Vertical Land Motion at Tide Gauges

GPS @ Tide Gauges

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- **Motivation**
- **Site-related issues**
- **Reference frame issues**
- **GPS Analysis strategies**
- **Signals in GPS time series**
- **Conclusions**

Major applications of tide gauge data:

- **Application A: Absolute, long-term sea level variations**

  Requirements:

  - vertical land movements (Co-location with GPS and absolute gravity);
  - long records;
  - monthly mean sea levels.

- **Application B: Relative sea level variations** (tides, ocean circulation, sea level extremes, ...)

  Requirements:

  - hourly, quality-controlled data.

- **Application C: Calibration of satellite altimetry**

  Requirements:

  - geographic location close to satellite track;
  - geocentric sea levels (GPS determined coordinates);
  - vertical land movements (co-location with GPS).

- **Application D: operational oceanography** (including storm surges)

  Requirements:

  - near real-time data, latency of hour to days.

Motivation

For Applications A and C, we look at the $<$ 1 mm/yr agenda for vertical land movements.

Two basic goals:

- Determine vertical land motion in a geocentric reference frame.
- Determine sea level in a geocentric reference frame.

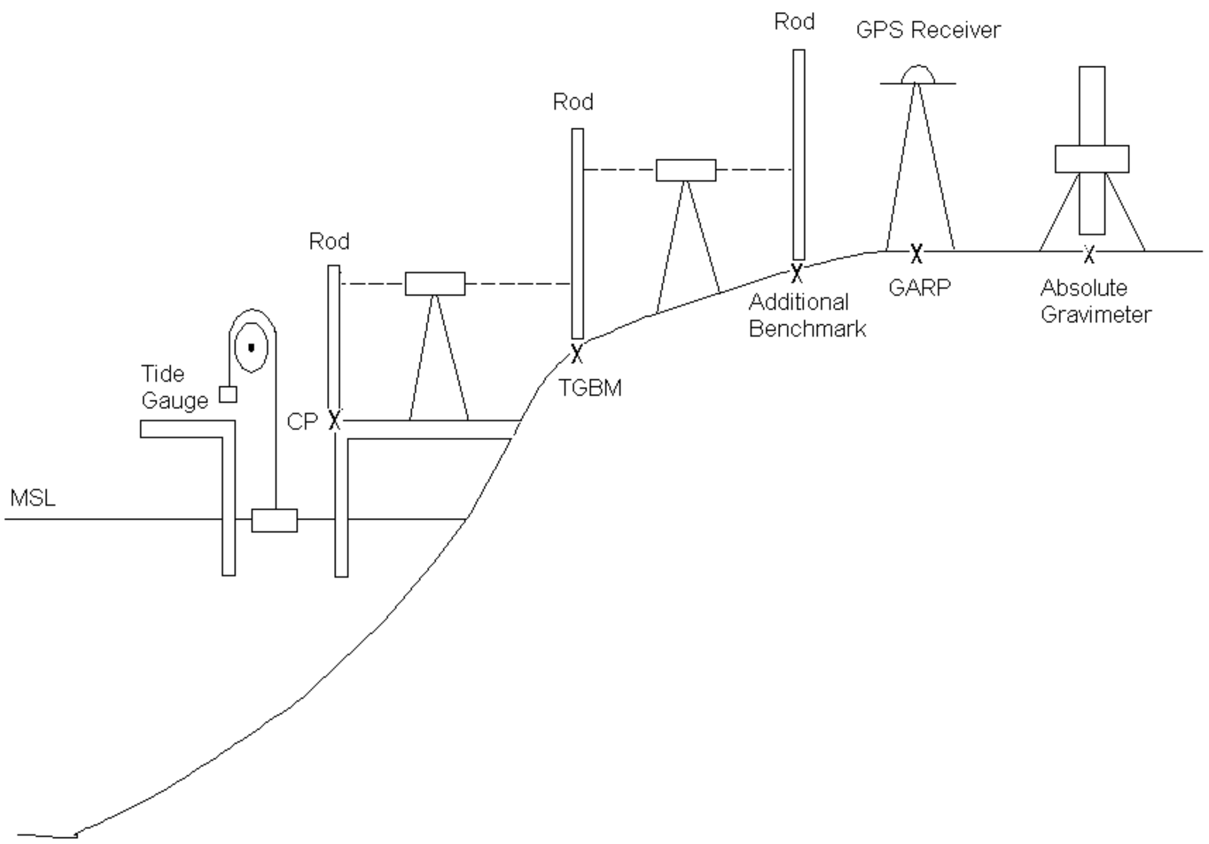
For a ground-based sea level observing system, what do we need in terms of spatial and temporal resolution?

Answer depends on signal contents!

For Application A, what are the characteristic spatial wavelengths of relevant signals?

- decadal to century scale steric and non-steric sea level variations,
- vertical land movement.

Methodology



Three primary points:

CP: Contact Point
TGBM: Tide Gauge Bench Mark
GARP: GPS Antenna Reference Point

Requirements for GPS co-location:

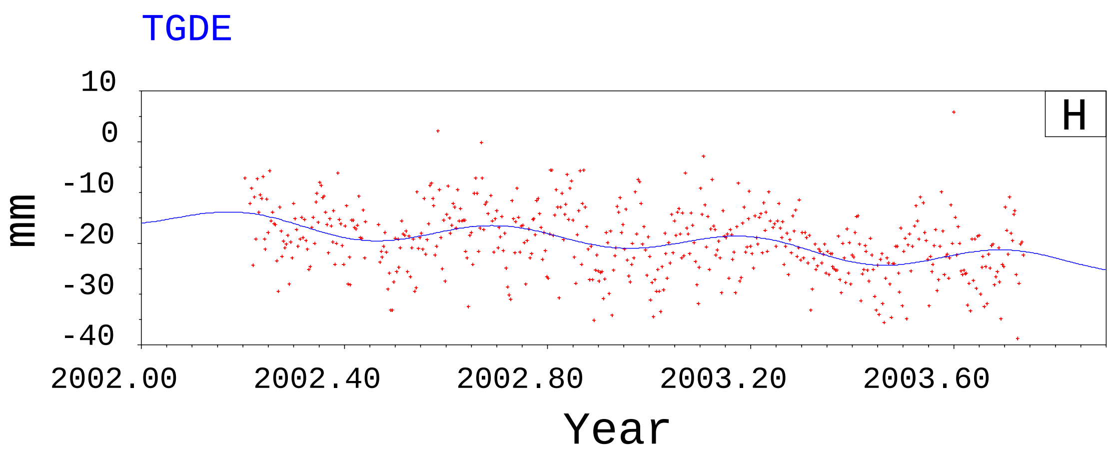
- As close as possible to the tide gauge bench mark.
- Good GPS conditions.
- Representative for vertical land movement.
- As little as possible additional measurements required in particular levelling
- Long-term observations, i.e. stable environment
- Operational.

In many locations, these are conflicting requirements!

Resulting observing systems:

- Two "end points":
  - For TG on solid rock, good GPS conditions:
    - one antenna on top of the TG
  - For TG on pier, in harbour: Dual receiver concept
    - one reference receiver in an optimal GPS
    - one receiver at the TG
- For other situations in between: site-dependent solution

Tregde, Southern Norway

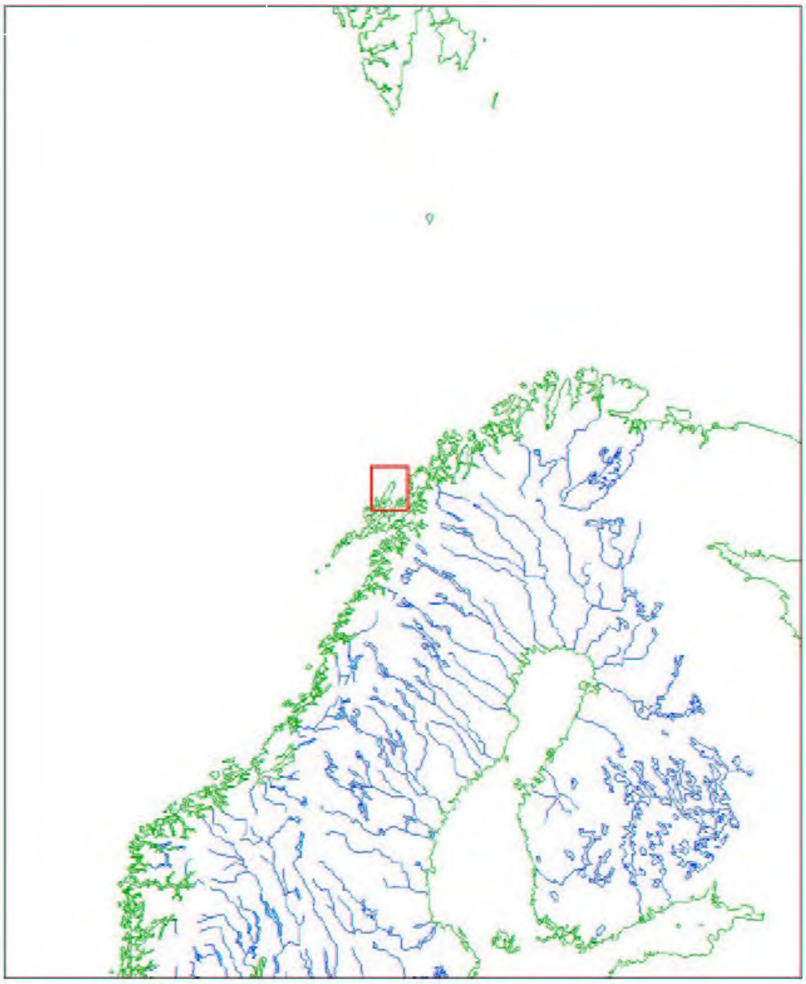


Station	Comp.	Annual		Semi-Annual		Trend
		mm	radian	mm	radian	mm/yr
TGDE	H	2.5	3.85	2.5	4.57	-0.2

Site-related issues

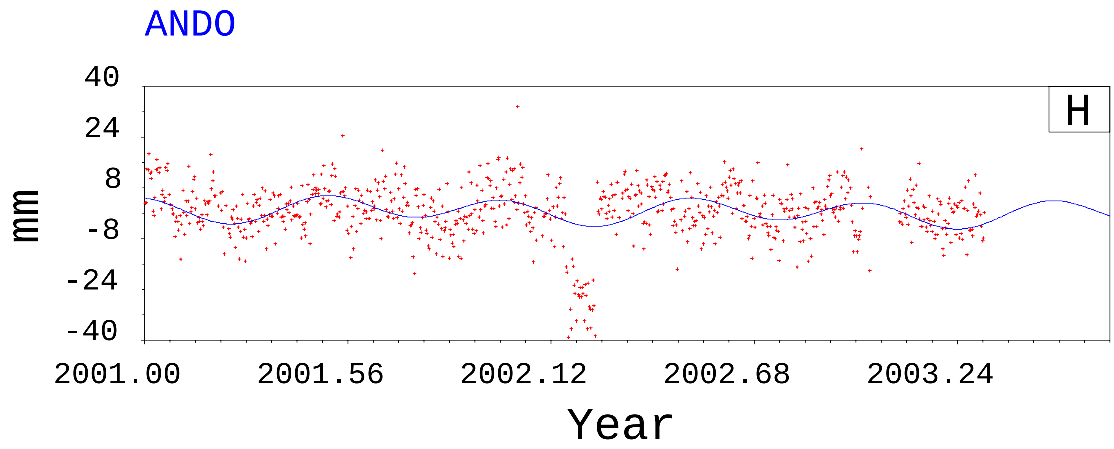
Site-related issues: dual Receiver

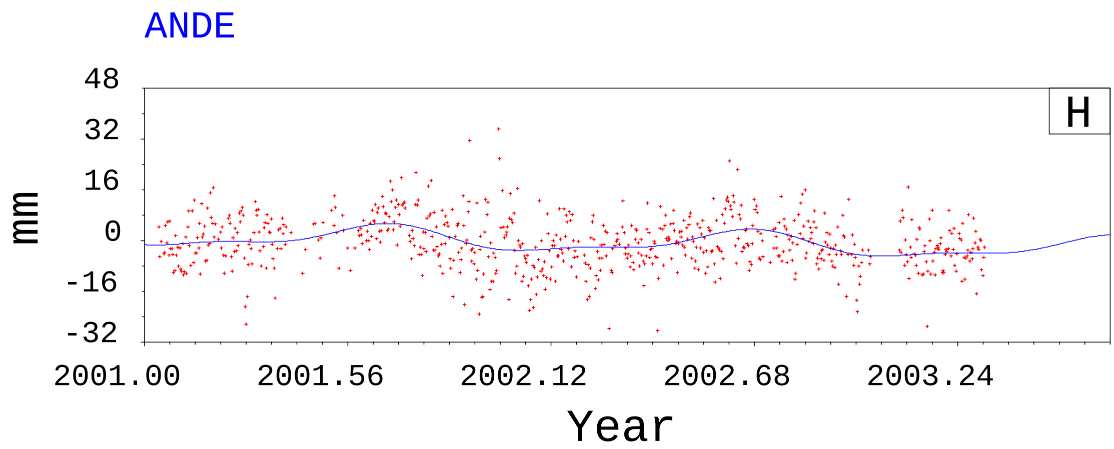
Andenes, Northern Norway



9	Site-related issues; dual receiver

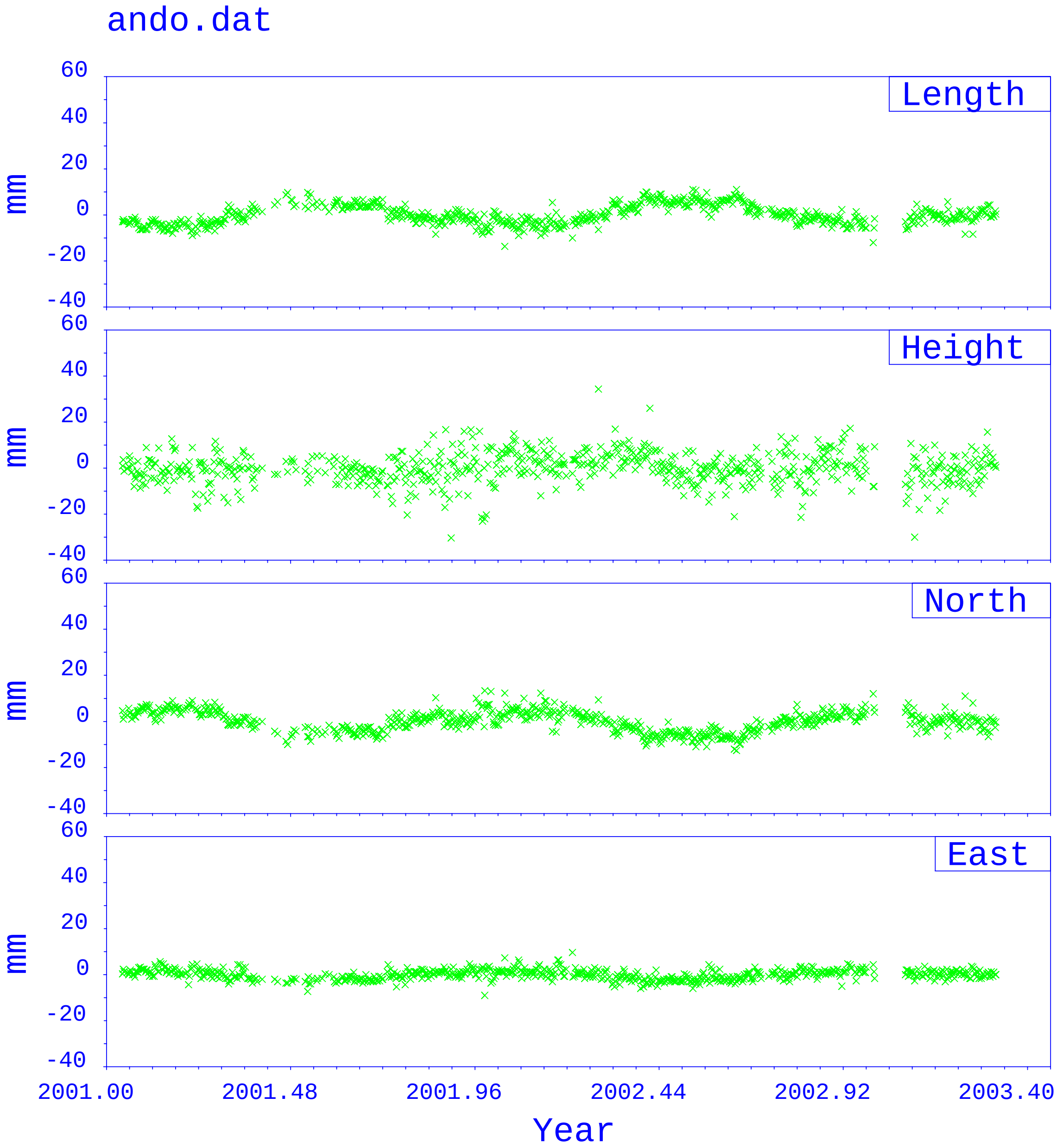
Site-related issues: dual receiver





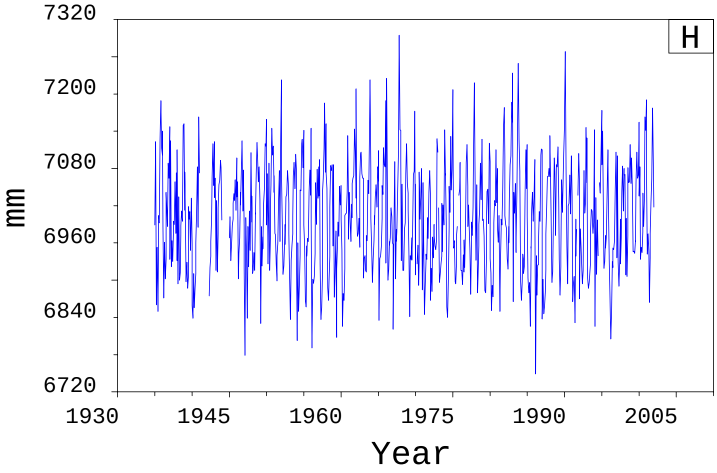
Station	Comp.	Annual		Semi-Annual		Trend
		mm	radian	mm	radian	mm/yr
ANDE	H	3.4	3.78	1.4	5.46	-1.8
ANDO	H	1.4	3.58	3.6	1.66	-0.8

Site-related issues: dual receiver

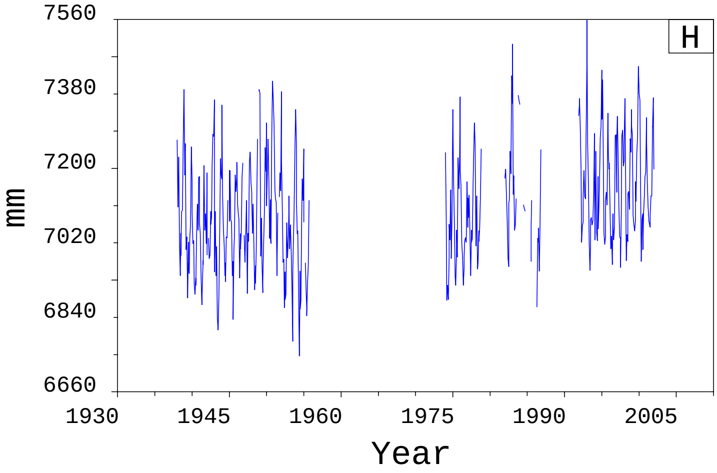


Reference Frame Issues: One Example

TREGDE

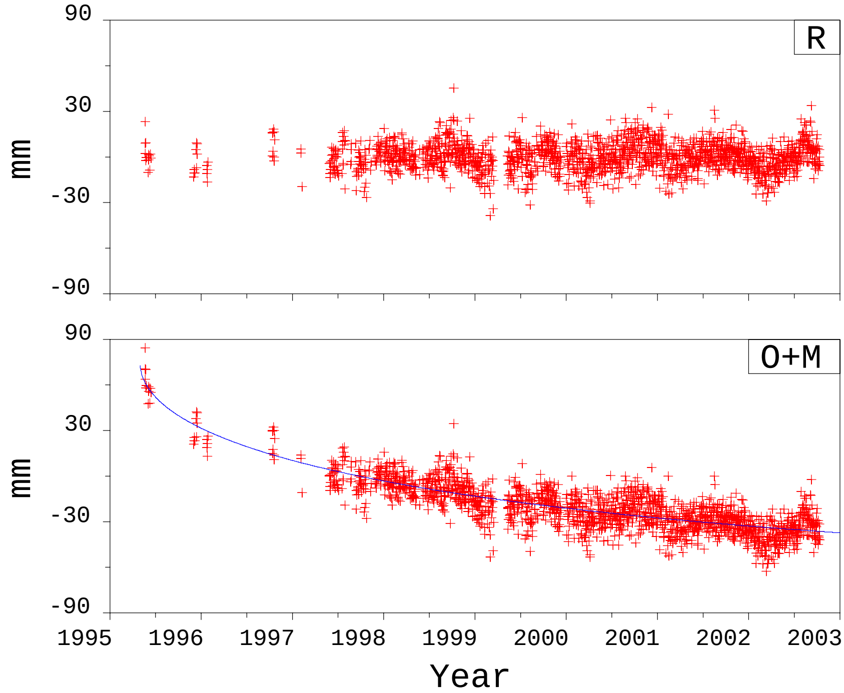


ANDENES



Site	A_1	φ_1	A_2	φ_2	b	GPS	Corrected
	mm	rad	mm	rad	mm/yr	mm/yr	mm/yr
Tregde	82.7	2.64	10.8	1.97	0.05	-0.2	-0.15
Andenes	141.0	2.01	10.8	1.61	1.70	-1.8	-0.10

Reference Issues: One More Example

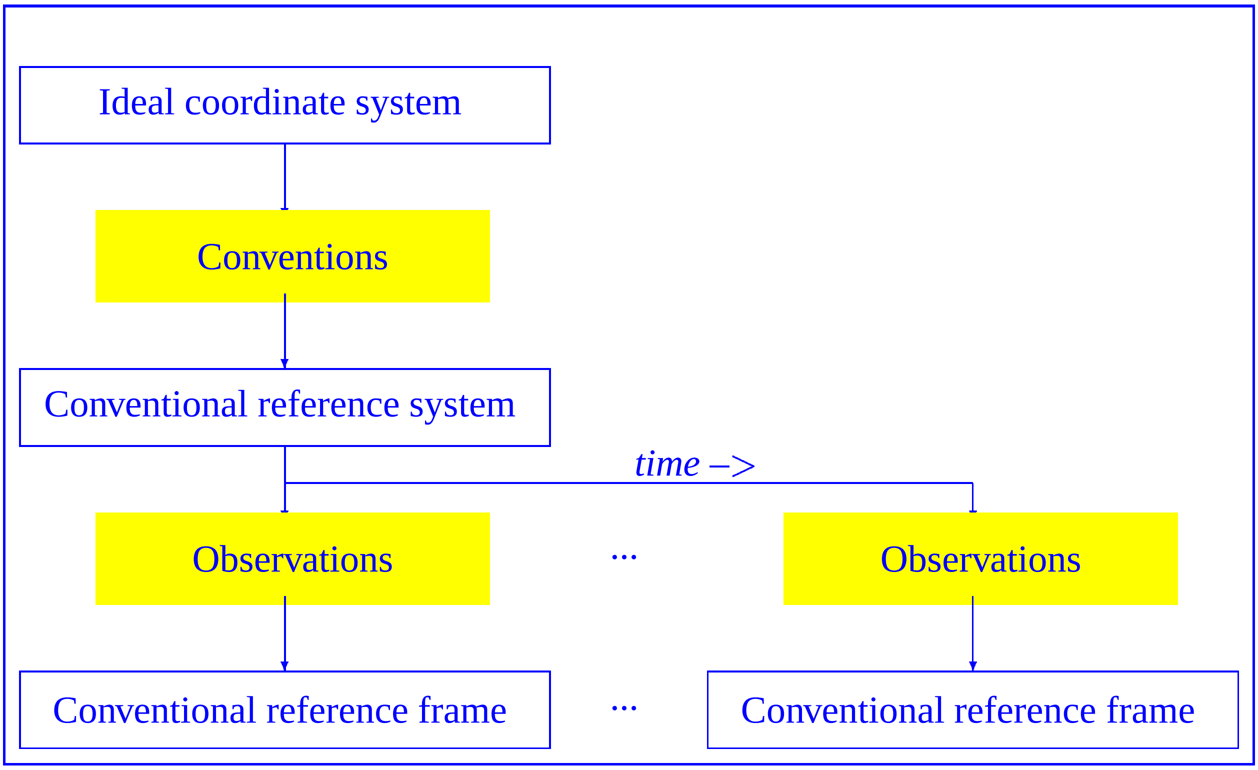


Monitoring of vertical motion.

Lower diagram: Daily vertical coordinates (symbols) determined from GPS measurement on a oil platform and fitted settlement curve ($\sqrt{t}$ plus linear trend, where t is time, solid line).
Upper diagram: residual with respect to the settlement curve.
From Plag (2003).

Difference between
settlement measurements and platform movement
gives a geocentric movememt of the sea floor of $+4 \pm 0.5$ mm/yr.

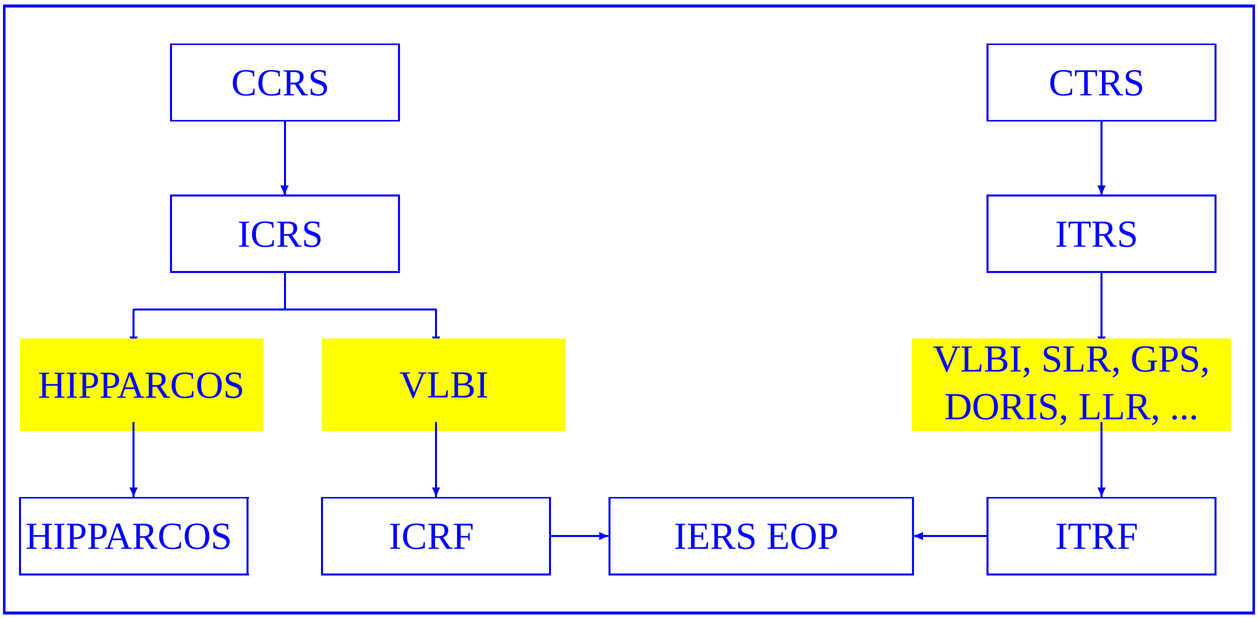
How accurate is this really?



Principle scheme for practically accessible coordinate systems.

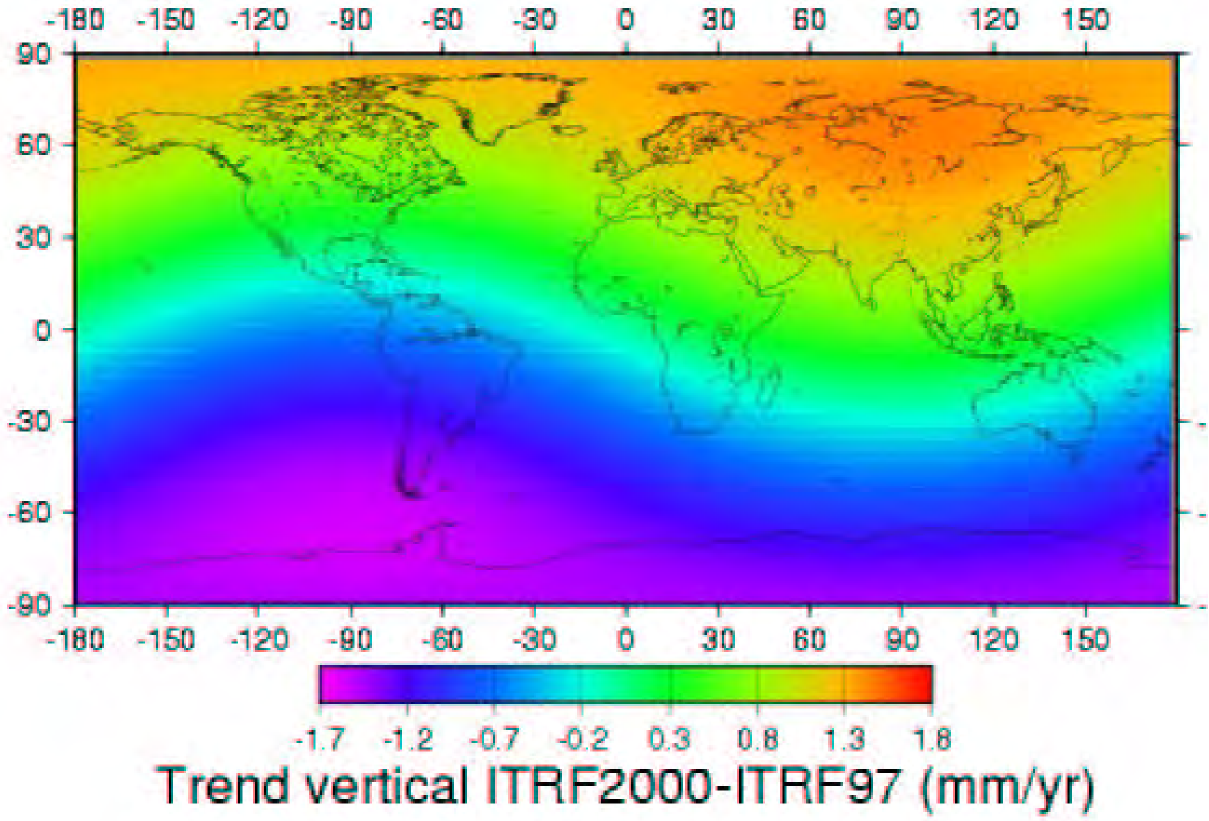
- Starting point: ideal reference system.
- Conventions (algorithms, constants) according to major applications, available observation techniques, knowledge with respect to models.
- Realisation: frame, based on certain observations, associated with specific errors.

Reference systems



Overview over current conventional reference systems and their realisations.

- The Conventional Celestial Reference Systems (CCRS) adopted by the IAU is the International Celestial Reference System (ICRS).
- Realised as ICRF through VLBI measurements, and also through the HIPPARCOS stellar frame.
- The Conventional Terrestrial Reference Systems (CTRS) accepted by IUGG is the International Terrestrial Reference System (ITRS),
- Realised through the International Terrestrial Reference Frames (ITRF) maintained by the IERS.
- Tie between the ICRF and ITRF is provided by the IERS Earth Orientation Parameters (EOP).



Transformation between to frames:

$$\begin{pmatrix} X_{ITRFxx} \\ Y_{ITRFxx} \\ Z_{ITRFxx} \end{pmatrix} = \begin{pmatrix} X_{ITRFyy} \\ Y_{ITRFyy} \\ Z_{ITRFyy} \end{pmatrix} + \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} + \begin{pmatrix} D & -R_3 & R_2 \\ R_3 & D & -R_1 \\ -R_2 & R_1 & D \end{pmatrix} \begin{pmatrix} X_{ITRFyy} \\ Y_{ITRFyy} \\ Z_{ITRFyy} \end{pmatrix} \quad (1)$$

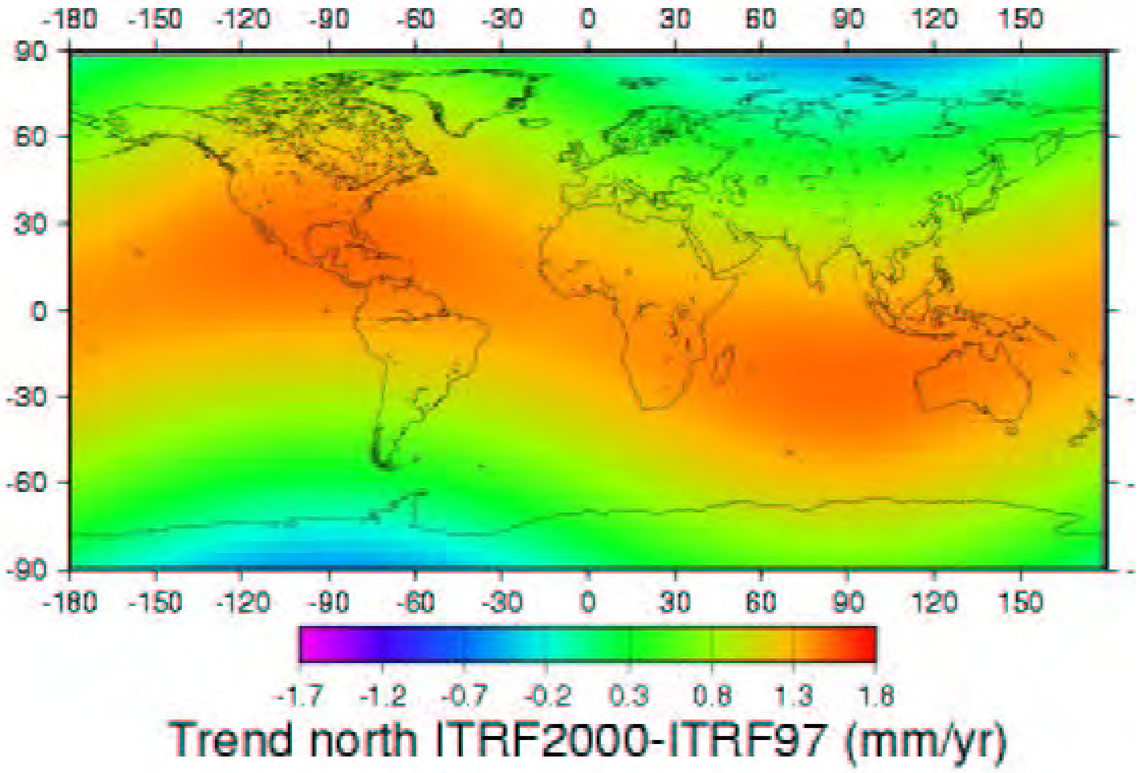
Velocities:

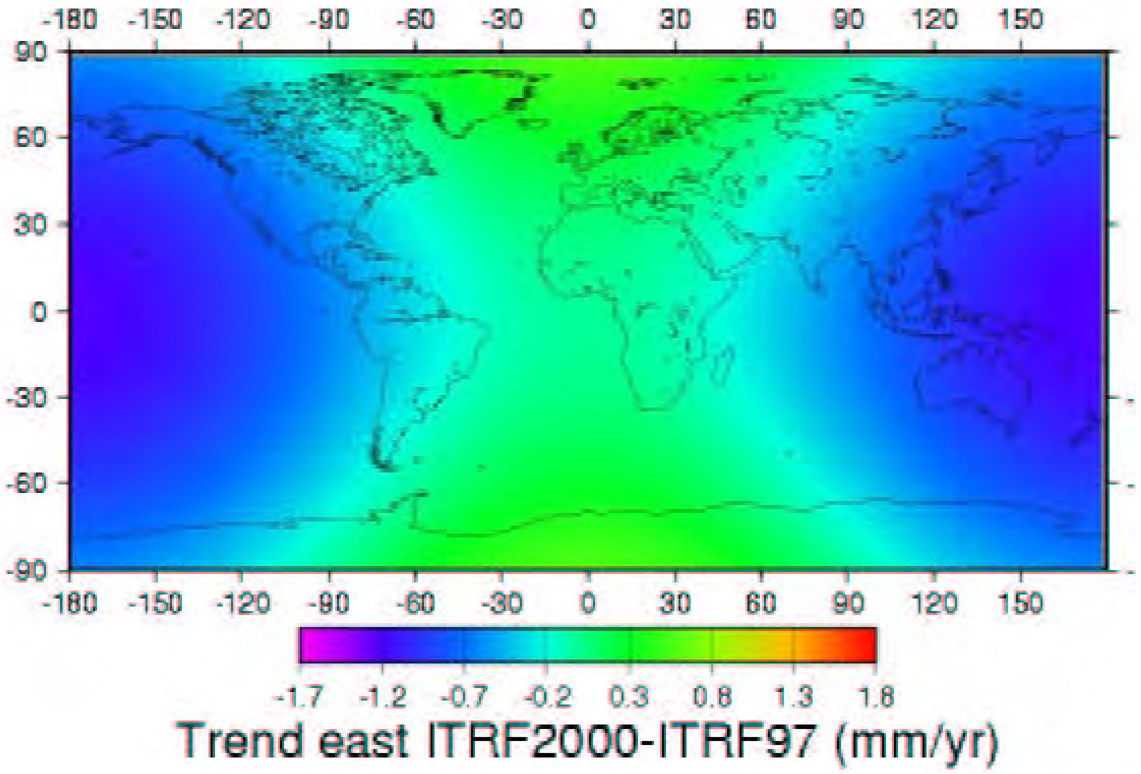
$$\begin{pmatrix} \dot{X}_{ITRFxx} \\ \dot{Y}_{ITRFxx} \\ \dot{Z}_{ITRFxx} \end{pmatrix} = \begin{pmatrix} \dot{X}_{ITRFyy} \\ \dot{Y}_{ITRFyy} \\ \dot{Z}_{ITRFyy} \end{pmatrix} + \begin{pmatrix} \dot{T}_1 \\ \dot{T}_2 \\ \dot{T}_3 \end{pmatrix} + \begin{pmatrix} \dot{D} & -\dot{R}_3 & \dot{R}_2 \\ \dot{R}_3 & \dot{D} & -\dot{R}_1 \\ -\dot{R}_2 & \dot{R}_1 & \dot{D} \end{pmatrix} \begin{pmatrix} X_{ITRFyy} \\ Y_{ITRFyy} \\ Z_{ITRFyy} \end{pmatrix} \quad (2)$$

T_i: Transformation vector,
R_i: rotation matrix,
D: scale,
$\dot{T}_i$, $\dot{R}_i$ and $\dot{D}$: change in the parameters

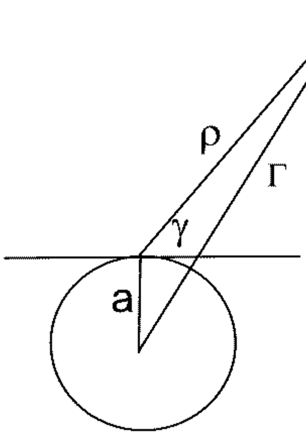
$\dot{T}_x = 0.$, $\dot{T}_y = 0.6$ mm/yr, $\dot{T}_z = 1.4$ mm/yr, $\dot{D} = 0.01$ ppb

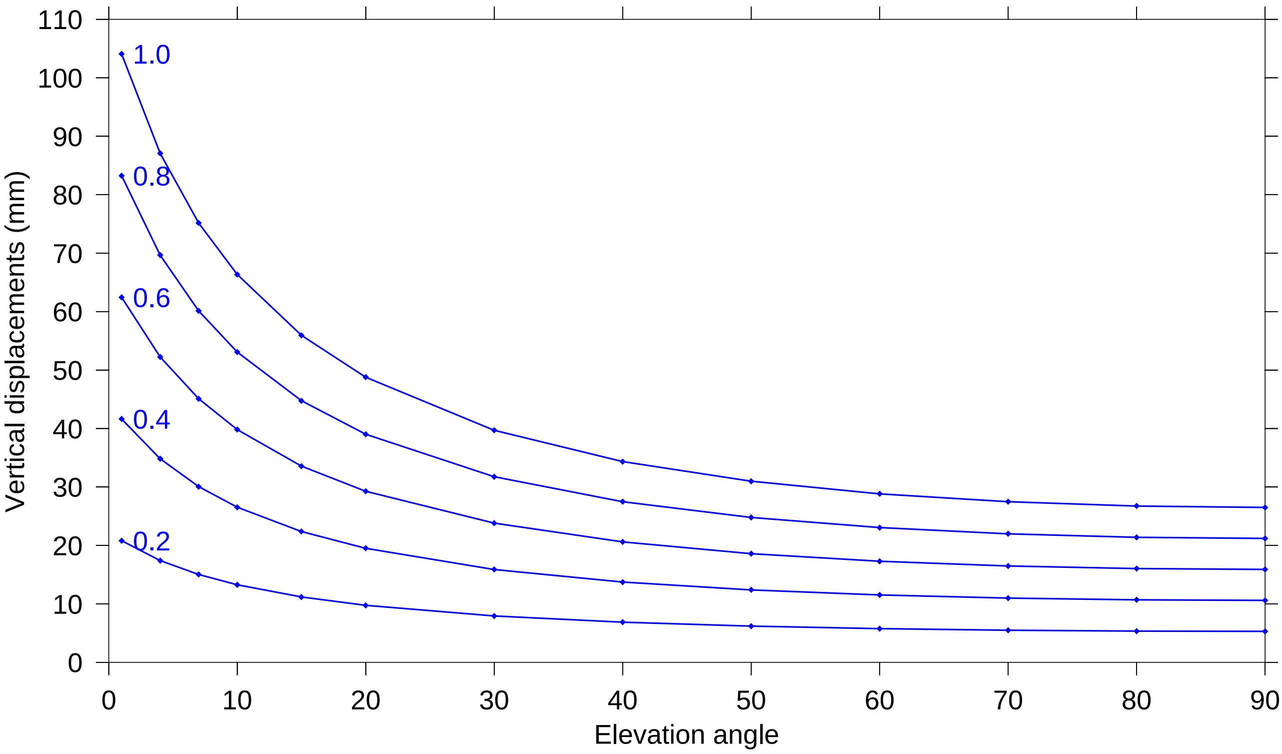
Reference frame-related issues





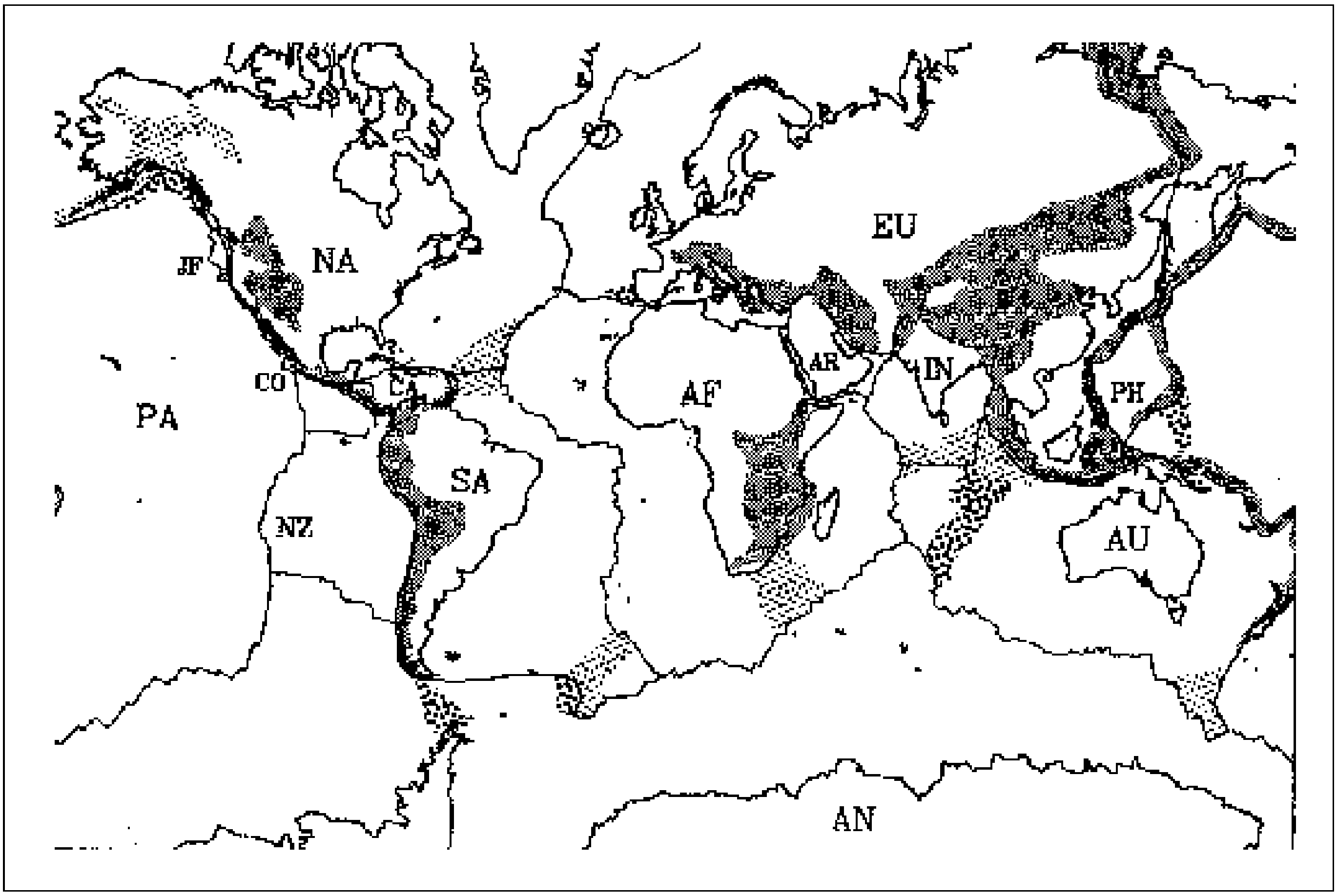
Potential effect of an unmodelled trend in scale:





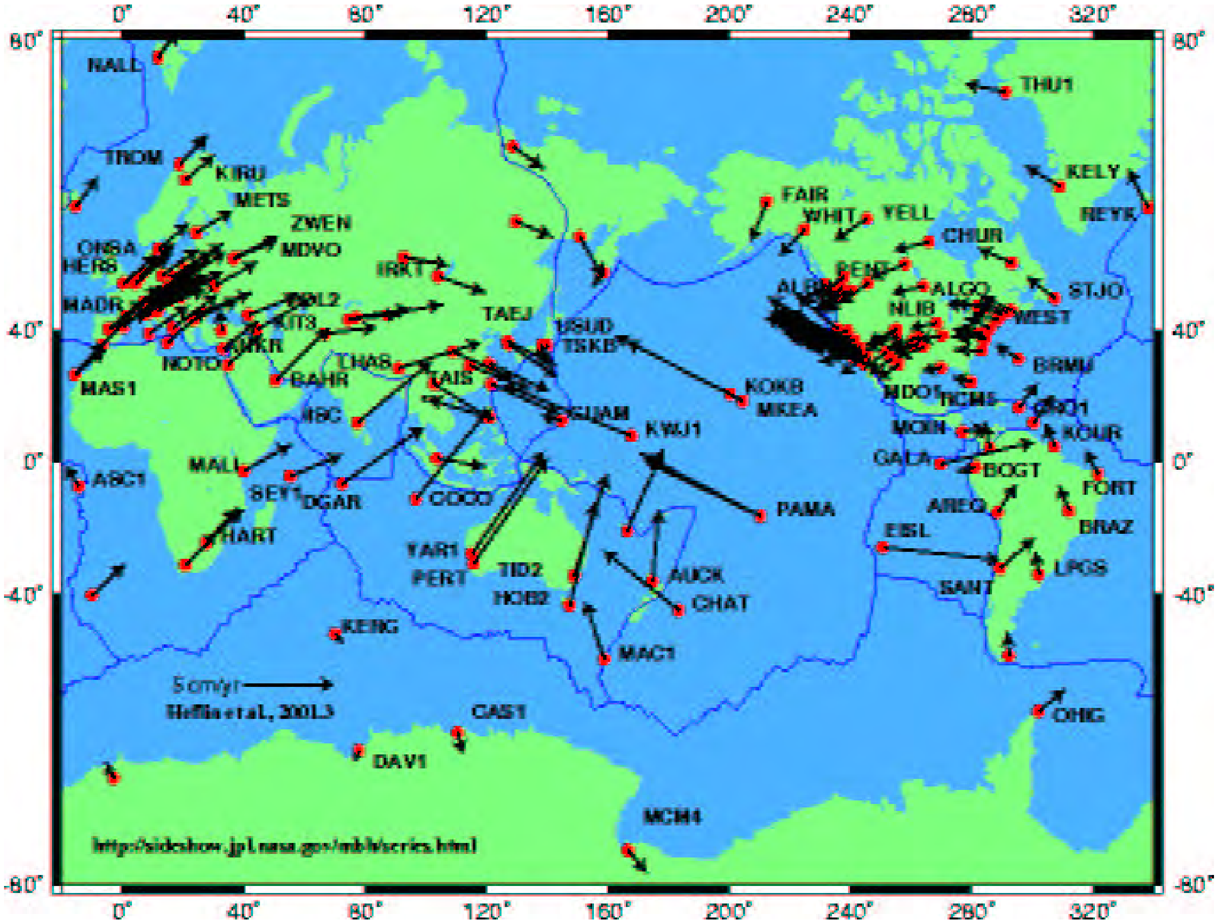
Required: No Net Translation (NNT) condition:

$$\int_{\mathrm{E}} \vec{V} \cdot d\vec{s} = 0 \qquad (3)$$



From Stein, 1993.

Current Network



From Heflin, 2002 (web page).

Summary Reference Frame Issues

Principle problems:

- Reference frame depends on stations used for the realisation.
- No Net Translation condition difficult to realise on a deforming Earth.
- Error in scale may introduce bias.

Consequences:

- CGPS at tide gauges is rapidly developing: station distribution is changing.
- Consequently, CGPS at tide gauges should not be part of the reference frame.
- Access to reference frame currently through IGS products.
- Need for recomputation of orbits, clocks.
- Consistency with the IGS proceedures.

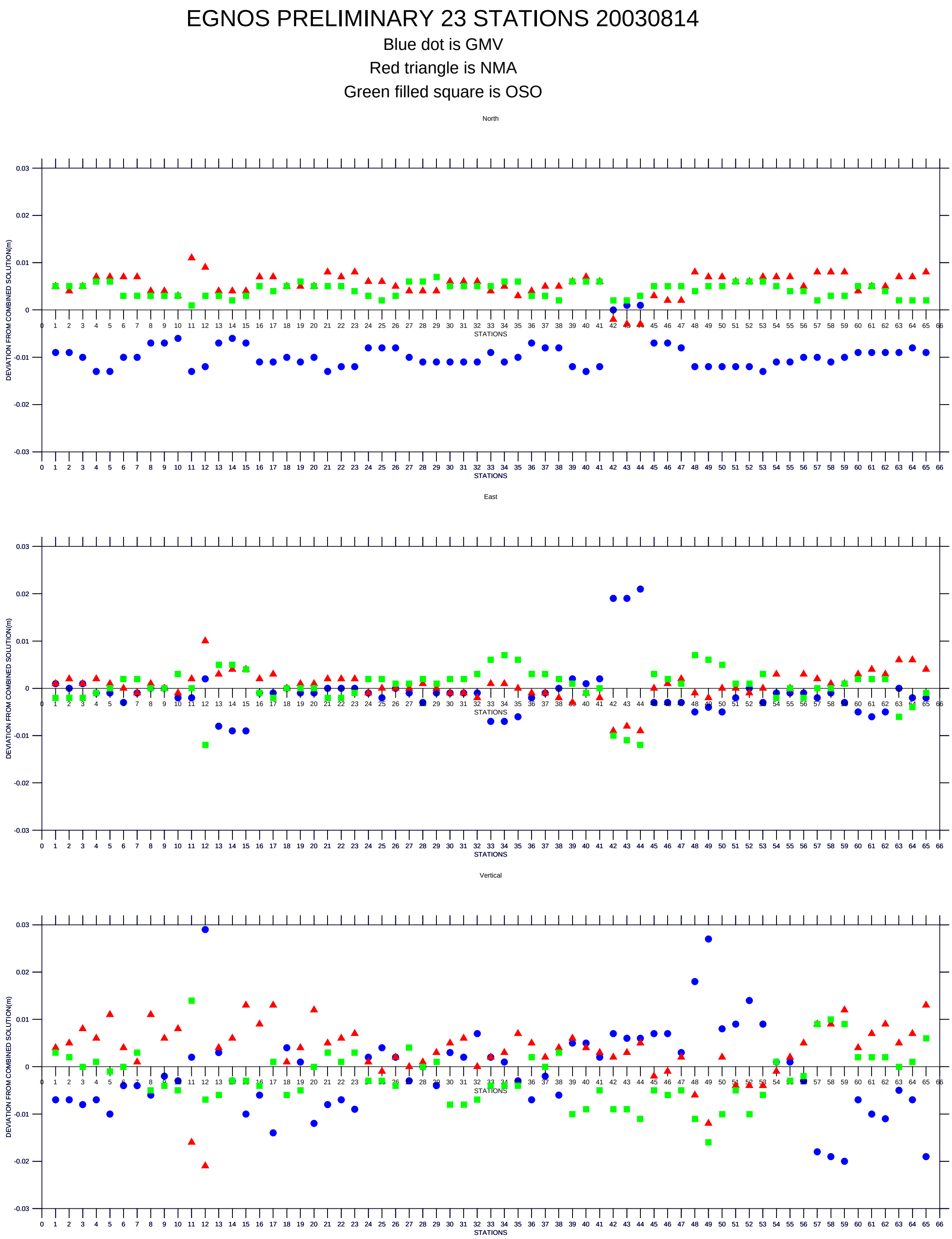
Conclusions of ESEAS-RI WP2 Meeting

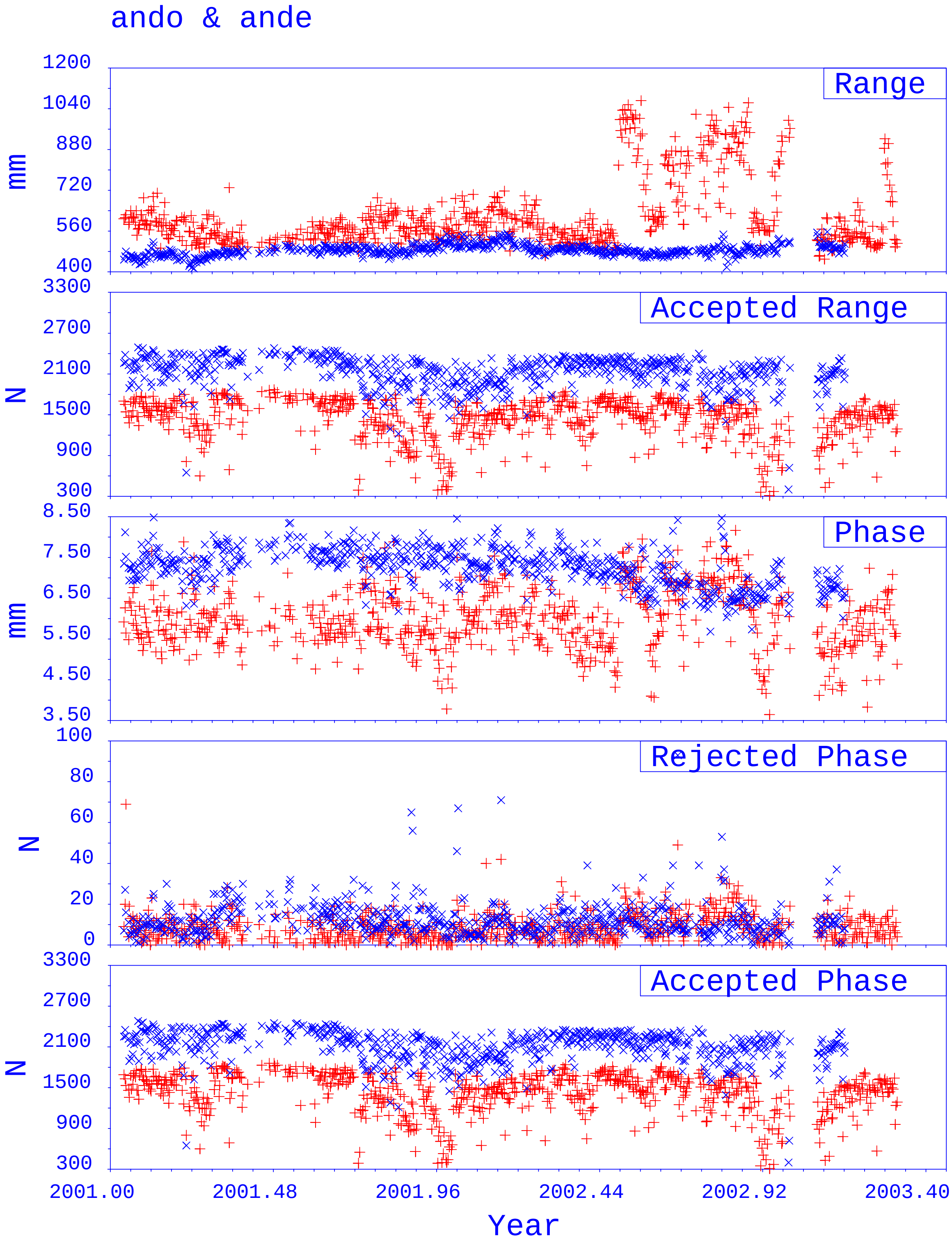
AIM: < 1 1 mm/yr accuracy!

Strategy:

- Separation of global and local parameter:
  - orbits, clocks and EOPs based on a global, ”stable”, network
  - coordinate time series of CGPS sites subsequently
- Each site at least three software/strategies:
  - GIPSY/OASIS, ppp: NMA, Norway
  - GIPSY/OASIS, ppp: ROA, Spain
  - Bernese, ppp: UNOTT, UP
  - Bernese, DD: SRC, Poland
  - GAMIT, DD: GCM, Turkey
  - Bernese, DD: UPC, Spain
- Physical parameters and models:
  - All models will be conventional
  - IERS conventions
  - Open issue: What to include in GPS analysis/what leave to time series analysis?
- Results in SINEX
- Definition of a Time series results file format: SINTEX in XML
- What parameters in results files:
  e, se, n, sn, v, sv, ZTD, ZWD, sZD, LC, nLC, noLC, PC, nPC, noPC

Analysis strategy related issues

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Rejected Phase
Accepted Phase
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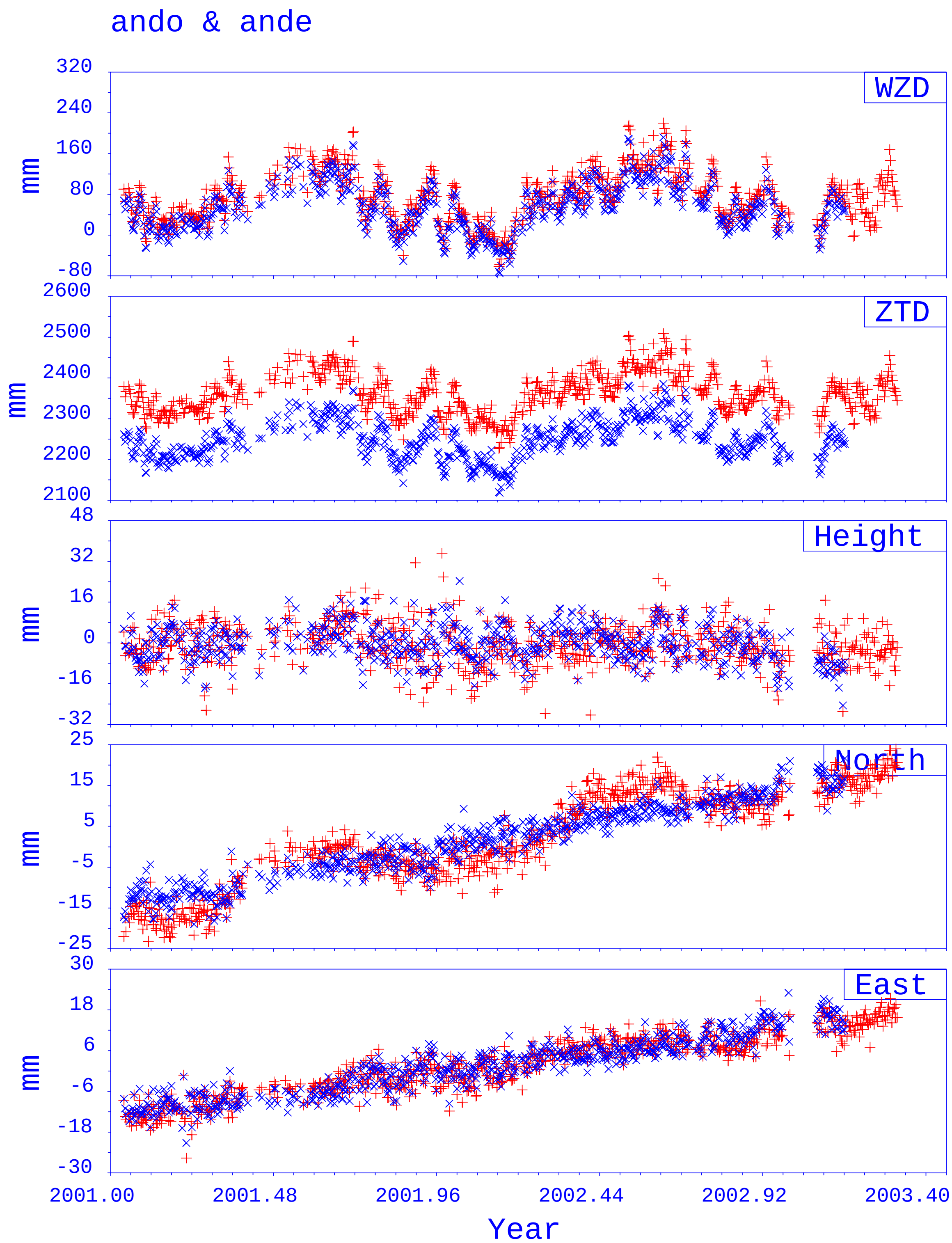
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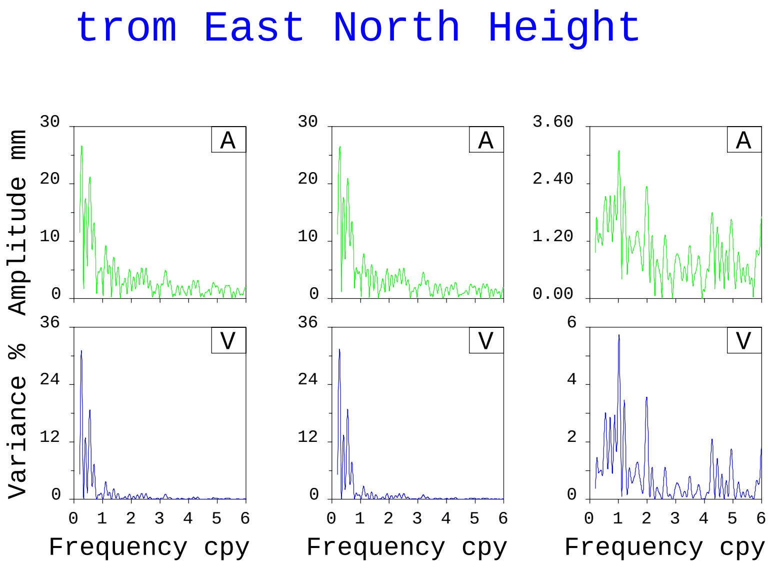
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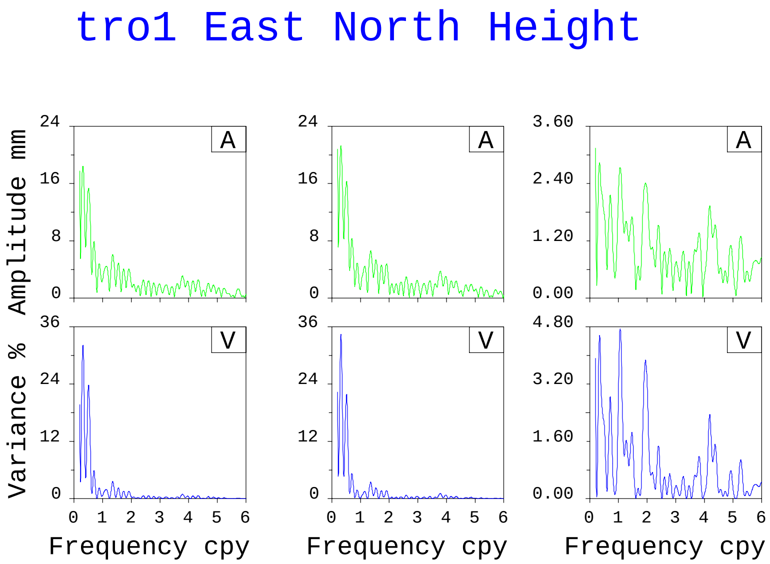
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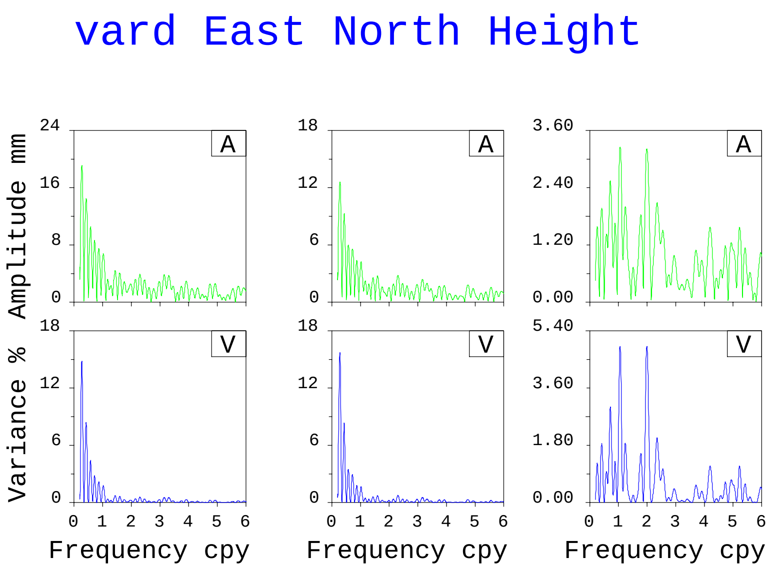
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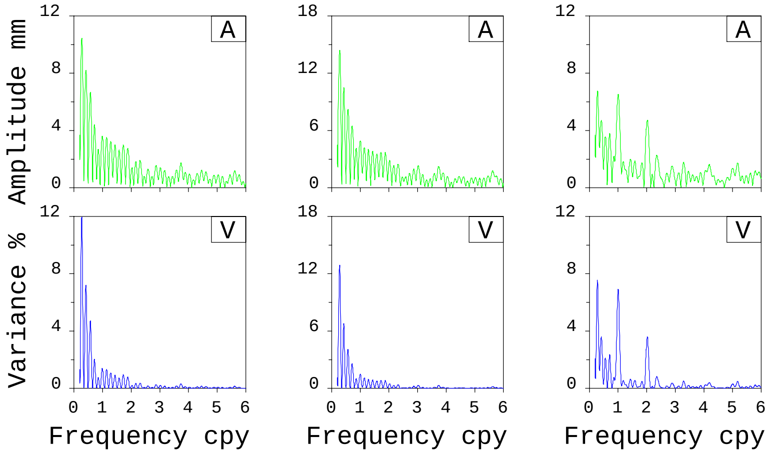

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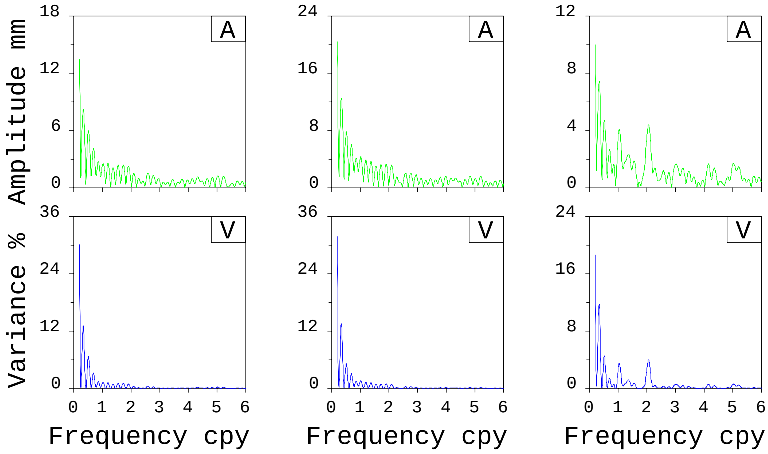

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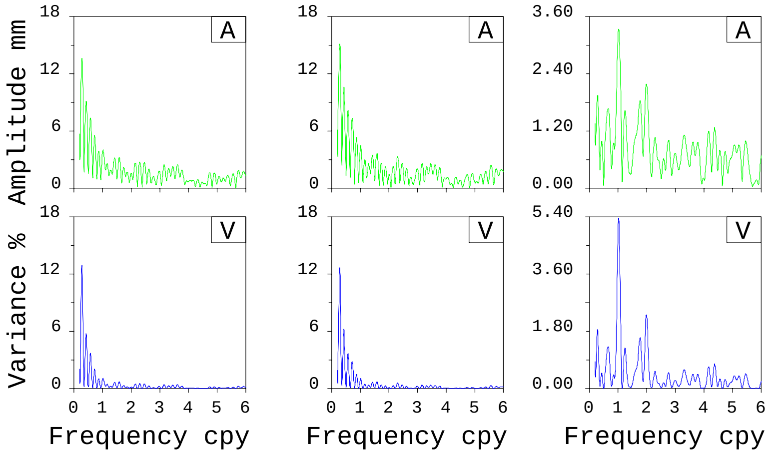

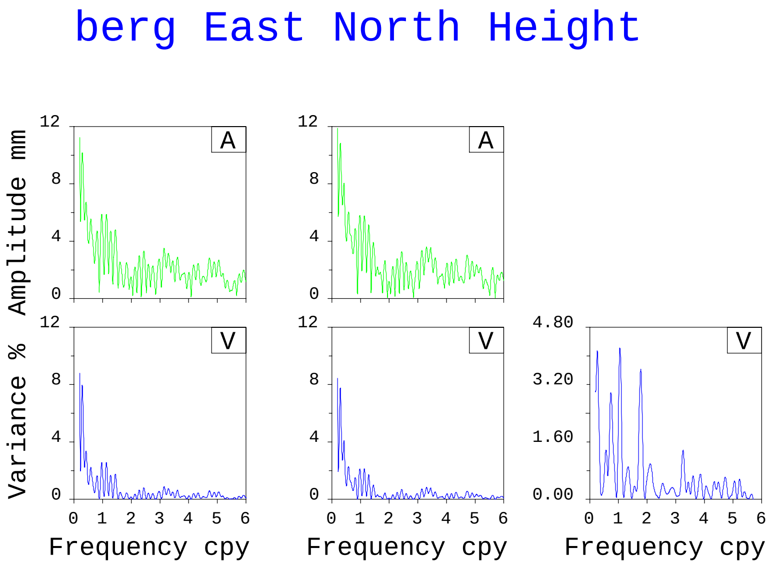
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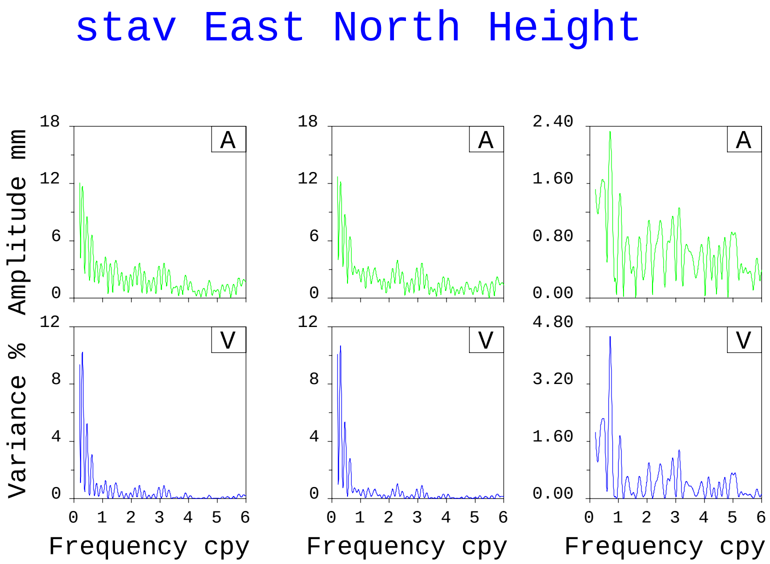
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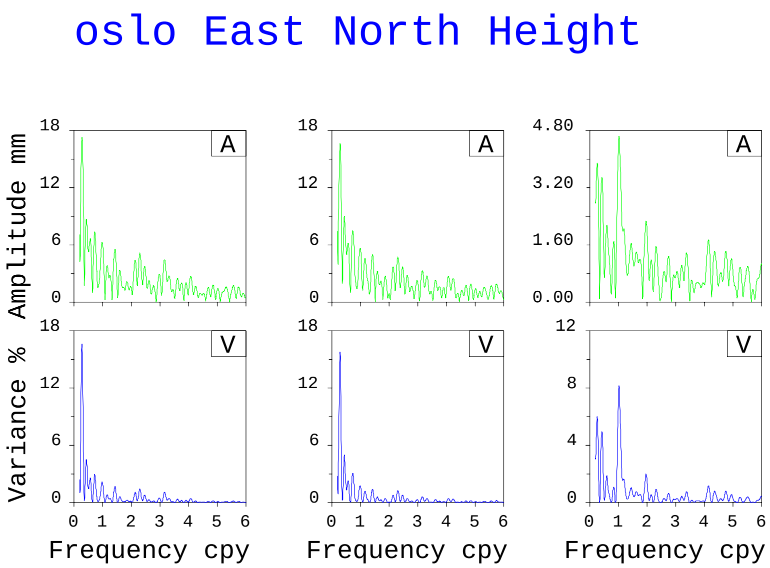
oslo East North Height
Amplitude mm
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Frequency cpy

Model parameters for CGPS time series.

Model is

$$y(t) = A_1 \sin(\omega_1 t + \varphi_1) + A_2 \sin(\omega_2 t + \varphi_2) + a + bt \quad (4)$$

ω_1 *and* ω_2*: annual and semiannual frequency, respectively.*

Site	A_1	φ_1	A_2	φ_2	b
	mm	rad	mm	rad	mm/yr
oslo	3.45	2.24	1.90	2.00	2.91
kris	0.83	5.24	1.70	1.70	0.60
stav	0.98	2.86	0.78	2.03	0.27
berg	1.60	2.64	0.88	0.55	1.38
ales	2.81	2.14	0.74	0.55	0.68
dags	5.28	2.35	1.03	4.81	2.38
trys	2.29	3.00	0.40	1.54	4.62
doms	5.10	2.47	2.09	5.46	0.09
tron	2.30	2.34	1.82	0.96	1.62
bodo	3.00	2.63	2.01	0.51	2.12
ando	1.41	3.58	3.61	1.66	-0.81
ande	3.39	3.78	1.41	5.46	-1.79
tro1	2.27	2.38	2.46	0.66	1.79
trom	3.17	2.29	2.59	0.80	0.58
vard	2.01	3.34	3.26	6.26	-1.17
nya1	1.96	2.22	3.57	0.14	7.51
nyal	4.06	1.89	3.31	6.20	6.78

Conclusions

- Site related:
  - Geodetic equipment of best quality
  - Long-term, stable environment
  - operational
    - near-real time quality control
    - near-real time analysis of the data
    - error/failure detection
  - dual receiver, if necessary
- Reference frame:
  - considerable uncertainty (long-term stability)
  - global offset due to violation of NNT, order estimated to be 0.5 mm/yr
  - potential effect of scale error, order estimated to be 0.2 ... 0.5 mm/yr
- GPS analysis strategy:
  - significant differences between different strategies
  - different strategies should be used for quality control
  - uncertainties of the order of 1 mm/yr
- Time series analysis:
  - site-dependent signal content due to local effects including loading, multi-path, monument effects, ...
  - spectrum analysis required
  - stable trend estimates may required different length of time series

Conclusions

We need to keep in mind what we want signal we want to observe!