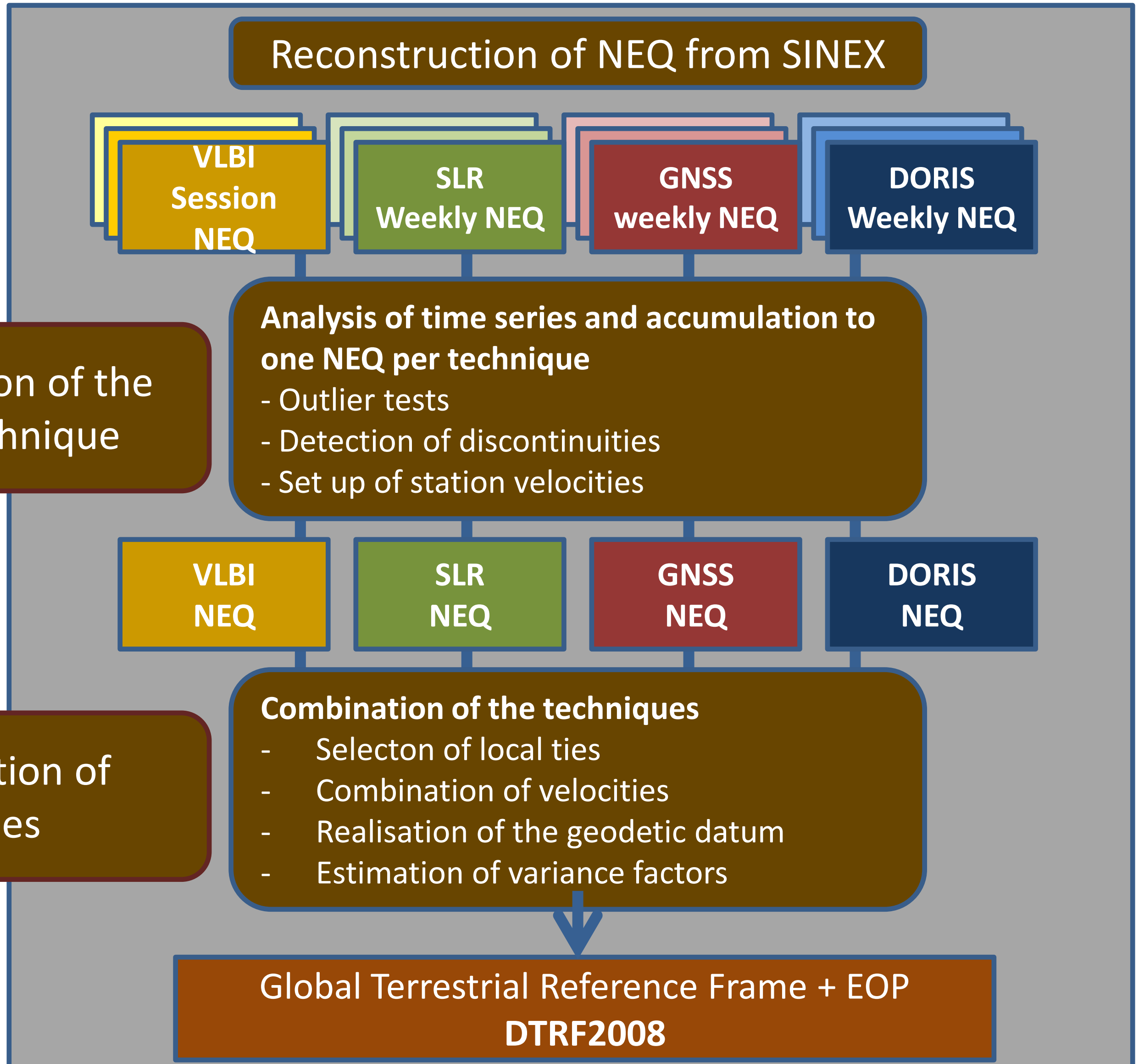


Computation of DGFI solution DTRF2008

Strategy

(1) Accumulation of the NEQs per technique

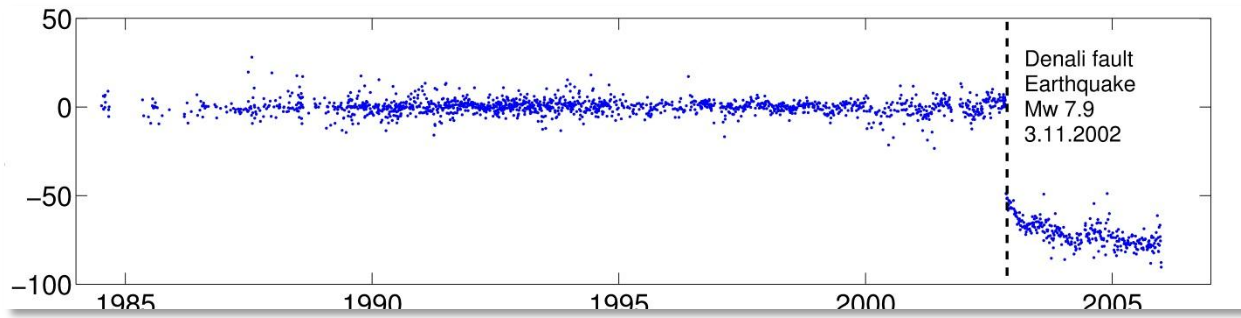
(2) Combination of techniques



Time series analysis …

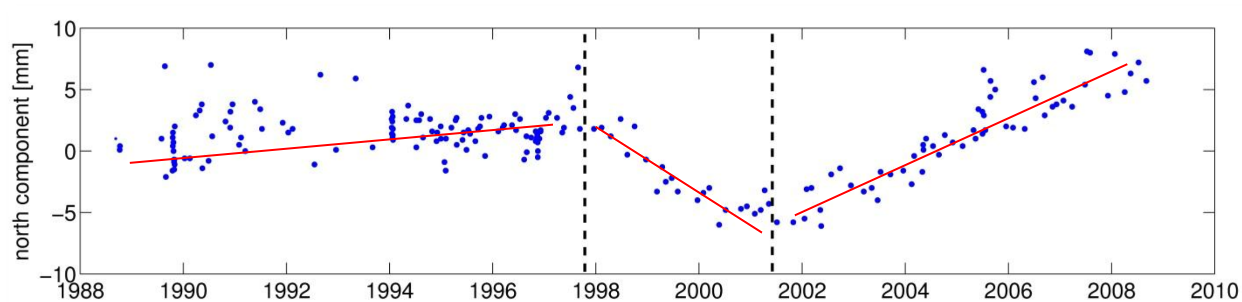
… for discontinuity detection

Discontinuity in the station movement due to an earthquake



North component of VLBI station Fairbanks [mm]

Discontinuity of station velocity

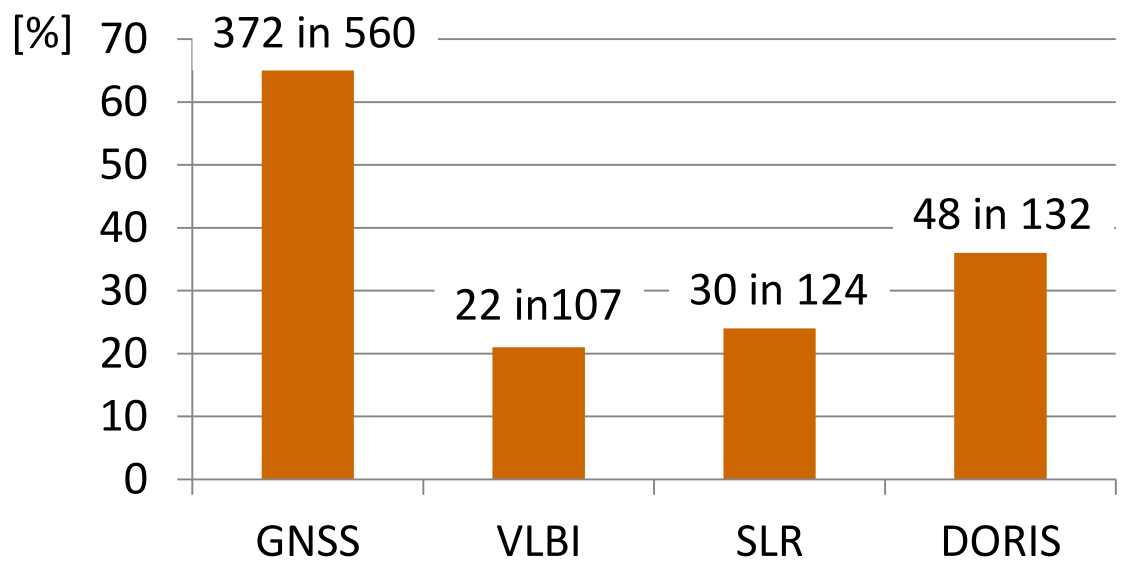


North component of VLBI station Pietown [mm]

Time series analysis …

… for discontinuity detection

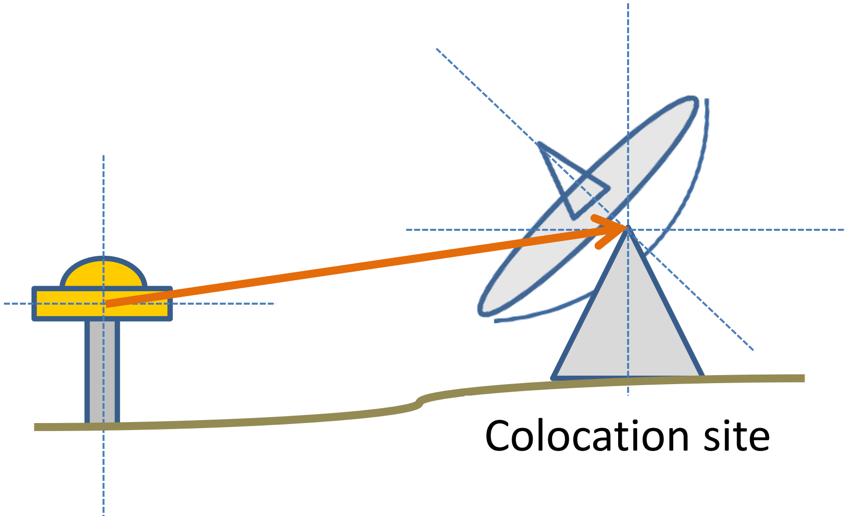
Number of stations affected by discontinuities in DTRF2008



Many GNSS stations are affected by discontinuities. In many cases, it can be related to equipment changes! A monitoring of these changes would help to reduce the number of discontinuities significantly.

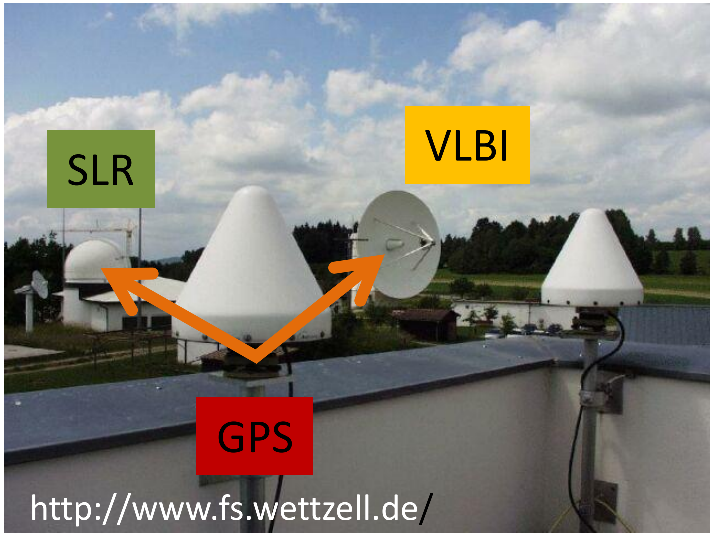
Colocation sites

Observations of different space geodetic techniques do usually not refer to common reference points



Difference measurements (terrestrial, GPS) are necessary for the combination of station positions.

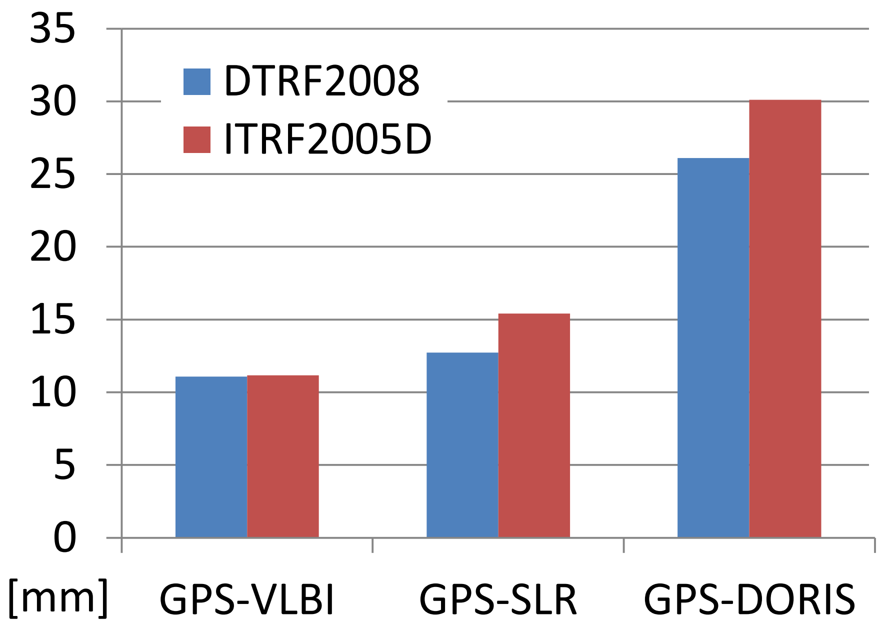
Geodetic observatory Wettzell, Bavarian Forest

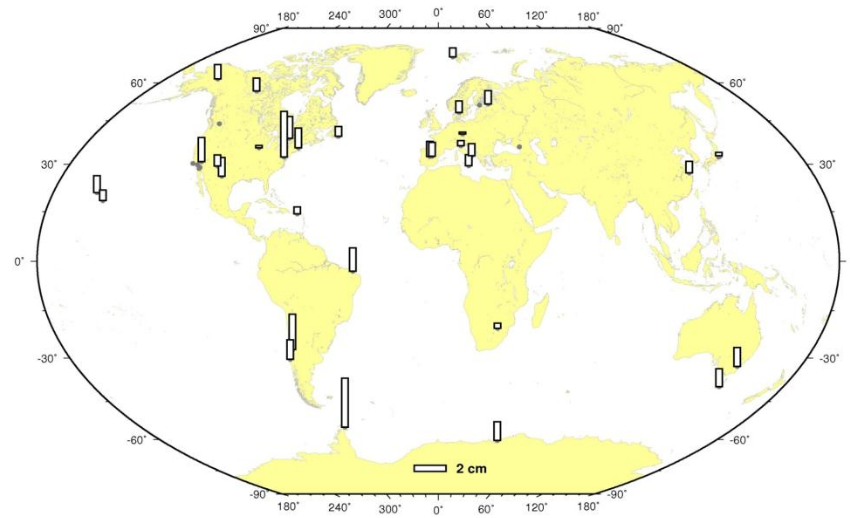


The difference vectors are named as „local ties“. Problem: They show large discrepancies w.r.t. the geodetic space techniques (some centimetres) at some sites. → the handling of local ties in ITRS realization is difficult.

Colocation sites

Local tie misfits from DTRF2008 computation (3-dimensional)



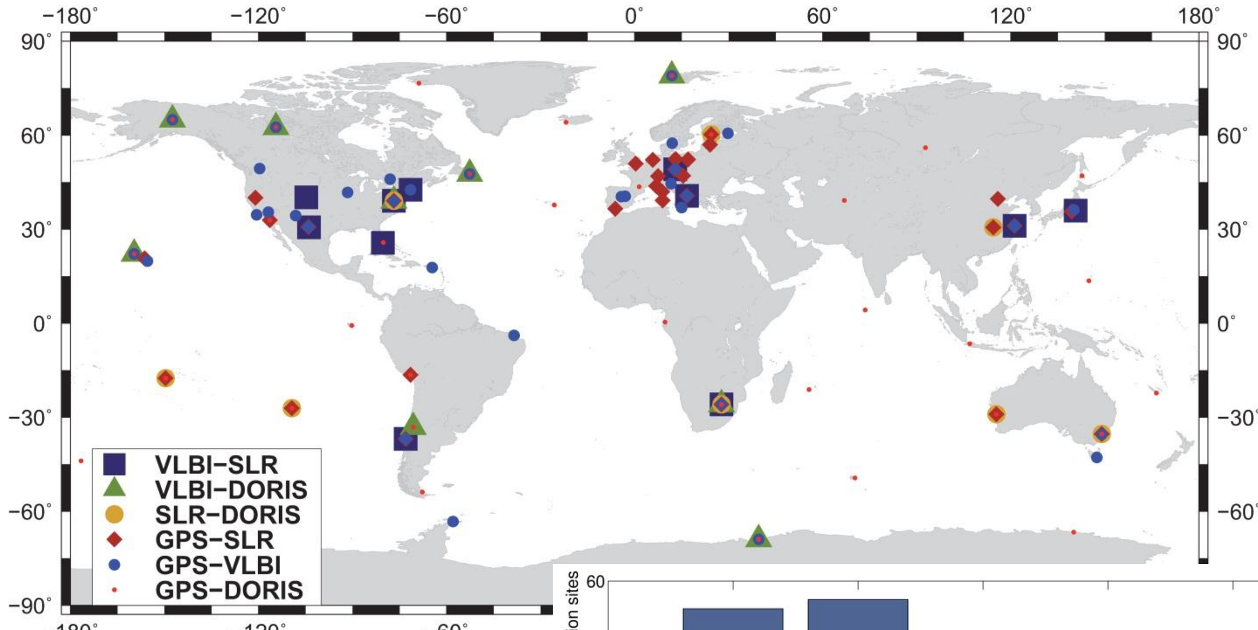


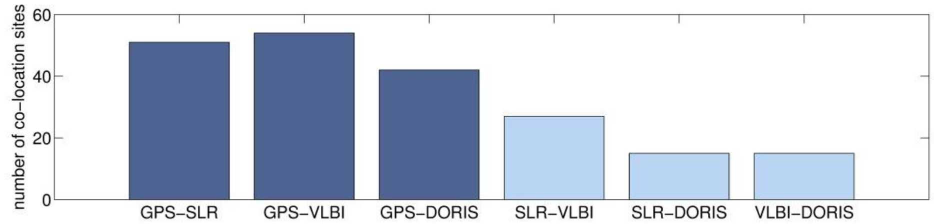
VLBI-GNSS colocation sites (DTRF2008 computation)

- Reasons: model deficiencies (space techniques) or local tie measurement errors
- Improvement w.r.t. ITRF2005 due to model improvements.
- But, local tie misfits reach still centimetres.
- VLBI-GNSS sites show the smallest discrepancies. For some stations even less than 5mm.

Global distribution of colocation sites

Colocation sites used in DTRF2008





GNSS contributes to most of the colocations. → GNSS is fundamental for the combination of all station networks on a high accuracy level.

Colocation sites and EOP

Combination of station coordinates provides one station network with

- One origin
- One orientation
- One scale

} ± uncertainty of realization

The combination of the EOP (pole coordinates) combines the orientation of the technique-specific networks (w.r.t. x and y axis)

→ Both ways must be consistent

Pole coordinates are used for the validation of the local ties: local ties and their standard deviations are chosen claiming

- that the offsets between the (still uncombined) pole coordinates are minimal
- that the deformation of the networks due to the combination is minimal

→ The two conditions are contrary and the introduction of local ties a complex process

Realisation of the geodetic datum …

… in accordance to the ITRS definition in the IERS Conventions

Origin	realized from SLR observations (VLBI not sensitive, GNSS and DORIS are affected by systematics)
Scale	realized from SLR and VLBI (GNSS and DORIS are affected by systematics)
Orientation	„no-net-rotation“ conditions w.r.t. ITRF2005 using a subset of GNSS stations (high accuracy, well globally distributed)

Conditions in the Gauß-Markov model

Solution

Because of the rank deficiency of $\boldsymbol{N}$, pseudo observations must be added

$$\hat{\boldsymbol{x}} = (\boldsymbol{N} + \boldsymbol{D})^{-1}(\boldsymbol{y} + \boldsymbol{d})$$

$\boldsymbol{D}$ is the NEQ matrix and

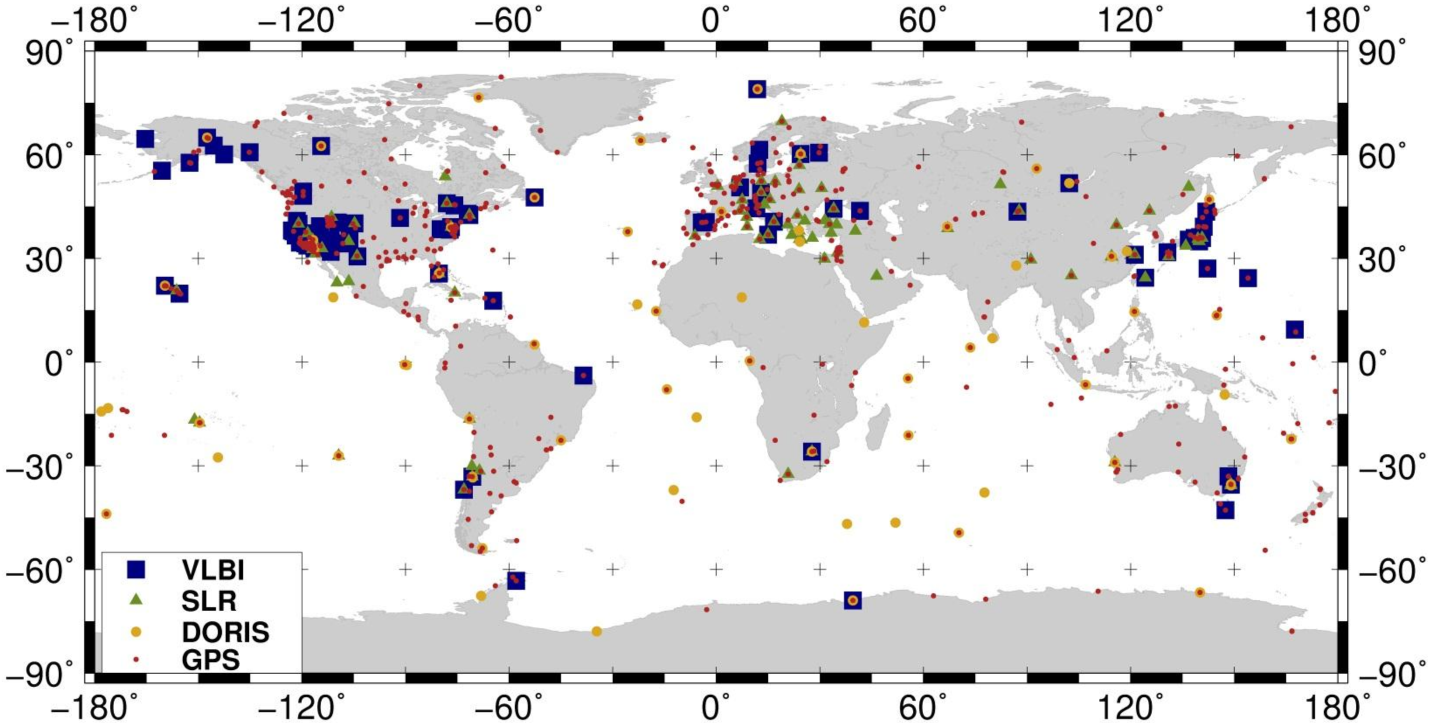
$\boldsymbol{d}$ the right hand side of normal equation of the conditions

In ITRS realization,

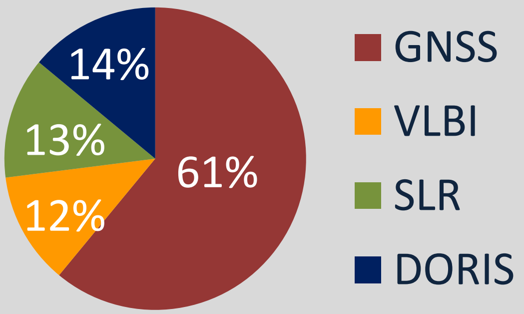
Pseudo-observations are used for the introduction of the local ties and combination of the velocities at colocation sites.

After doing this, $\boldsymbol{N}$ has still a rank deficiency with respect to datum parameters of orientation: No-net-rotation conditions are added based on a subset of GPS stations which provide a high accuracy.

DTRF2008: station distribution



VLBI	106
SLR	122
GNSS	559
DORIS	132
Total	≈1000



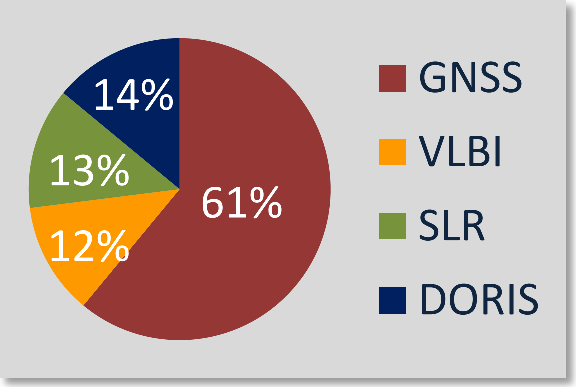
DTRF2008: station distribution

Discussion:

GNSS dominates the frame and contributes to most of the colocations but many of the GNSS stations are affected by discontinuities (equipment changes).
Furthermore, the GNSS observation time span is more than 10 years shorter as for VLBI and SLR.

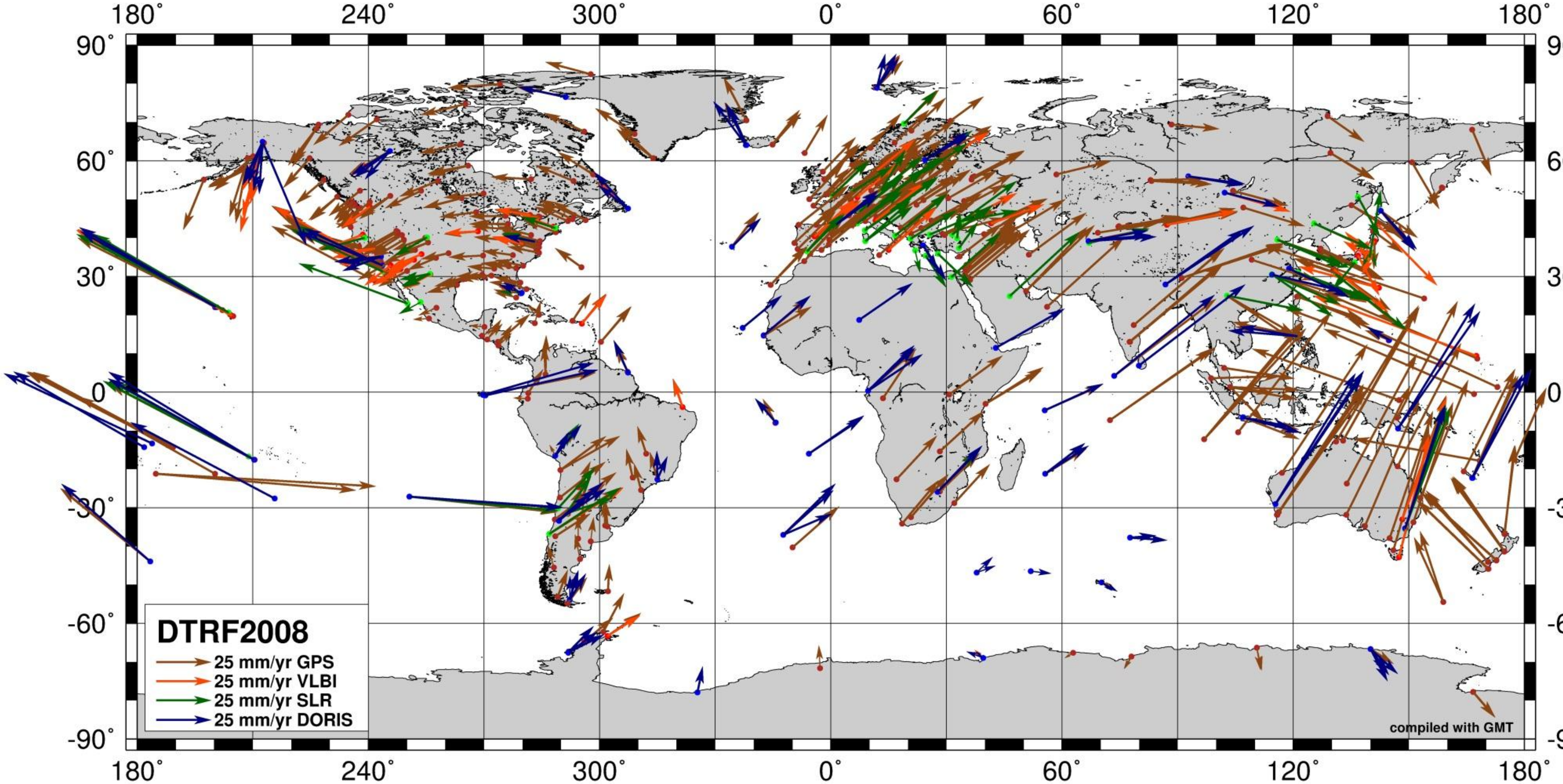
→ A reduction of discontinuities in GNSS time series will lead to a significant improvement of accuracy and long-term stability of the frame.

VLBI	106
SLR	122
GNSS	559
DORIS	132
Total	≈1000



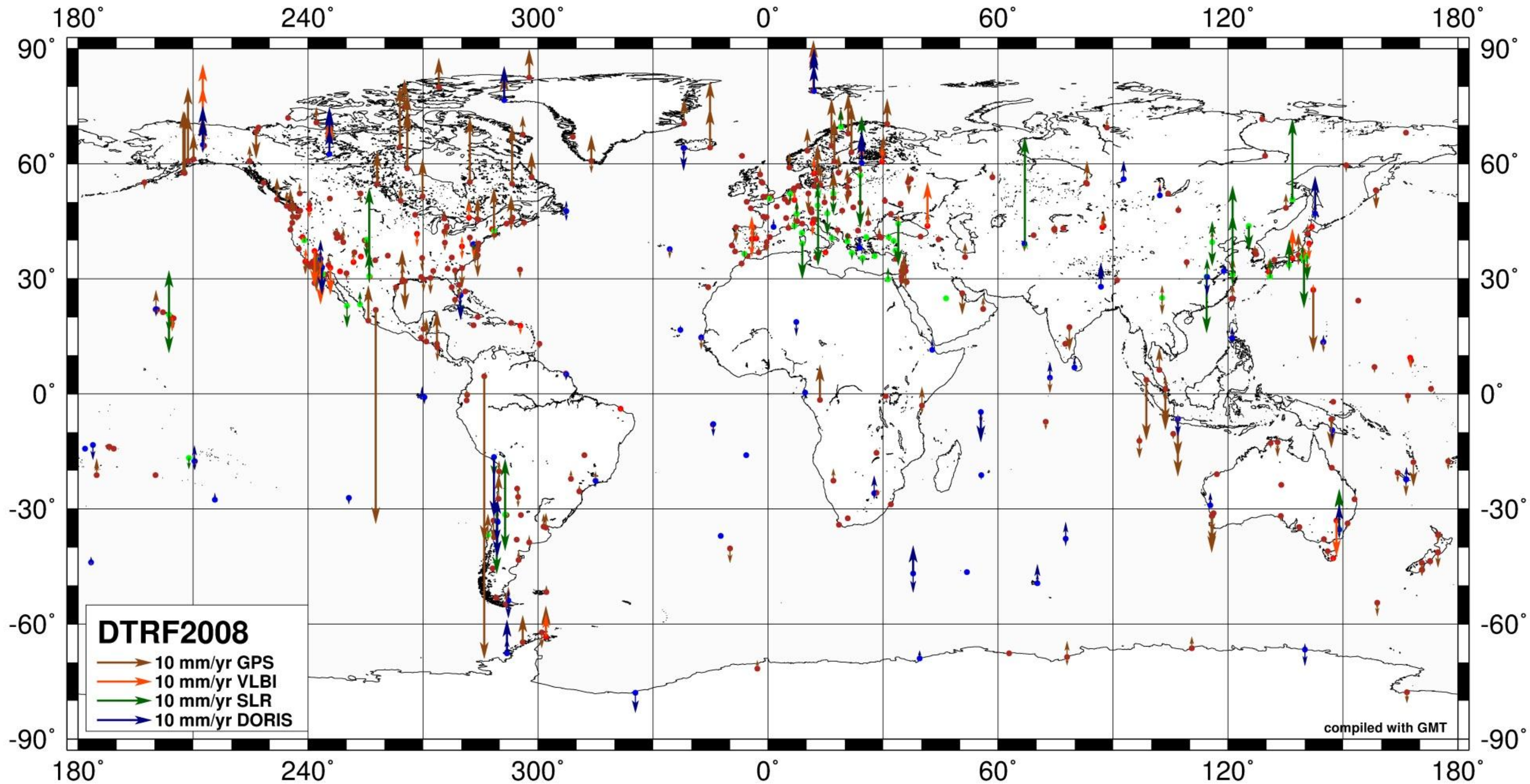
DTRF2008: velocity field

Horizontal velocity field of DTRF2008



DTRF2008: velocity field

Vertical velocity field of DTRF2008



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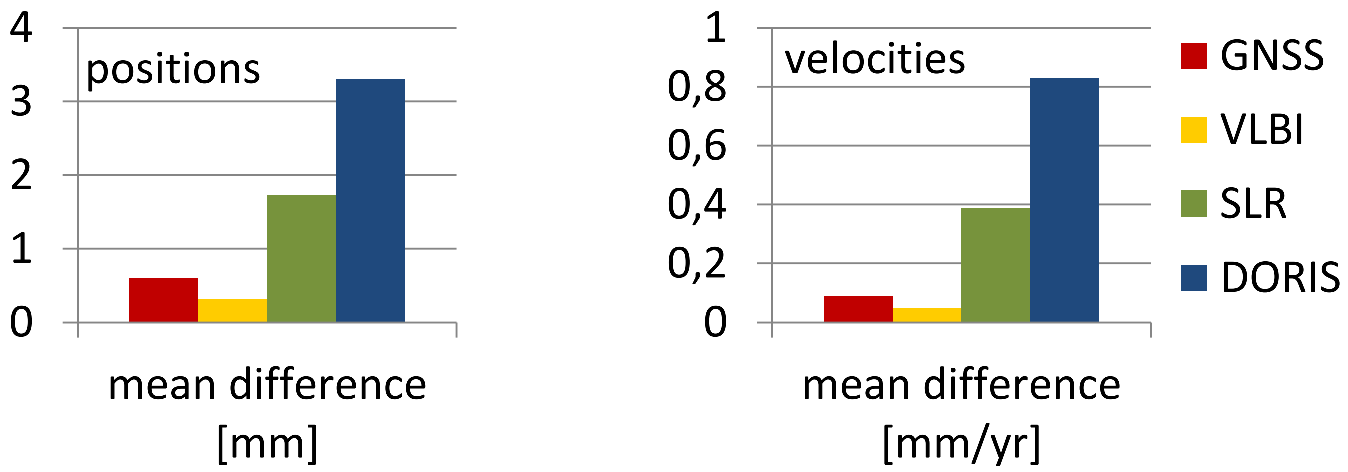
DTRF2008: accuracy

Internal accuracy

- **Geodetic datum:** within 0.6 mm and 0.1 mm/yr
- **Network geometry** (for good stations):

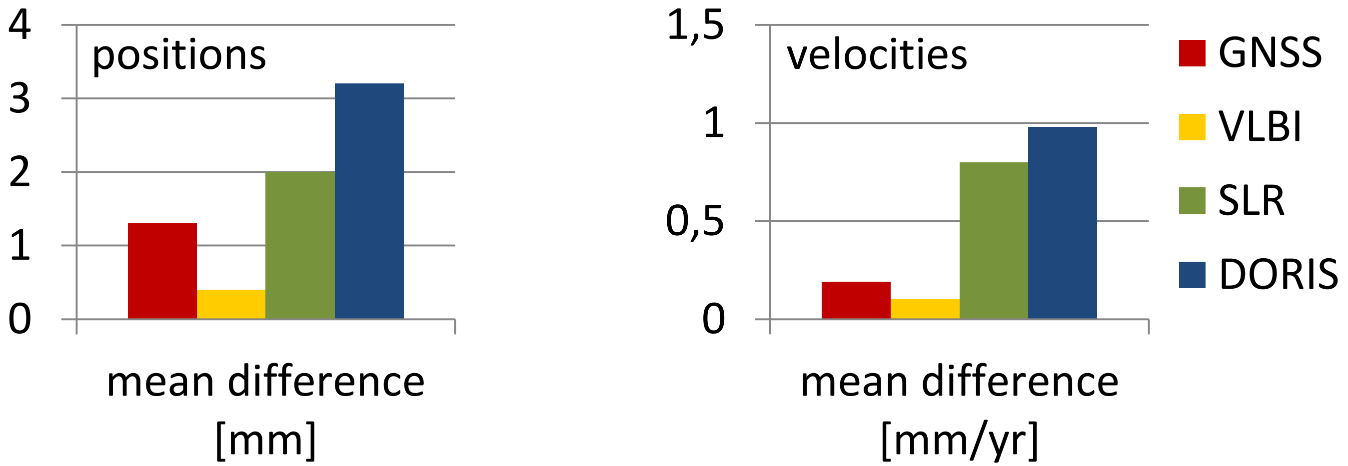


A high internal accuracy is achieved for good stations. For stations with short observation time spans the values can reach centimetres and some mm/yr.

DTRF2008: external accuracy

Comparison with ITRF2008 (IGN)

- **Geodetic datum** (origin, orientation, scale):
  Discrepancies ≤ 6 mm and ≤ 0.5 mm/a
- **Network geometry**
  Subset of good and well distributed stations

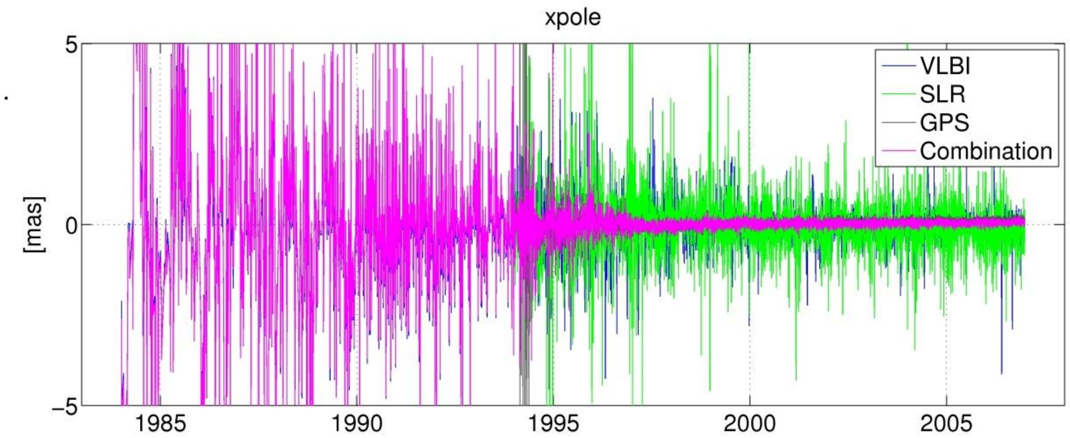


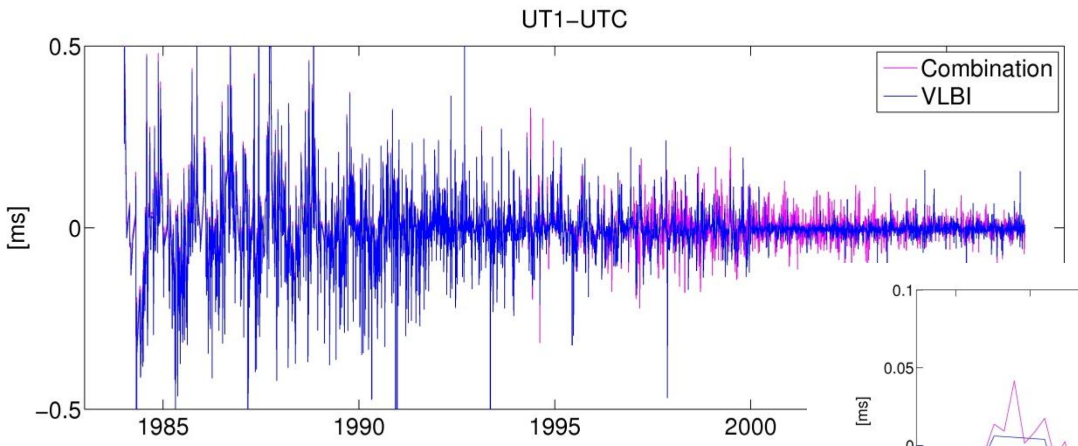
Individual stations: discrepancies of some centimetres.

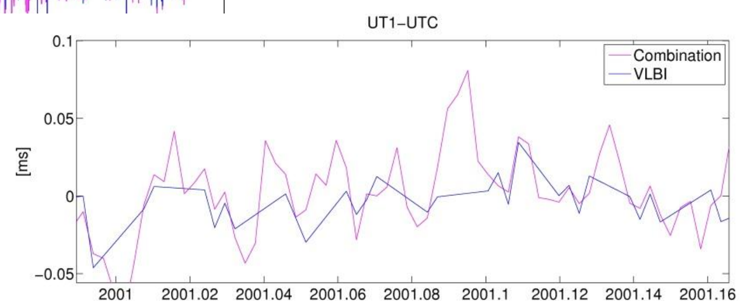
→ The comparison of TRF solutions shows, that the GGOS requirements [1mm and 0.1 m/yr] (Rothacher et al. 2012) are not yet reached! Further developments are necessary!

DTRF2008: EOP time series

EOP with respect to IERS 08 C04







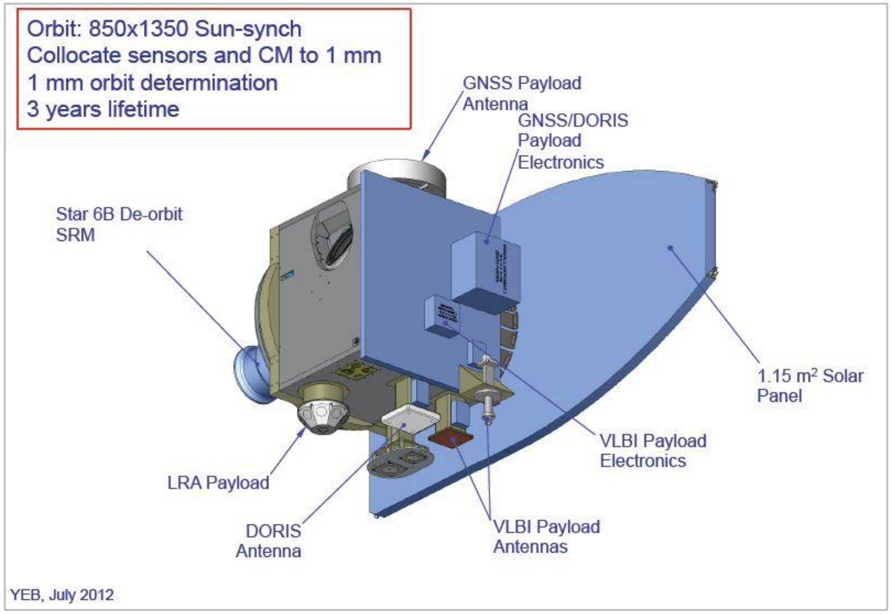
- The scatter is reduced by the combination
- UT1-UTC: from 1997 the time series are continuous, because the available GNSS and SLR rates allow for an interpolation

Summary TRF

- The combination of the space leads to a TRF solution of high accuracy and long-term stability.
- The individual strengths of the techniques are used for TRF computation. VLBI is unique to link ITRF and ICRF. Furthermore, the accuracy of VLBI stations in ITRF is very high due to long observation time series (about 30 years) and a low number of discontinuities in station position time series.
- Station coordinates and EOP are estimated consistently in one adjustment.
- The agreement of TRFs computed by different ITRF CC is for good stations within 6 mm and 1.5 mm/yr. But for some stations also centimeter differences exist.
- In order to guarantee for a high accuracy of the ITRF a new realization is computed every 3-5 years.

Summary TRF

- The reduction of discontinuities in GNSS station position time series would lead to a further improvement of the long-term stability.
- A better global distribution of the colocation sites would also lead to a higher accuracy of the TRF.
- Colocation satellites (see e.g. the GRASP proposal by NASA/JPL) are expect to improve the reference frame significantly.



By Bar-Server et al., JPL

Summary TRF

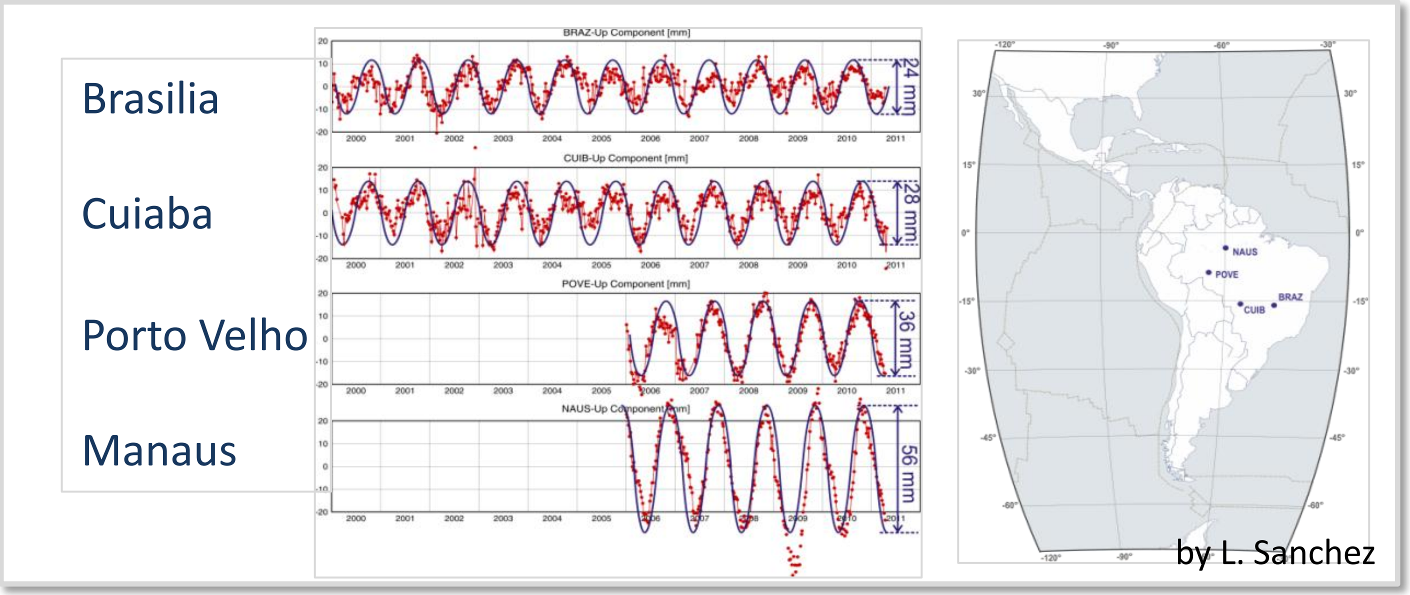
Research topics

- non-linear station movements mainly caused by changes in mass distribution and mass load are not yet considered because the modeling is quite difficult. The station coordinates and consistently estimated parameters can be falsified.
  - → The IERS Global Geophysical Fluid Centre is working on models which have a sufficient accuracy.
  - → Another idea: time series of epoch reference frames in addition to the ITRF
- ITRF and ICRF and the related EOP are not consistent today as they are computed from different data sets, by different institutions and with different software packages. The International Union of Geodesy and Geophysics (IUGG) adopt a resolution on a consistent realization of both frames and the International Astronomical Union (IAU) established a working group which aims for a ICRF-3 which is consistent to the ITRF.
  - → first investigations are performed by DGFI

Epoch reference frames: Motivation

- Station displacements due to changes of the mass distribution in the Earth system and mass load changes on Earth's crust are not (or not adequately) considered by TRF computation today. This limits their accuracy.

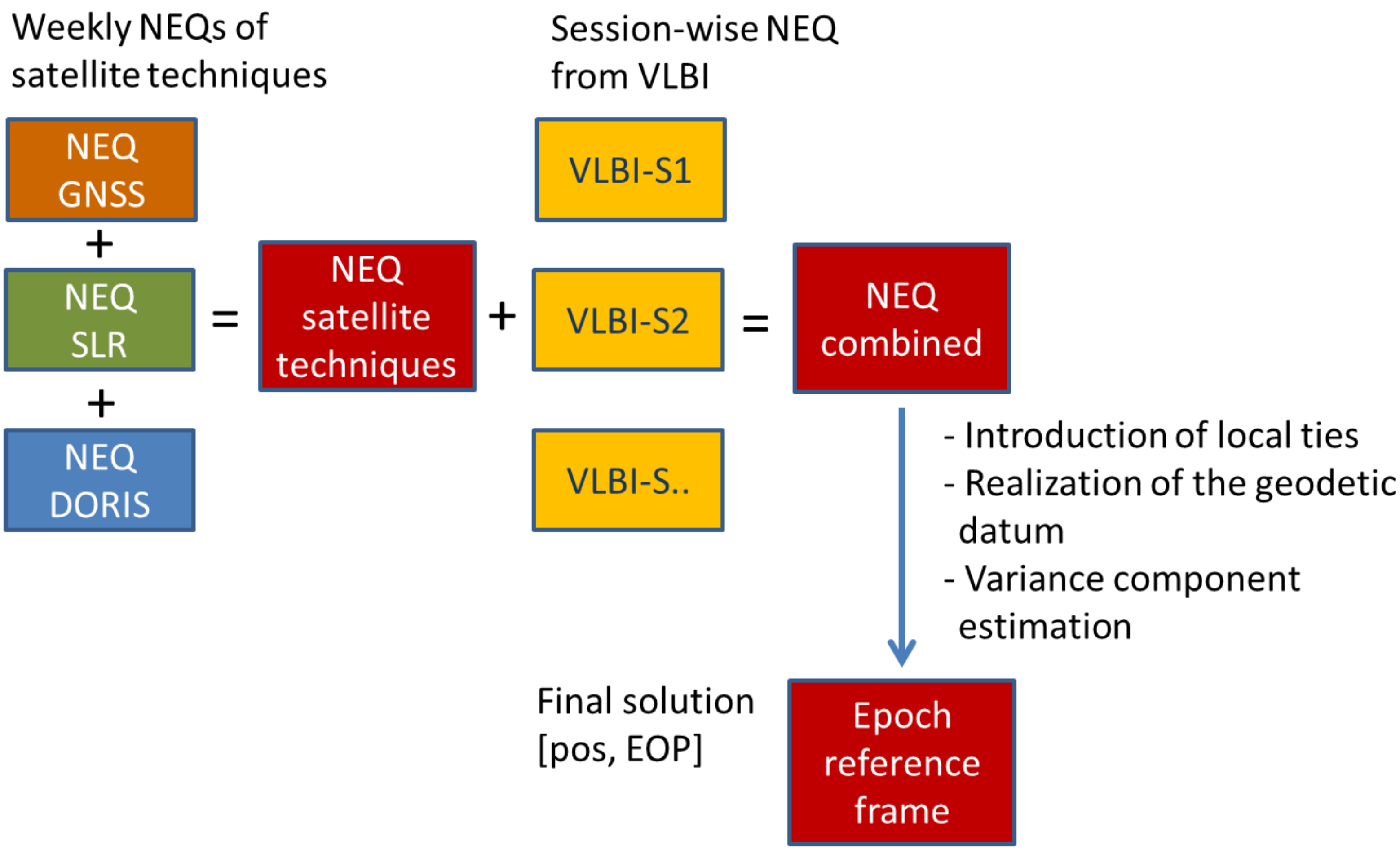
→ Epoch-wise (e.g. weekly) estimation of station positions allows for approximating the displacements with high accuracy.



Examples for large vertical station displacements due to atmospheric and hydrologic mass load changes

Epoch reference frames: Strategy

Weekly combination of space geodetic techniques



Epoch reference frames: Discussion

Pros

- Approximates the true station movement w.r.t. the center of mass with high accuracy (e.g. the alignment of regional frames would improve significantly)
- Consequently, consistent estimated parameters (e.g. EOP) can not suffer from non-modeled non-linear movements
- Benefits from the combination of the techniques (compared to the single-technique epoch solutions)
- Fast computation to provide new positions is possible (e.g. after earthquakes)

Cons

- Accuracy is not as high as for the ITRF (low redundancy, lower density of station networks, only a few local ties)
- Low long-term stability
- Dependency from ITRF: alignment w.r.t. frame orientation
- Frames of the early years do not benefit from the high quality of the present observations (compared to ITRF)

Epoch reference frames: Discussion

Pros

- Approximates the true station movement w.r.t. the center of mass with high accuracy (e.g. the alignment of regional frames would improve significantly)
- Consequently, consistent estimated parameters (e.g. EOP) can not suffer

Conclusion:

Epoch reference frames will become more important in future, but more investigations are necessary to improve their stability.

station networks, only a few local ties)

- Low long-term stability
- Dependency from ITRF: alignment w.r.t. frame orientation
- Frames of the early years do not benefit from the high quality of the present observations (compared to ITRF)

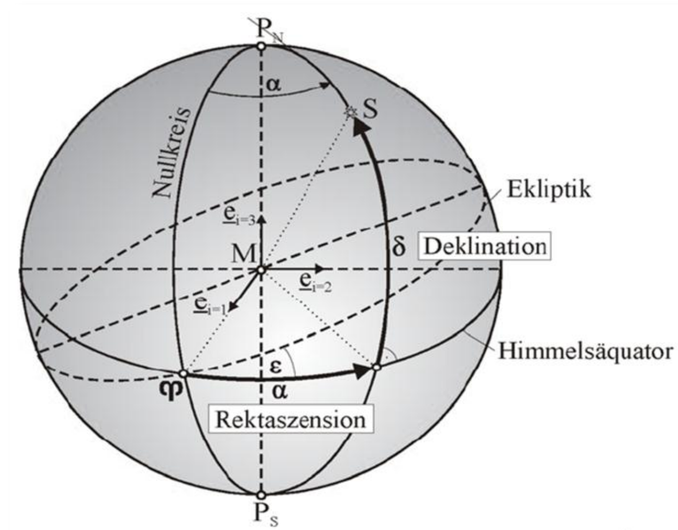
The Terrestrial and the Celestial Reference Frame

- How they are related?
- How consistent they are?

Celestial Reference System (ICRS)

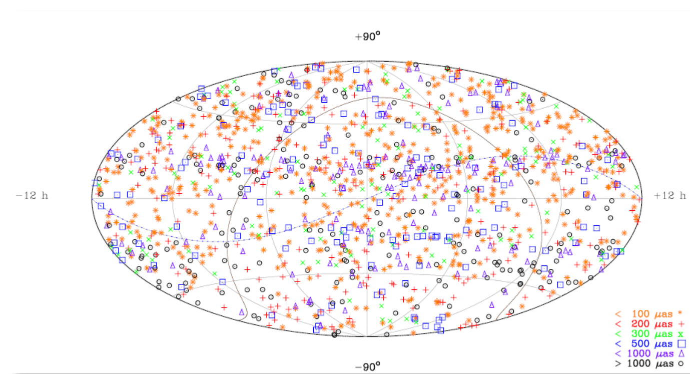
Definition

- The origin M is located in the barycentre of the solar system
- The $\underline{\mathbf{e}}_3$ **axis** is the mean Earth rotation axis
- The $\underline{\mathbf{e}}_1$ and $\underline{\mathbf{e}}_2$ **axis** lie within the plane of the mean celestial equator of epoch J2000.0
- The $\underline{\mathbf{e}}_1$ axis is directed to the point of the Vernal equinox ♈

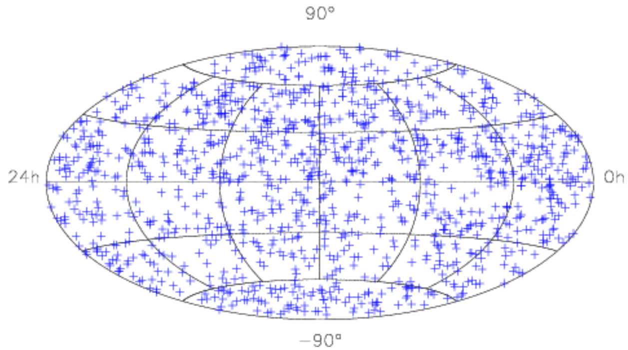


Realization (ICRF)

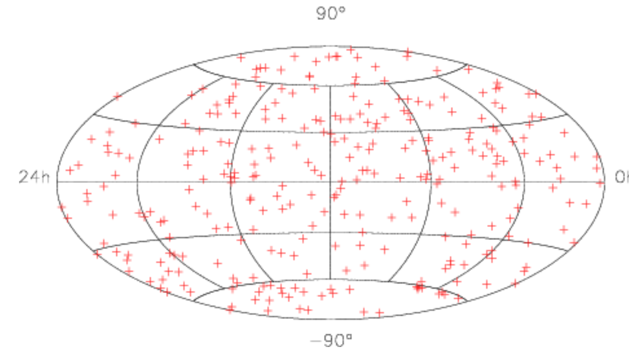
- Coordinates (α,δ) of radio sources
- Only sources with a high accurate position are used for the definition of the axes



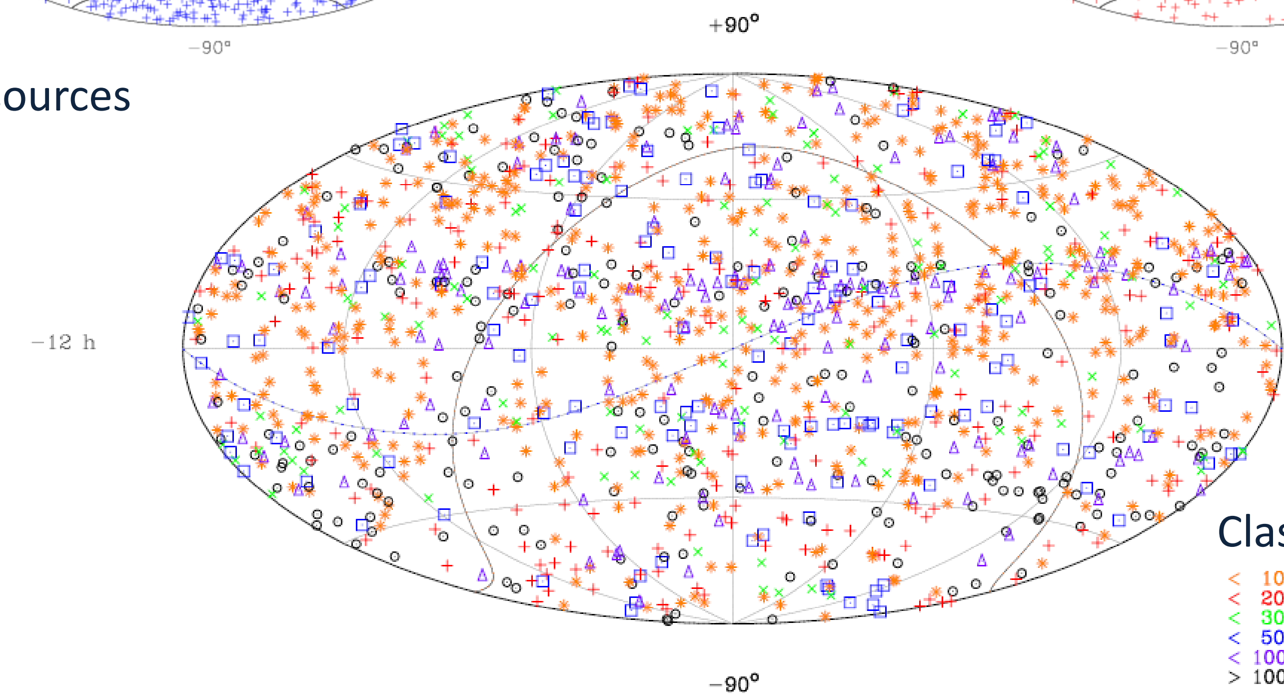
Celestial Reference System (ICRS)



All sources



Datum sources



Classification

< 100 μas *
< 200 μas +
< 300 μas x
< 500 μas □
< 1000 μas Δ
> 1000 μas o

Source: http://hpiers.obspm.fr/icrs-pc/icrf2/icrf2.html

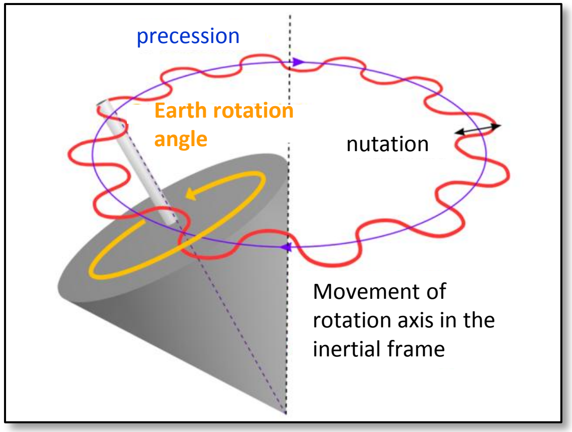
ITRF and ICRF

Transformation between the frames by means of Earth rotation parameters

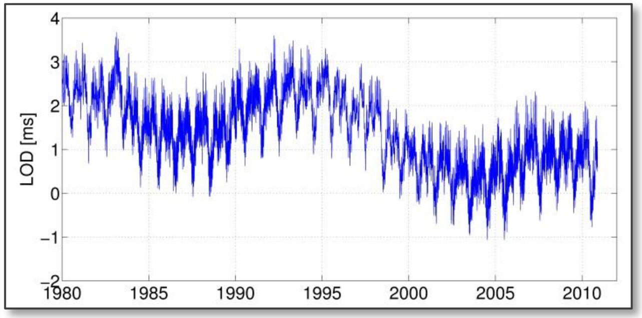
$$x_{ICRS}(t) = P(t)N(t)R_3(-\theta)R_2(X)R_1(Y)x_{ITRS}(t)$$

- Movement of the Earth rotation axis in the celestial frame (Precession, Nutation)
- Rotation of the Earth about its rotation axis
- Movement of the Earth rotation axis in the terrestrial frame (polar motion)

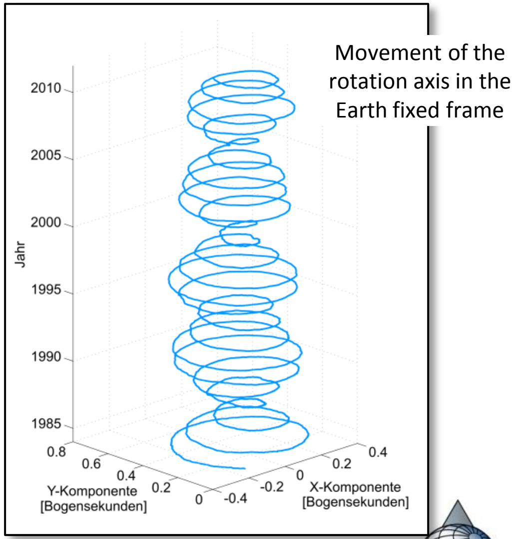
Precession and Nutation



LOD = - δUT1/δt

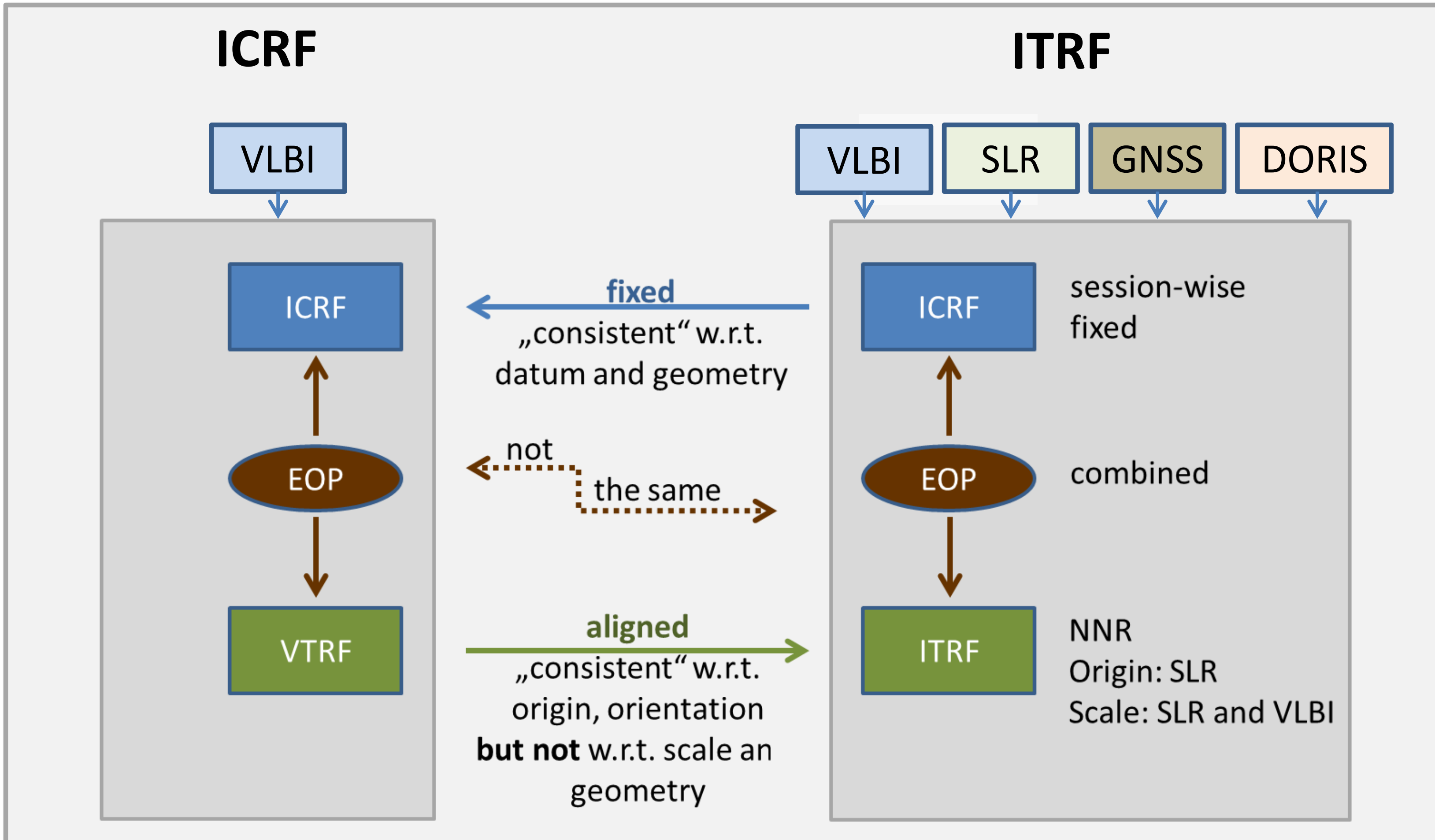


Polar motion

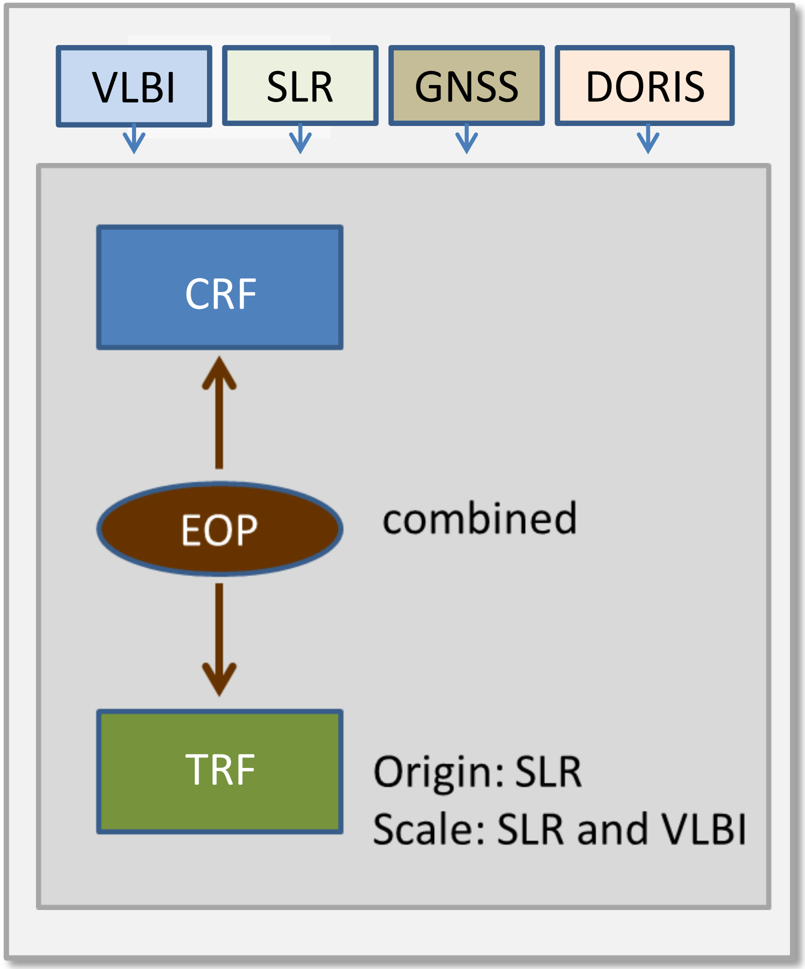


Computation of ITRF and ICRF

Current Situation



Consistent computation of TRF and CRF



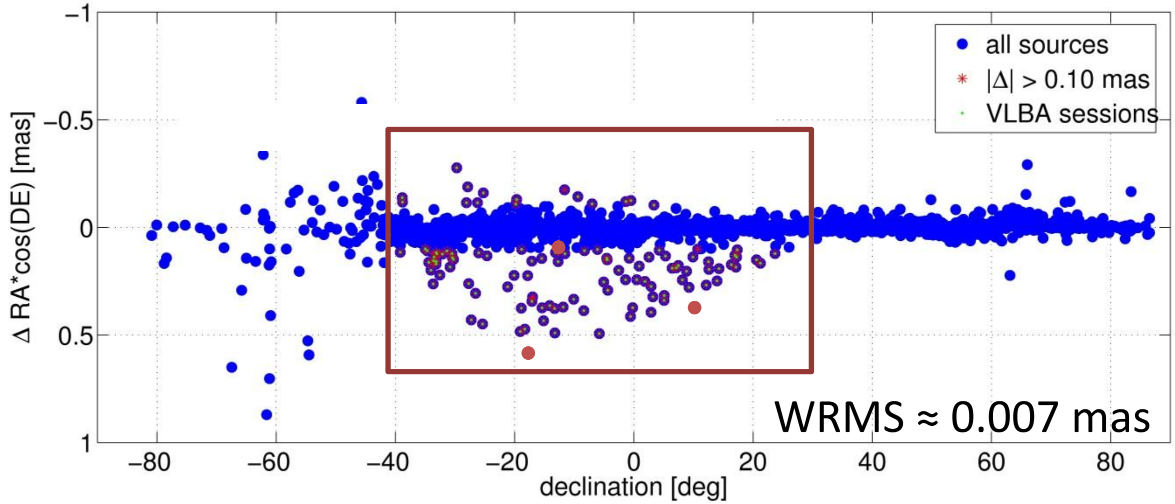
- TRF, CRF and EOP are estimated simultaneously in one adjustment
- Origin and scale are realized according to the standards applied for ITRF computation (IERS Conventions)

→ ≈ 45 000 parameters are estimated

CGE DGFI

Consistent computation of TRF and CRF

Effect in right ascension (α)



Marked sources

- – 40° < DE < 30°
- |ΔRA·cos(DE)| ≥ 0.1 mas
- 108 sources in 21 sessions / 18 regional (VLBA) sessions (105 sources)

→ EOP of regional VLBI and global GNSS networks show systematic differences

→Effect on CRF due to combination of techniques. Improvement?

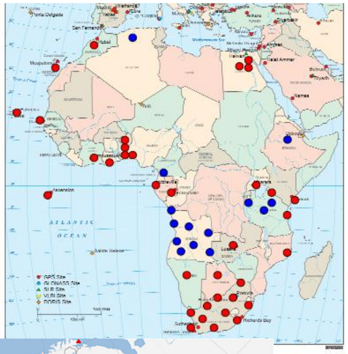
Regional reference frames

- Their function as densifications of the ITRF
- The example SIRGAS

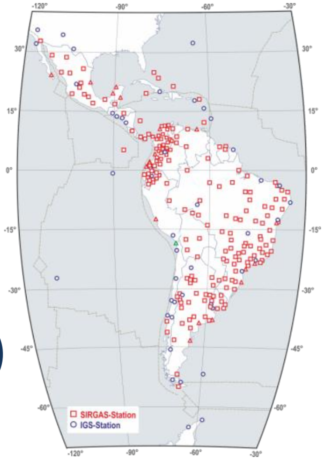
Regional reference frames

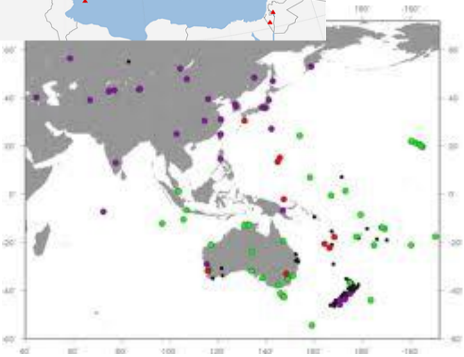
The ITRF is densified by regional reference frames

- They are the basis for scientific and practical applications with a high temporal and spatial resolution.
- They provide the access to the ITRF on regional and national level.
- They allow for the generation and the use of precise geo-referenced data.
- They are mainly based on GNSS stations (low costs).
- Examples:
  - Africa (AFREF)
  - Asia and Pacific Region (APREF)
  - Europe (EUREF)
  - North America (NAD83)
  - Latin America and Caribbean (SIRGAS)



http://geodesy.hartrao.ac.za/pastevents/workshop2/Wonnacott_AFREF.pdf





http://epncb.oma.be/IAG/results.php

Hierarchy of reference frames

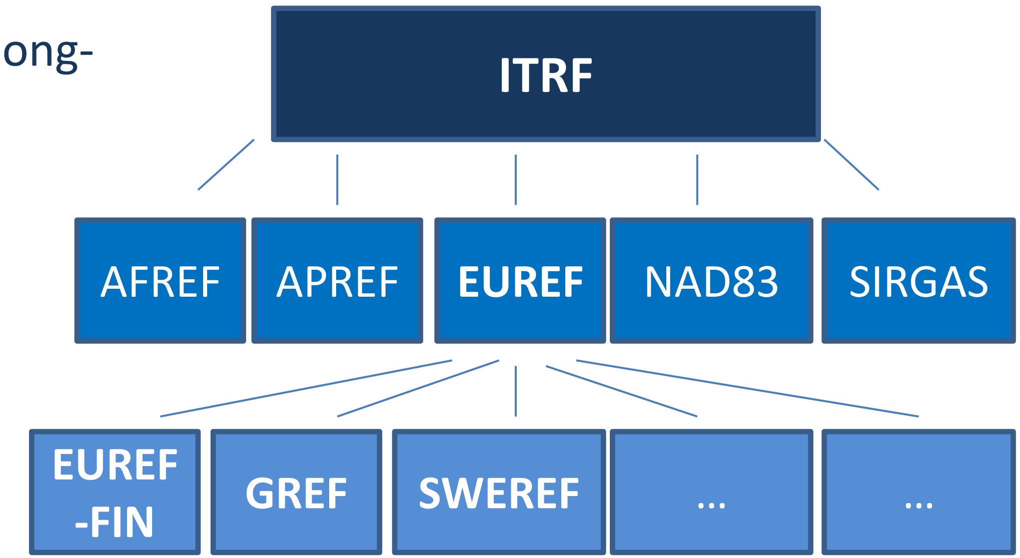
Global terrestrial reference frame (long-term solution → [pos, vel, EOP]

Regional reference frames

GNSS based (long-term solution)

National reference frames

GNSS based (long-term solution)

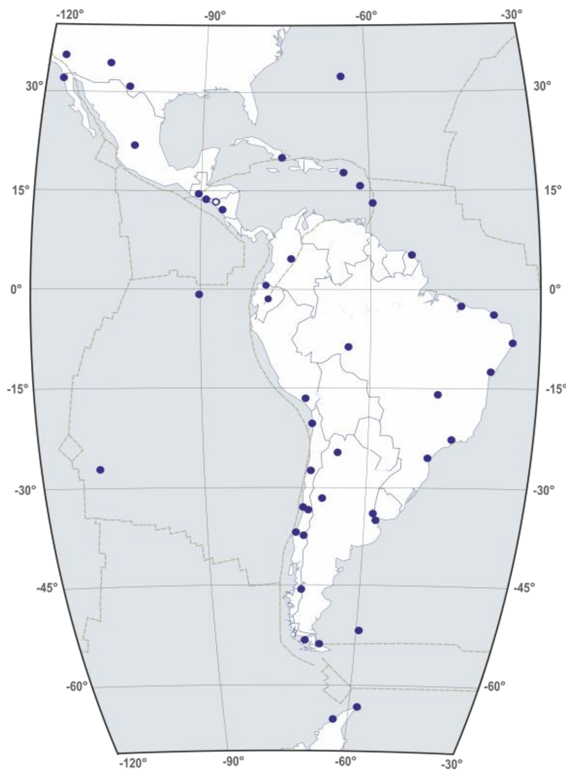


Short-term global technique specific (epoch → [pos, EOP]) **reference frames** aligned to ITRF: densified by regional epoch frames as well

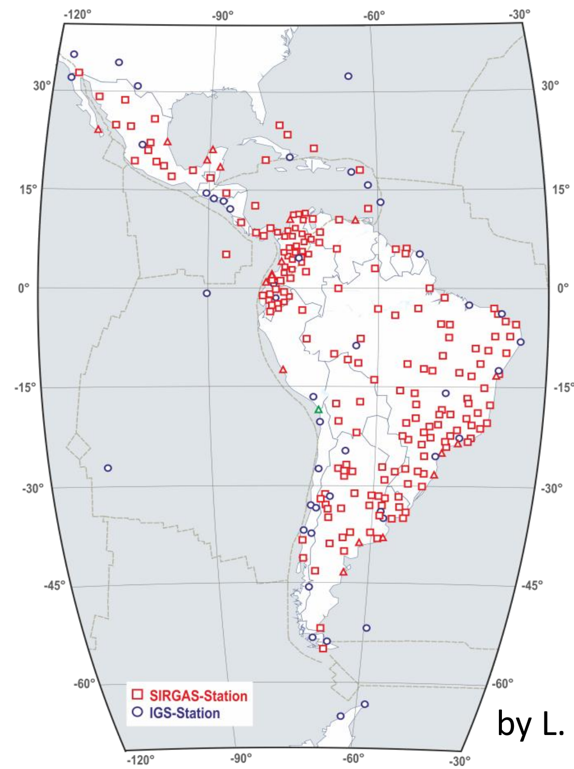
GNSS	SLR	DORIS	VLBI
IGS products: weekly station positions, orbits and EOP	ILRS products: weekly station positions, orbits and EOP	IDS products: weekly station positions, orbits and EOP	IVS products: session-wise station positions, EOP

Example: The regional reference frame SIRGAS

DGFI is responsible for the computation of the reference frame for Latin America and the Caribbean (SIRGAS).



ITRF stations in Latin America (presently 50)



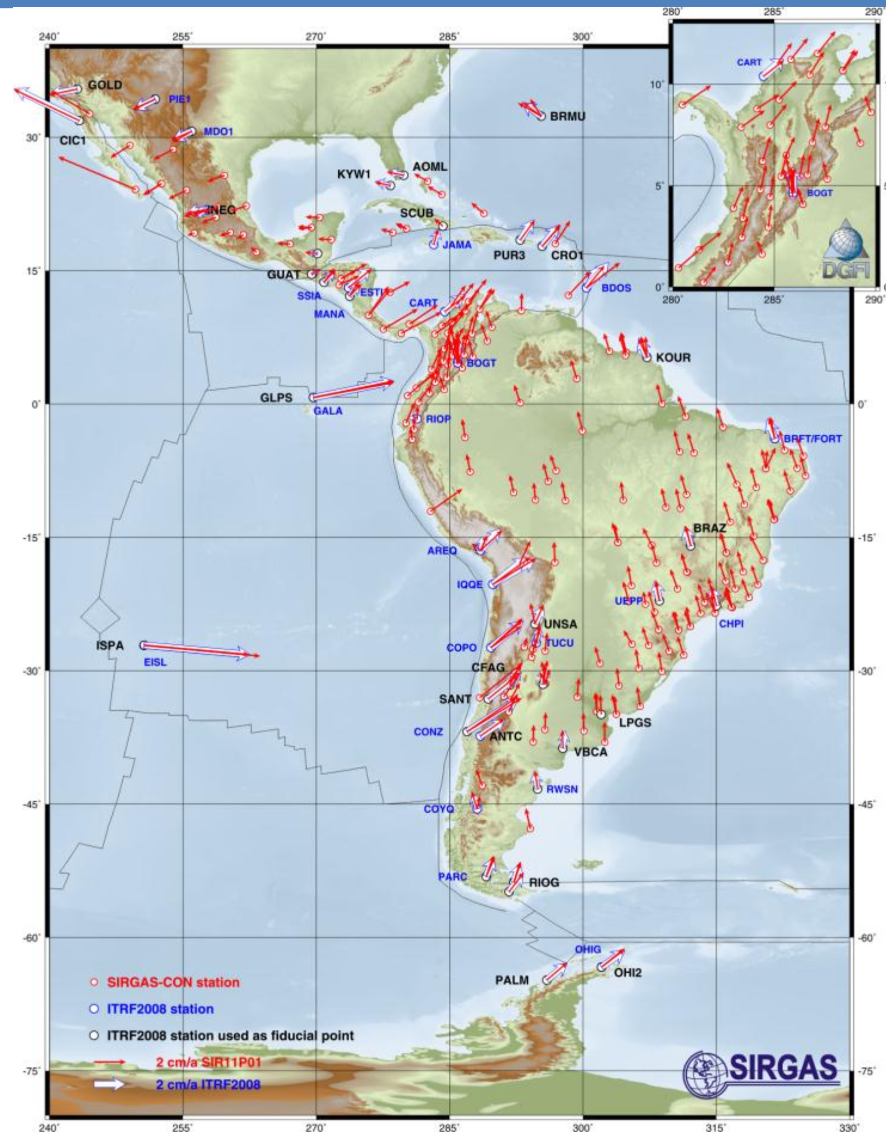
by L. Sanchez

***SIRGAS**: ITRF densification in Latin America (presently about 300 stations)*

SIRGAS activities and products

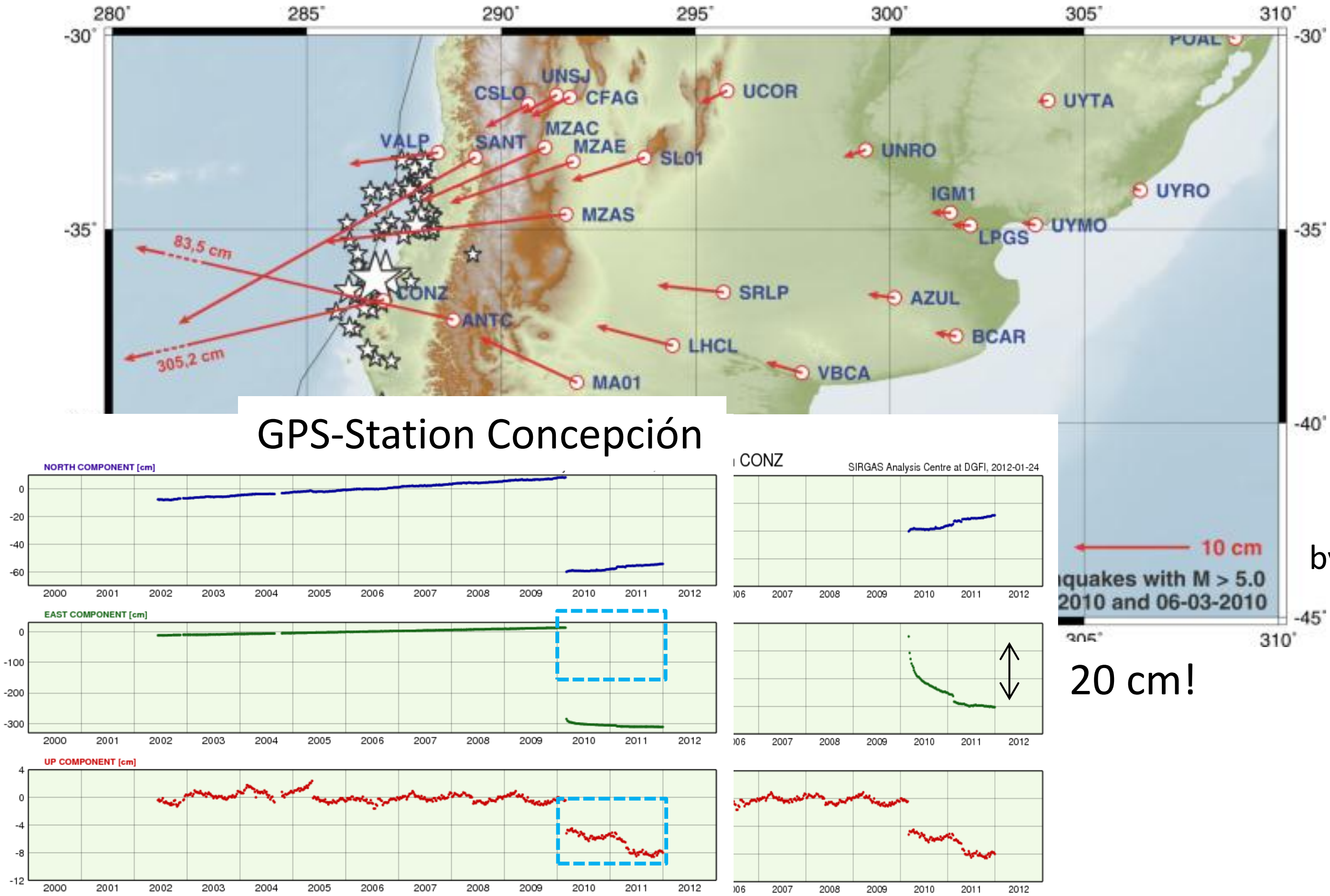
Continuous analysis of the reference frame and publication of

- Weekly station coordinates
- Long-term solutions (constant velocities)
- Time series of station coordinates



Horizontal velocity field of the long-term solution SIR11P01

Co-seismic movements after the earthquake in Maule, Chile, February 2010



by L. Sanchez

ITRF no more valid after the earthquake in that region. Recomputation needs a long time.

→ Fast computation of new coordinates within SIRGAS possible.

Applications of reference frames

Applications of reference frames

Everybody‘s applications

- Car, ship and plane navigation
- Orientation by using a GPS navigation system and maps with a “GPS grid”
- Land survey by GPS, mapping
- Geocaching

Examples for geophysical applications

Determination of

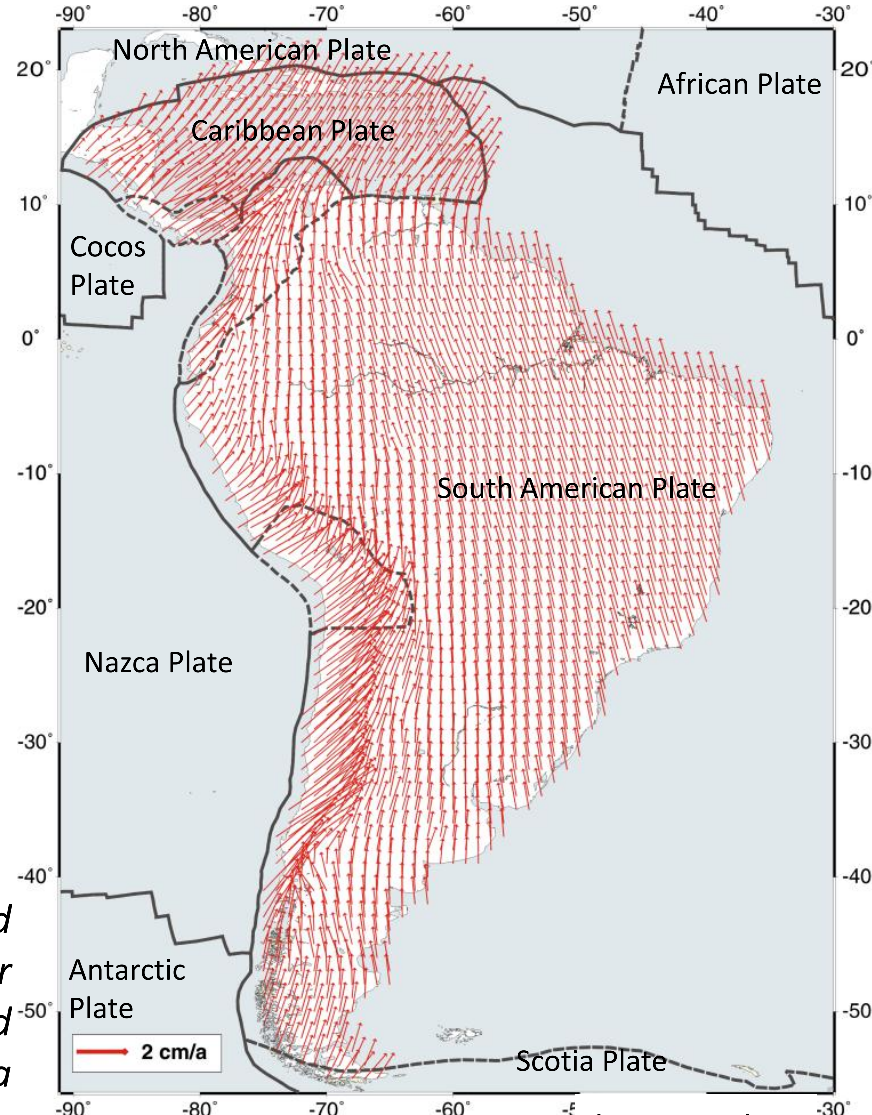
- plate tectonics and crustal deformation,
- sea level change,
- post-glacial uplift.

Application: Plate tectonics and deformation

Modeling of plate motion and deformations of the Earths surface induced by geophysical processes, e.g.

- Plate tectonics
- Earthquakes

Deformation models allow to study plate tectonics and deformation zones and to predict the station movement in particular for new stations.

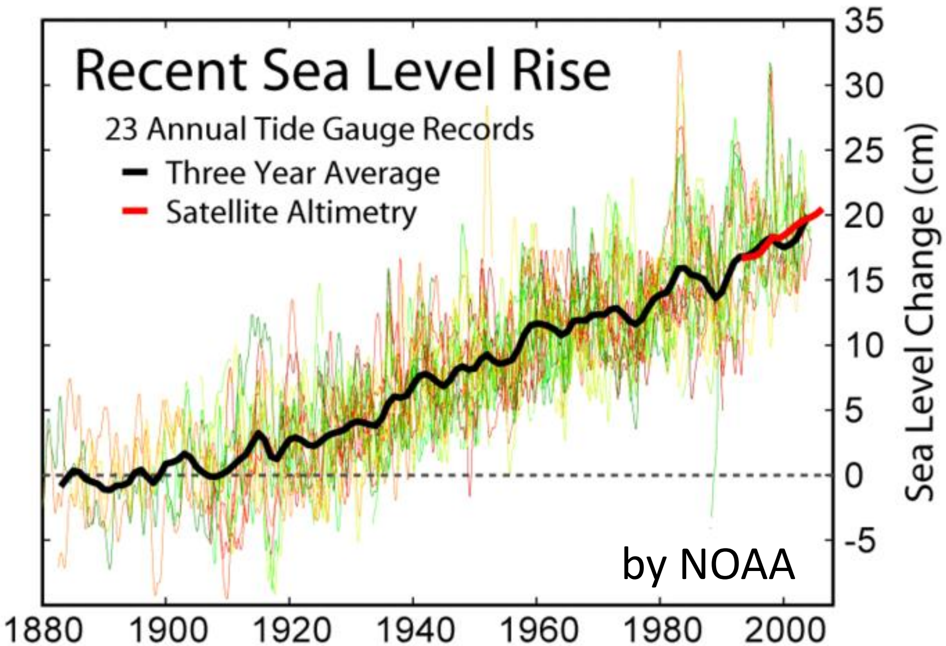


Station movement and deformation model for the Caribbean and Latin America

by L. Sanchez

Application: Determination of sea level rise

Global sea level rise



Increasing trend:
Tide gauges: 1.7 mm/yr
Altimetry: 2.6 mm/yr

- Tide gauges are very important for the long-term trend, but they provide only local observations and no observations on the open sea.
- A global and long-term stable reference frame is required to obtain global sea level rise with high accuracy.

Application: Determination of sea level rise

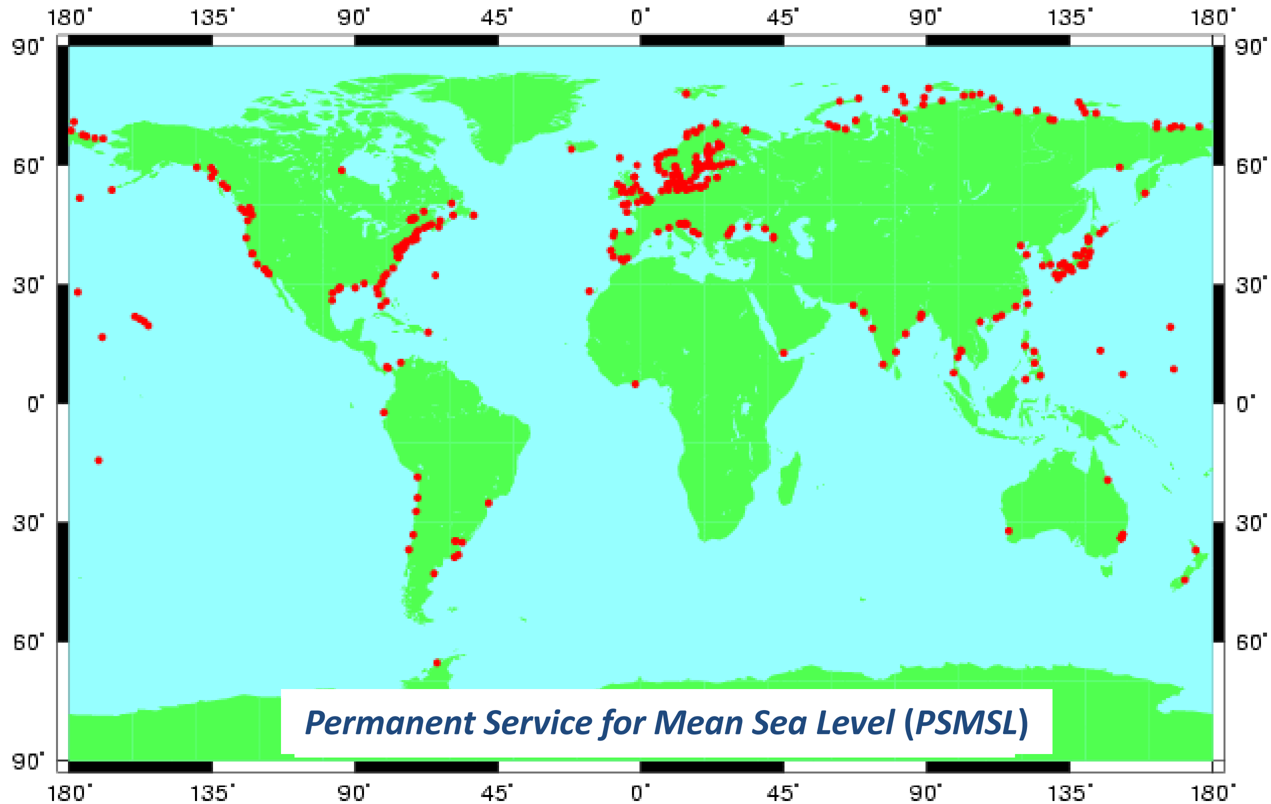
Global sea level rise

Today

- Acoustic or radar tide gauges
- Electronic registration with high temporal resolution

Application: Determination of sea level rise

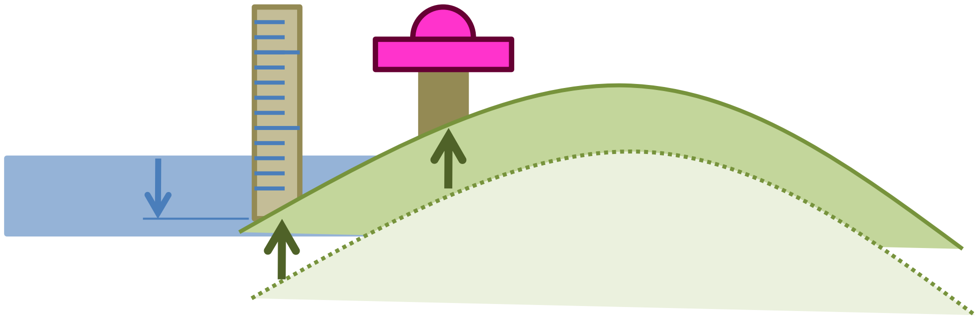
Tide gauges at sea coasts (PSMSL data base)



Advantage compared to modern techniques (satellite altimetry): long time series (for some tide gauges more than 100 years).

Tide gauge measurements are relative

- The tide gauge observes the sea level relative to its position.
- But what to do, when the site is moving?



- The site motion has to be determined with respect to a global reference frame. → GPS stations are installed in immediate proximity of the tide gauges.

sea level rise = tide gauge + GPS measurement

- One reason for an uplift of tide gauge stations is the postglacial rebound. Not correcting for the effect would lead to a falsification of sea level rise for a large region and thus to a wrong global sea level rise.

Application: Determination of sea level rise

Tide gauge measurements are relative

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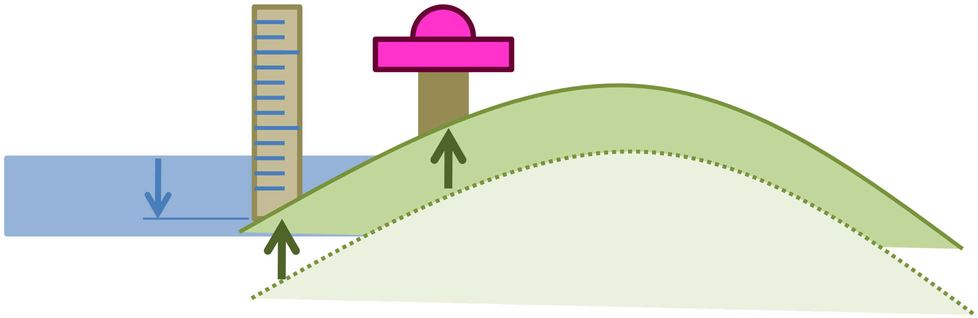


- The site motion has to be determined with respect to a global reference frame. → GPS stations are installed in immediate proximity of the tide gauges.

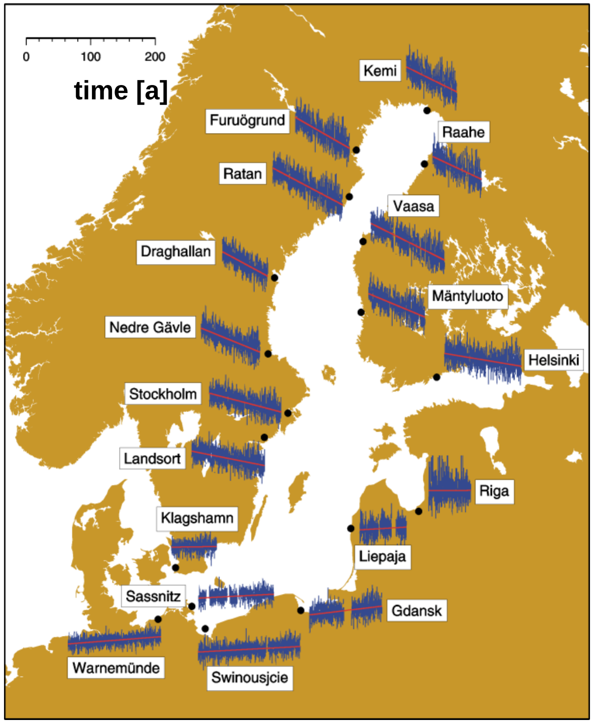
sea level rise = tide gauge + GPS measurement

→ without a global reference frame (represented by the GPS stations and the GPS orbits), the global sea level rise can not be determined

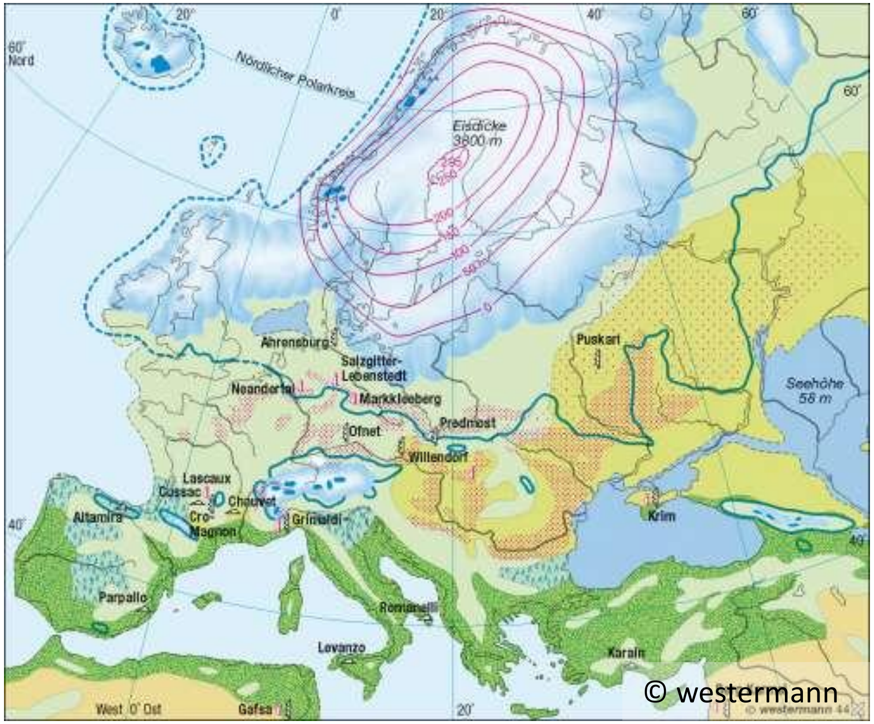
Applications: Determination of sea level rise

The apparent lowering of sea level in Scandinavia

Time series of tide gauges



Ice coverage in Scandinavia during the last ice age



Postglacial uplift of 1 cm/year due to the melting of the ice sheet after the last ice age. → A very slow and thus long-lasting process.

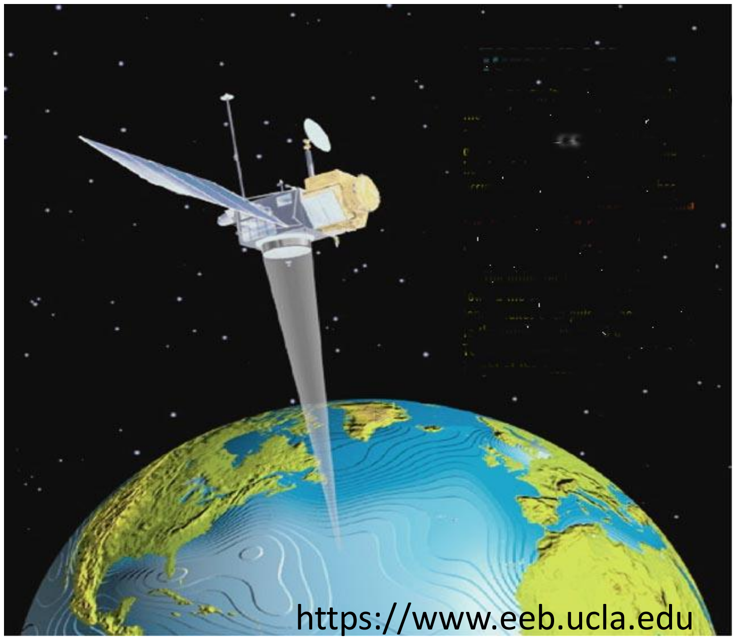
Application: Determination of sea level rise

The Helsinki tide gauge

The Helsinki tide gauge is inside this hut.
A GPS station on a granite pillar is close by.

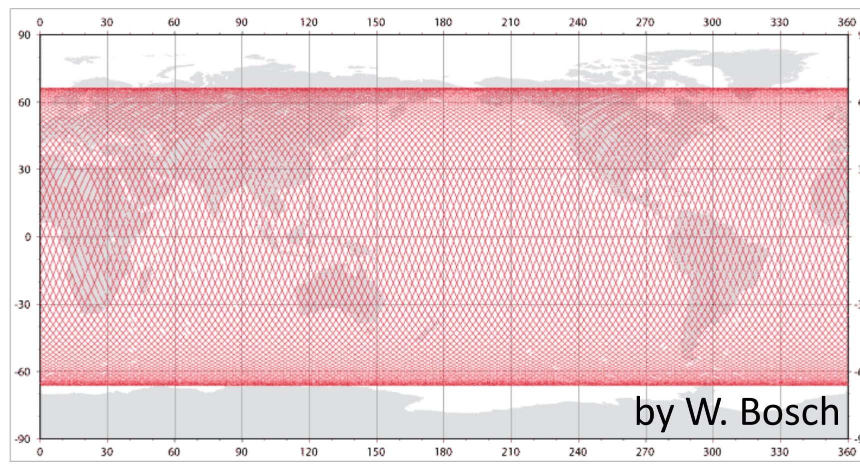
The GPS station is not only used for referencing the tide gauge but also by the Geocache community for calibrating their (quote) toys.
(http://www.geocaching.com)

… from Altimetry missions



Altimetry measures the time taken by a radar pulse to go from satellite to the sea surface and back to the satellite receiver.

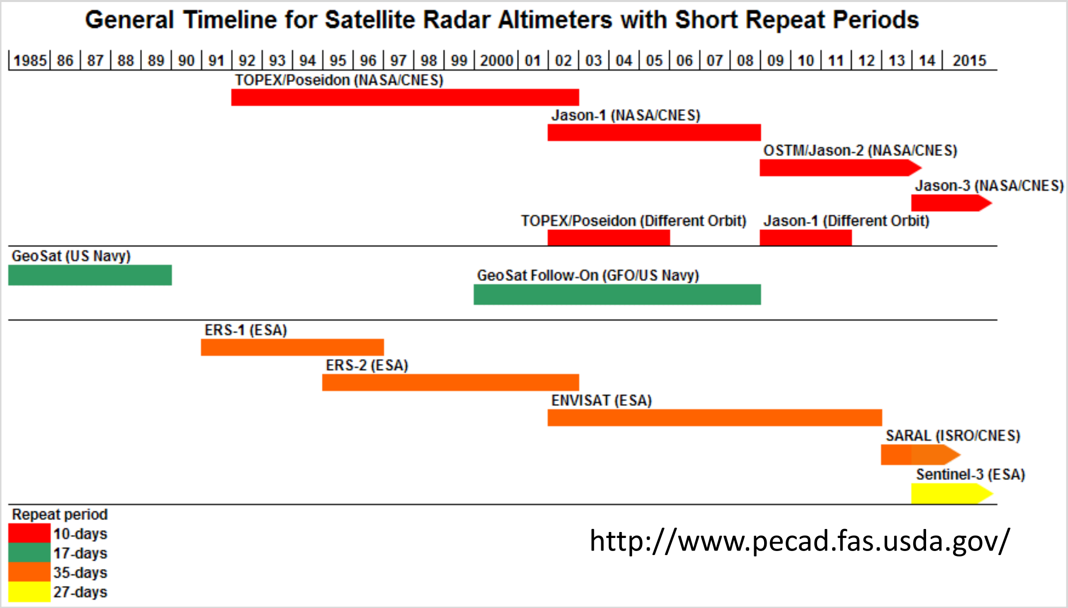
Altimetry provides a global data set.



Ground tracks of TOPEX/Poseidon mission

Application: Determination of sea level rise …

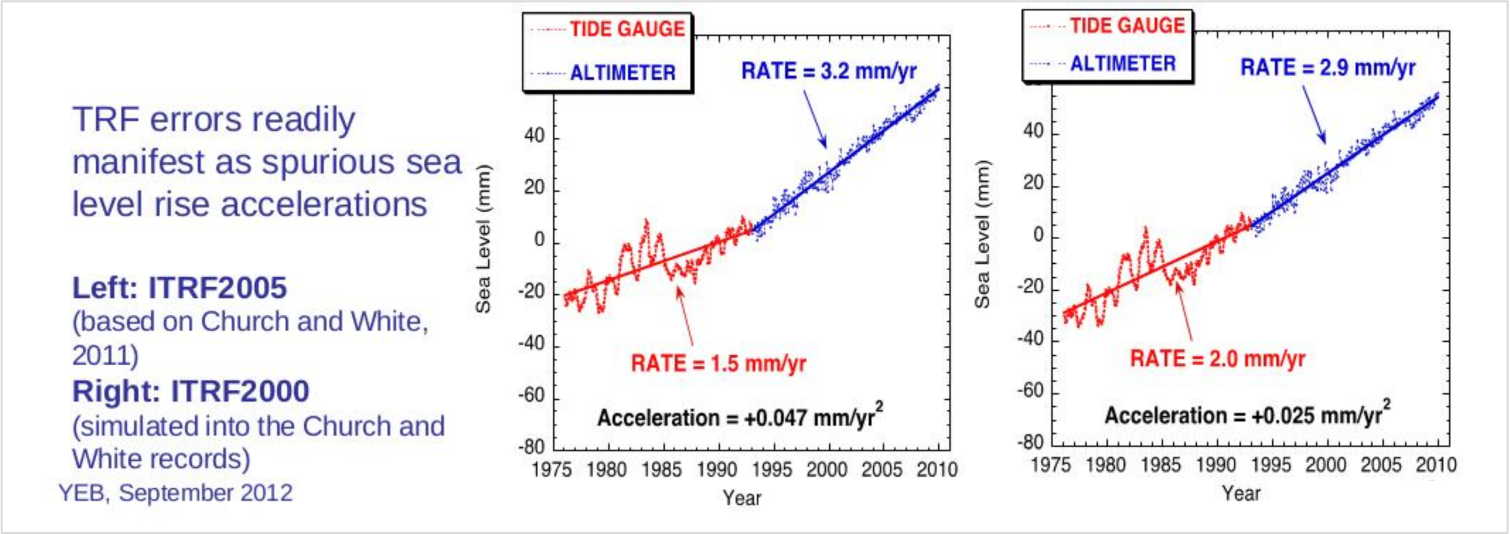
… from Altimetry missions



- At least two missions in parallel since 1992.
- Global coverage and high spatial density of observations.

Application: Determination of sea level rise

Sea level change and ITRF



by Y. Bar-Server, JPL

→All satellite orbits must be determined in the same reference frame with high accuracy in order to obtain the global sea level change. Reference frame errors can affect the sea level change significantly.

Application: Determination of sea level variation

Research: GNSS-tide gauges

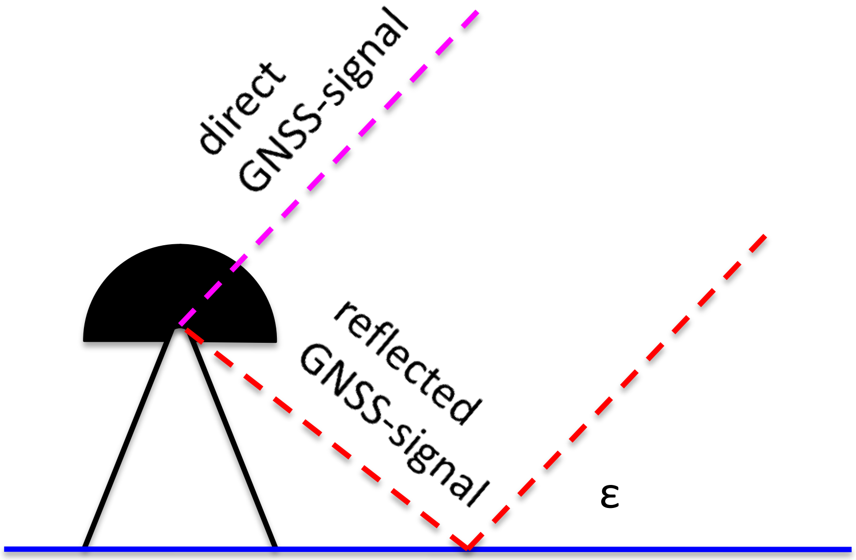
Sea level measurement based on GNSS only using reflected GNSS-signals:

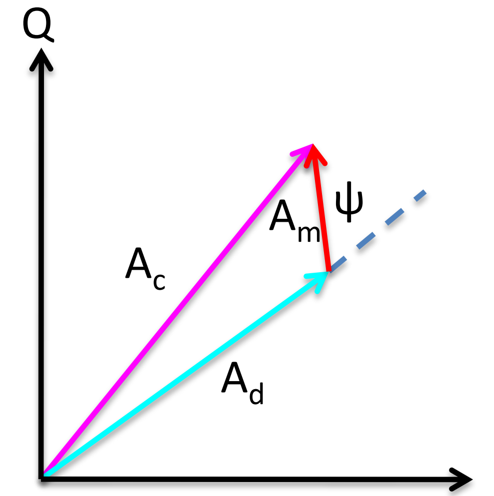
a) SNR-analysis with standard coastal GNSS-installations (e.g. Brest FR)

b) Geodetic GNSS analysis with two-antenna installations (e.g. Onsala, SE)

Onsala Space Observatory (OSO), Sweden

GNSS-tide gauge with SNR-analysis, e.g. Brest

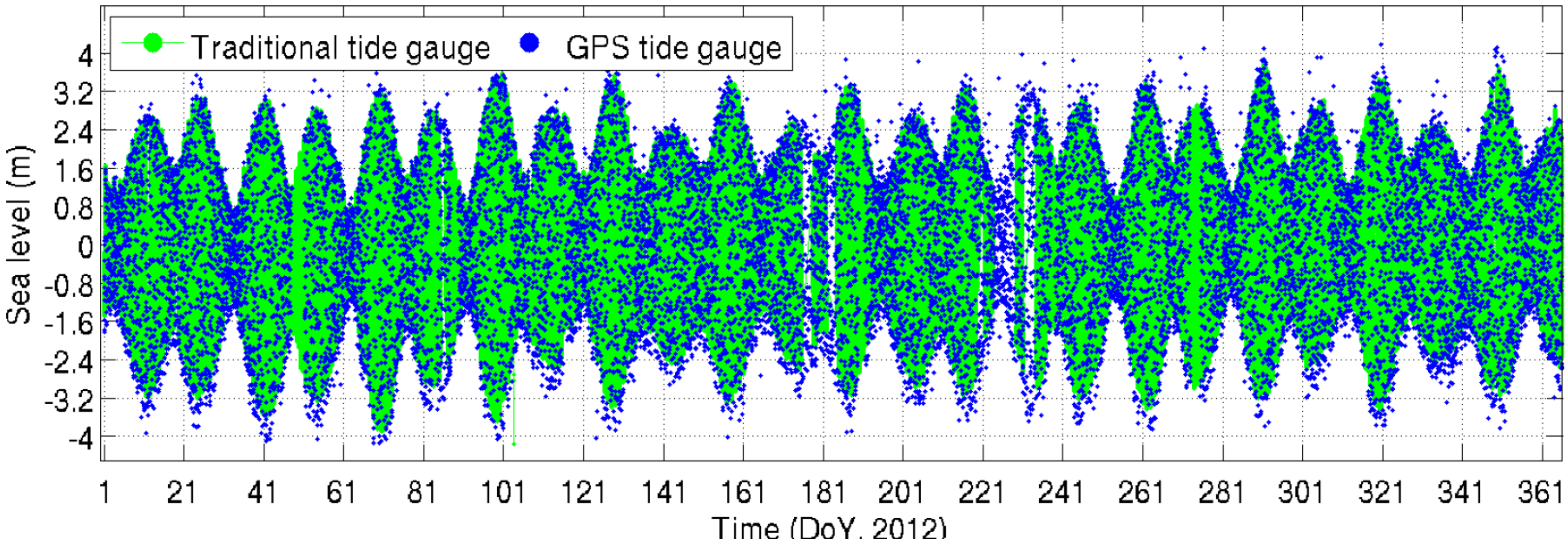




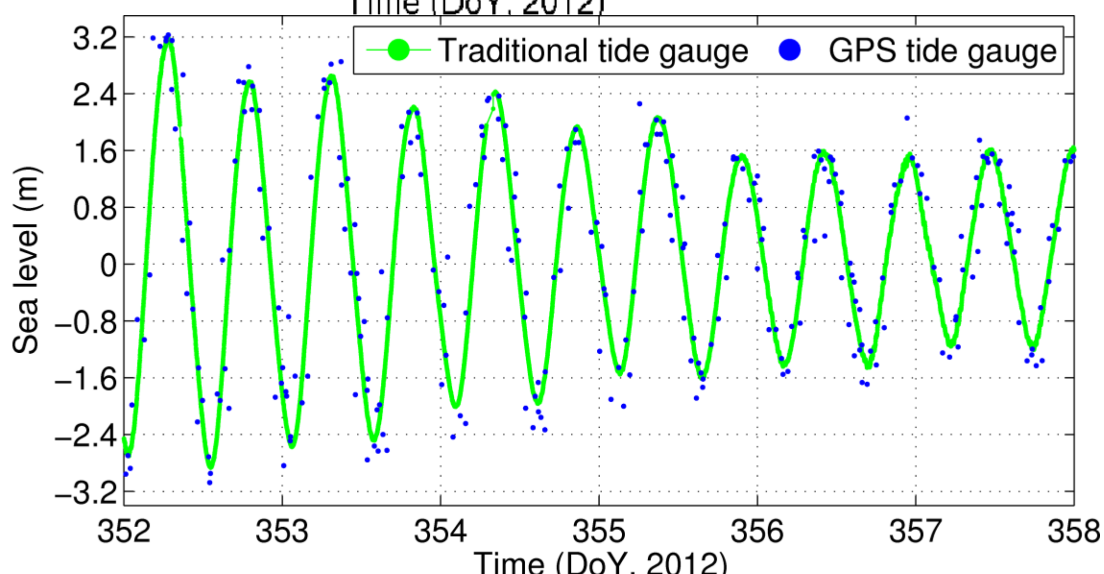
- GNSS receiver: $SNR^2 = A_c{}^2 = A_d{}^2 + A_m{}^2 + A_d\, A_m \cos\psi$
- Multipath varies with: $d\psi/dt = (2\pi/\lambda)\ 2\ h \cos\varepsilon\ (d\varepsilon/dt)$
- SNR varies with: $SNR = A_c \cos(4\pi h/\lambda \sin\varepsilon + \phi)$

- Literatur: t.ex. Georgiadou & Kleusberg (1988); Bilich *et al.* (2007); Larson *et al.* (2007); Löfgren *et al.* (2011); Larson *et al.* (2013)

GNSS-tide gauge with SNR-analysis, e.g. Brest



IGS station
Brest, France

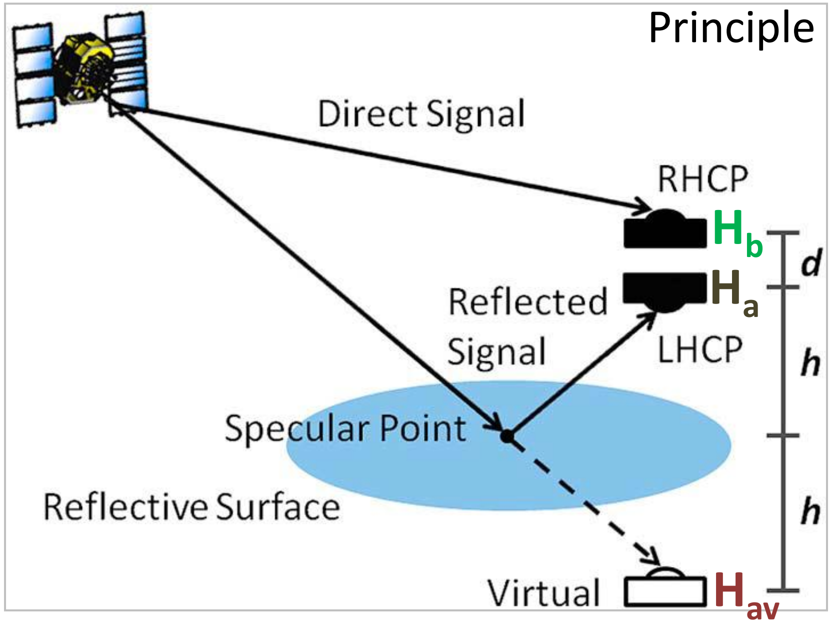


CGE DGFI

Application: Determination of sea level variation

Research: GNSS-tide gauge with two-antennas

Sea level measurement based on GNSS only.



Löfgren et al. 2011

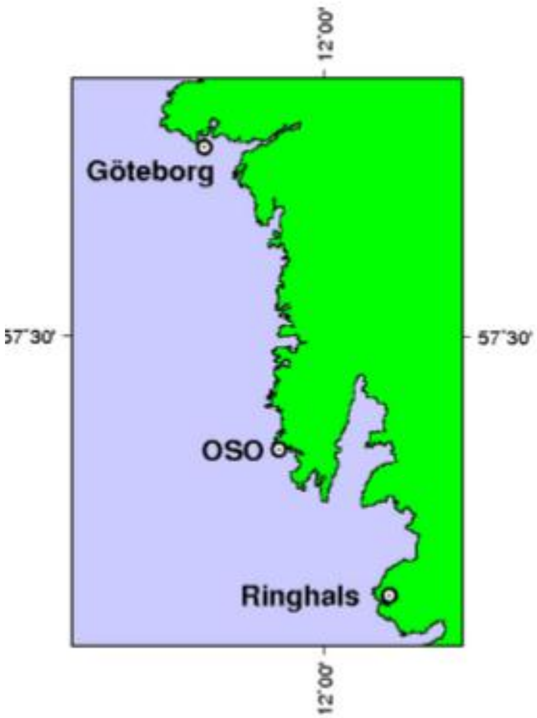
Instrument consists of two GNSS antennas. The height difference ***d*** of the antenna reference points is known with high accuracy.

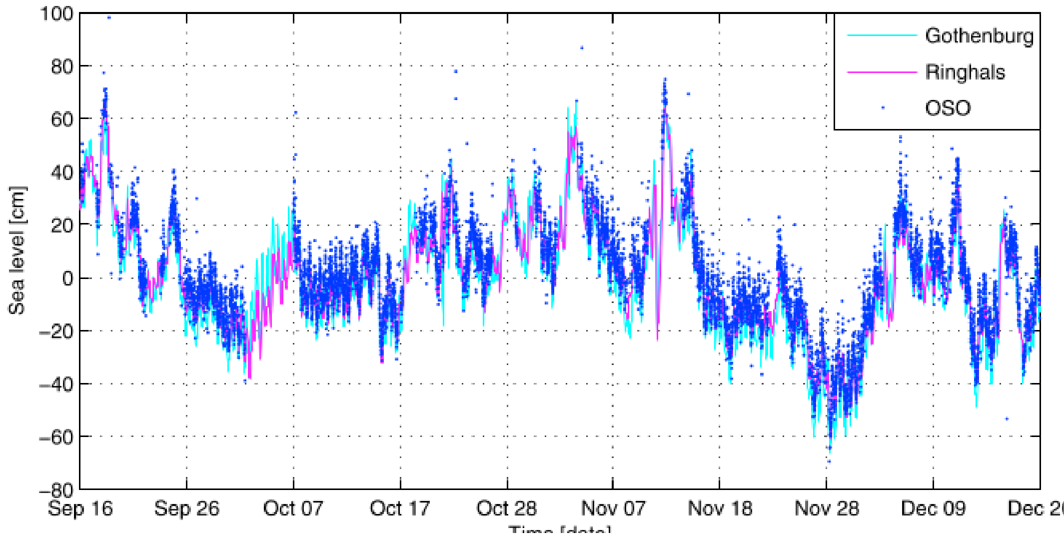
- **b**: Upper antenna, right hand polarized: direct GNSS signals.
- **a**: Lower antenna, upside down, left hand polarized: GNSS signals reflected by the sea surface.
  → virtual height of **a**
  H_{av} = sea level height – ***h***

$$\text{Sea level height} = \frac{(H_b - d + H_{av})}{2}$$

GNSS-tide gauge with geodetic GNSS analysis: OSO

Comparison of OSO and two stilling well tide gauges





Löfgren et al. 2011

Summary

- The ITRF is computed from the combination of different space geodetic techniques by exploiting their individual strengths.
- VLBI is essential for ITRF because
  - it gives the link to the ICRF
  - of its high accuracy and long-term stability
- The consistency of ITRF and ICRF and the related EOP as well as the consideration of non-linear station motions are important research topics in the next years.
- Regional reference frames allow to access to the ITRF on regional level. The high (GNSS) station density ensures a high frame accuracy.
- Many geophysical applications require a high accuracy of the reference frame (e.g. the determination of the sea level change).
- The accuracy requirement specified for GGOS is 1mm and 0.1mm/yr for positions and velocities, respectively. This target is not yet reached and more research in the field of reference frame computation is necessary.

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