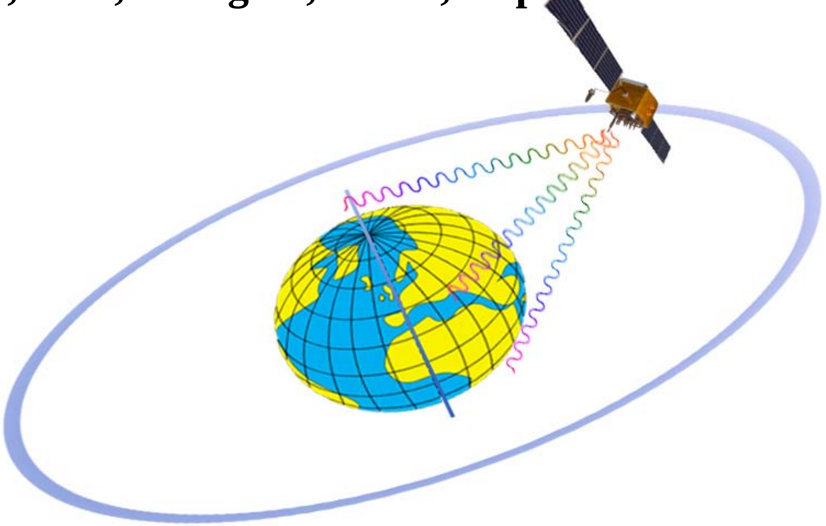
International Symposium on
Space Geodesy and Earth System
(SGES2012)

August 18-21, 2012, Shanghai, China; http://www.shao.ac.cn/meetings



Venue: 3rd floor of Astronomical Building

Shanghai Astronomical Observatory, Chinese Academy of Sciences

Recent Results from ITRF Combination Activities

Zuheir Altamimi, Xavier Collilieux,
Laurent Metivier, Paul Rebischung
IGN, France

Outline

- Preparation for ITRF2013
- Extended analysis beyond ITRF2008 time span
  - Revisit the relative weighting btw space geodesy (SG) and local ties
  - Impact of uncalibrated radomes at co-location sites?
  - Re-assess the scale and origin "accuracy"
  - Working analysis in preparation for ITRF2013
  - Results shown are not definitive
- Recommendations for future contribution to ITRF2013

Next ITRF solution (ITRF2013)

- To be ready in mid 2014:
  - CfP for ITRF2013 will be issued by Fall 2012
  - Outcome of the evaluation of solutions submitted following the ITRS/GGFC call, with & without atmospheric loading corrections
  - All techniques to submit solutions by Jan-Feb, 2014
- Expected Improvements & Developments:
  - Reprocessed solutions;
  - Revisiting the weighting of Local Ties and Space Geodesy solutions included in the ITRF combination;
  - Improving the process of detection of discontinuities in the time series;
  - Modelling the post-seismic & non-linear station motions.

Extended analysis beyond ITRF2008 time-span

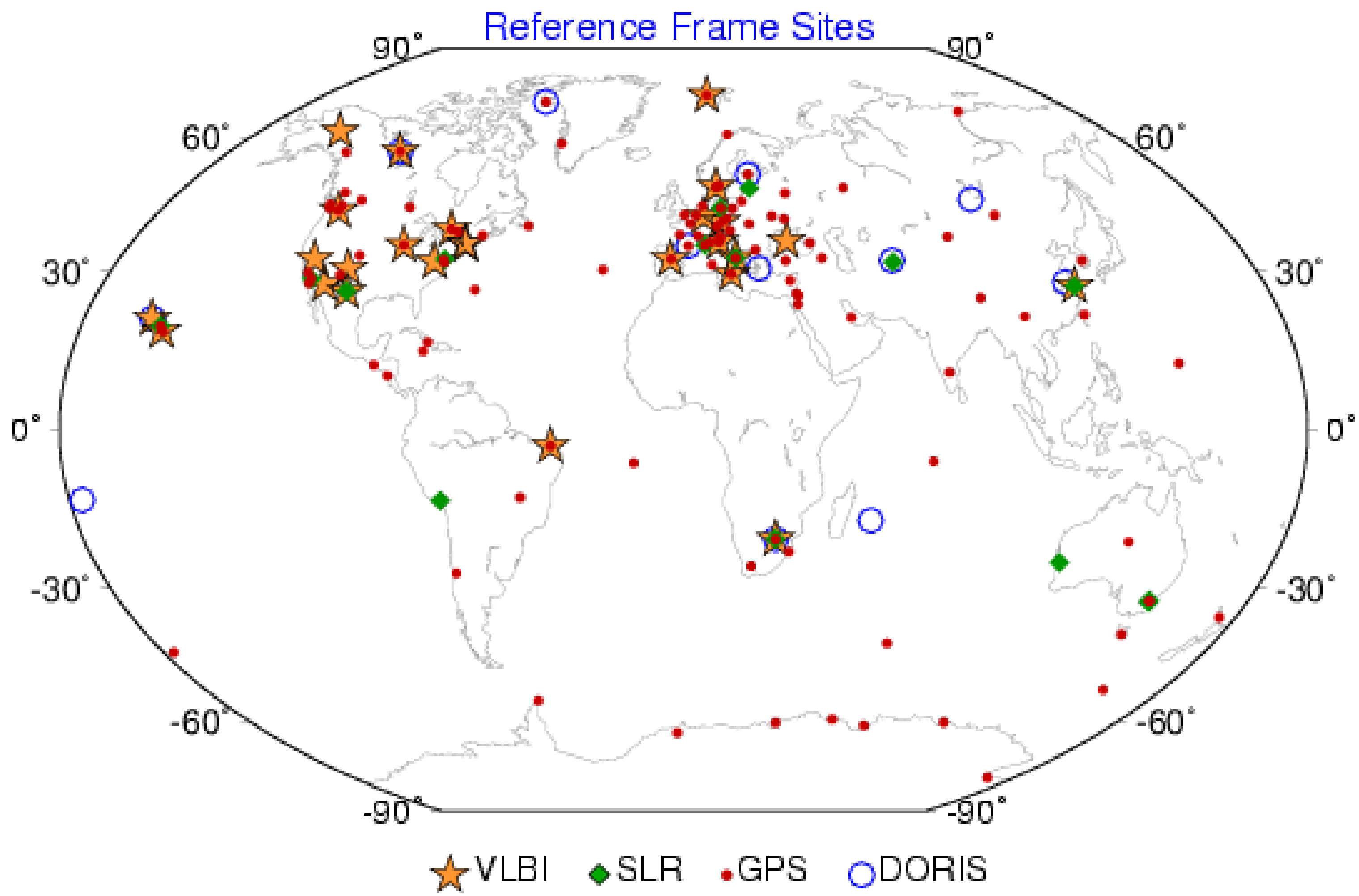
- **VLBI: IVS daily SINEX files up to epoch 2012.0 (S. Bachmann)**

- **SLR: ILRSA weekly SINEX up to epoch 2012.1**

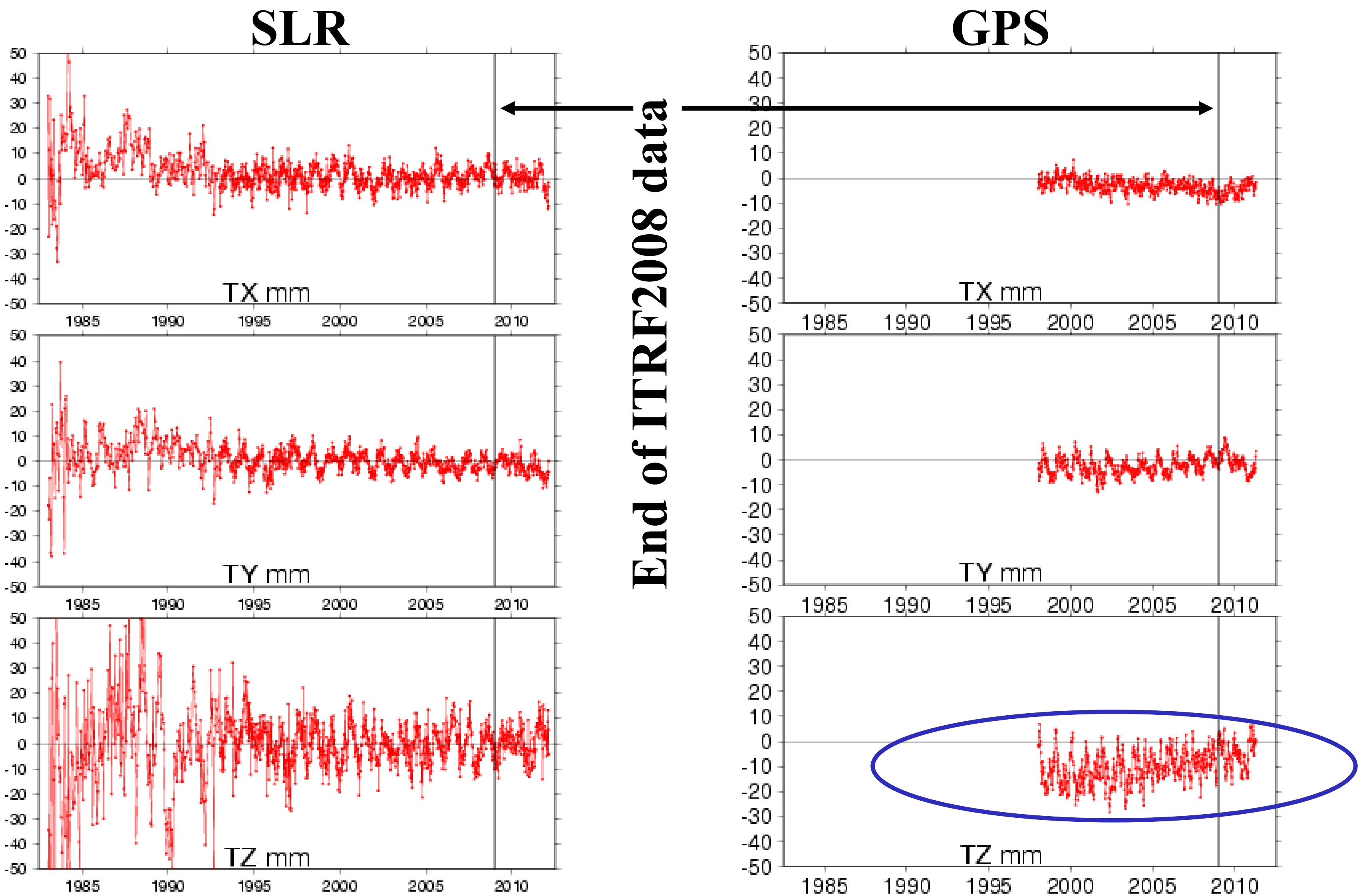
- **GPS: Improved IGS combined weekly SINEX up to 2011.3 where mean origin and scale are preserved**

- **DORIS: Extended by weekly solutions up to 2011.7, provided by G. Moreaux**

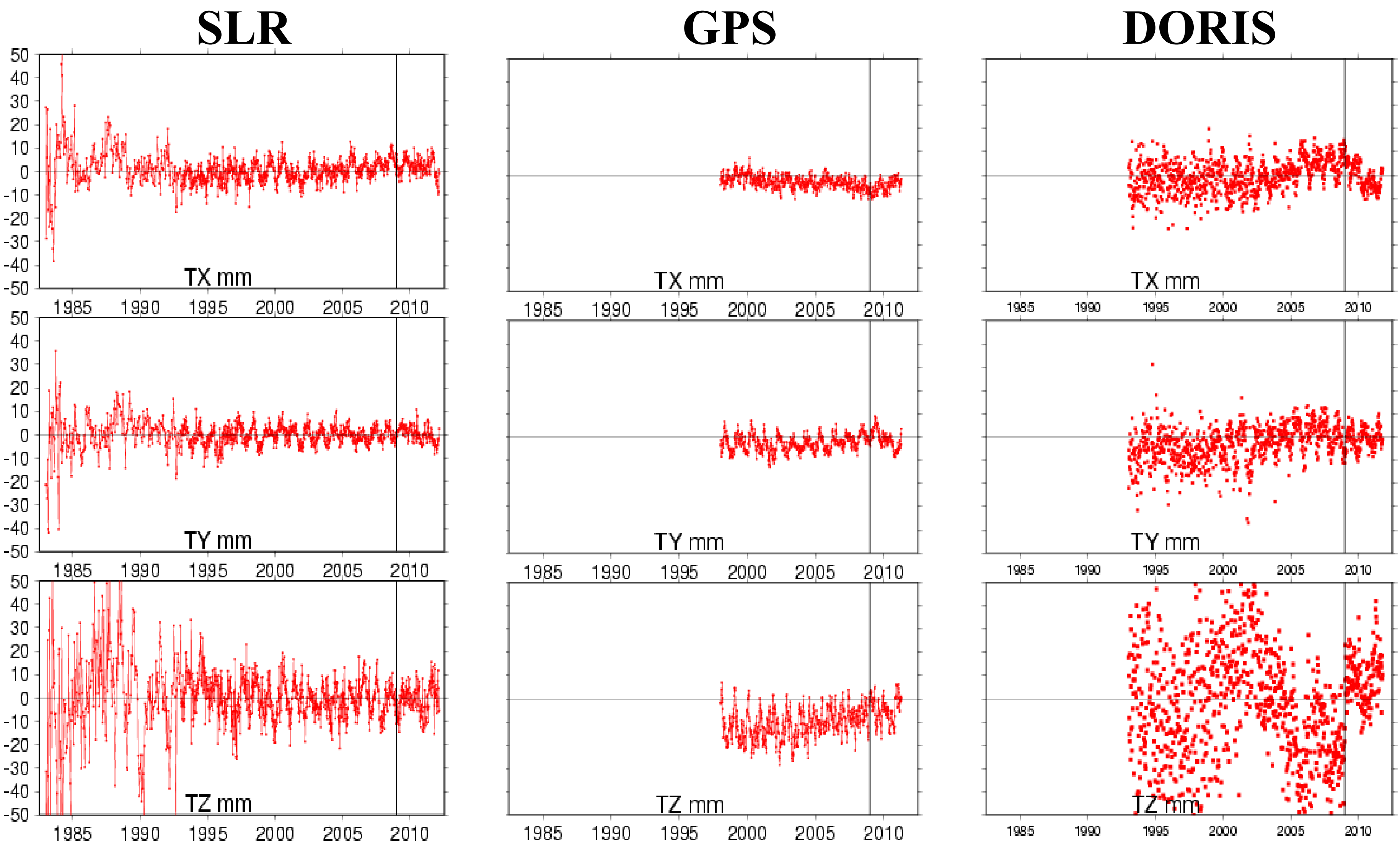
Reference Frame Sites



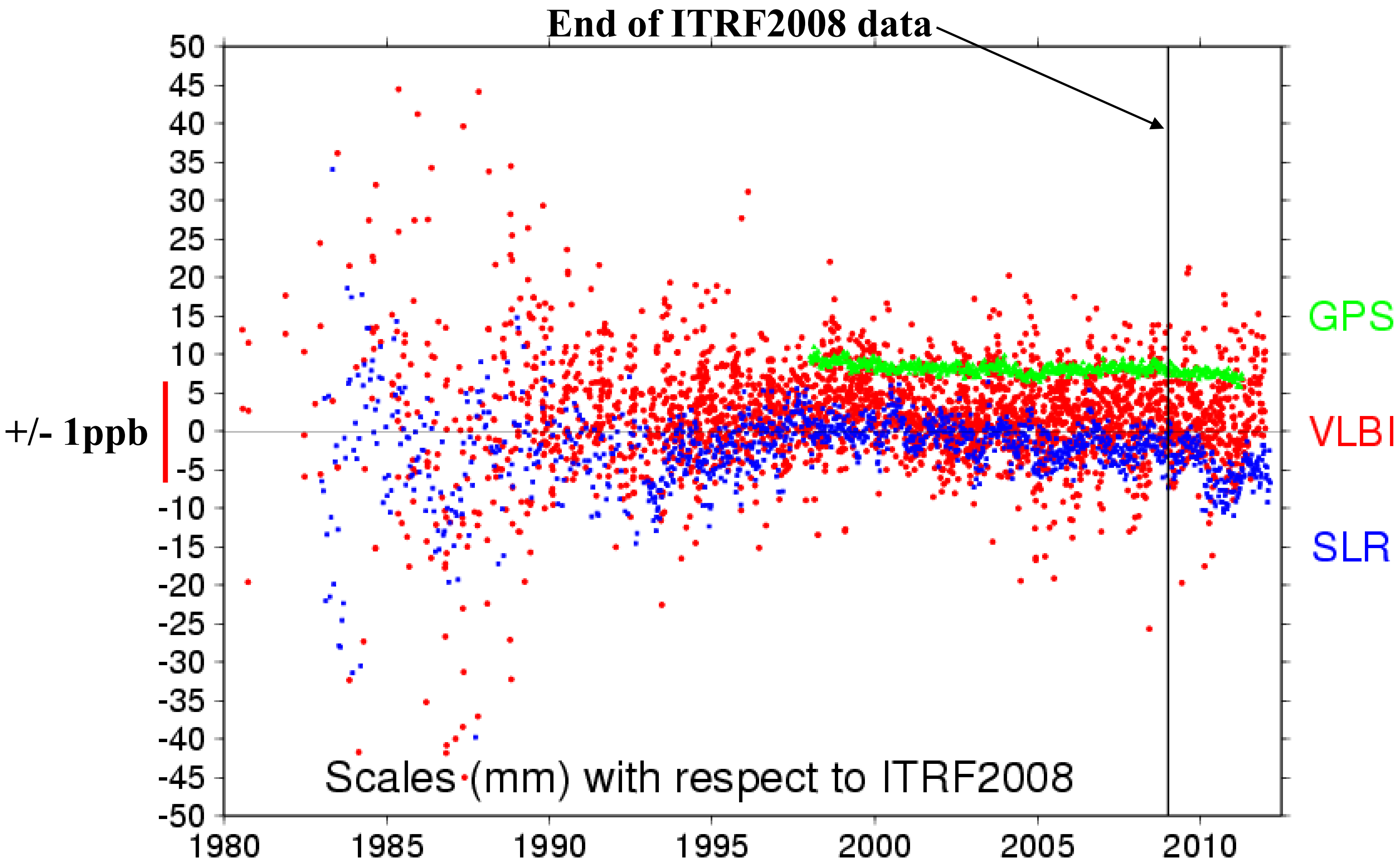
Origin components wrt ITRF2008



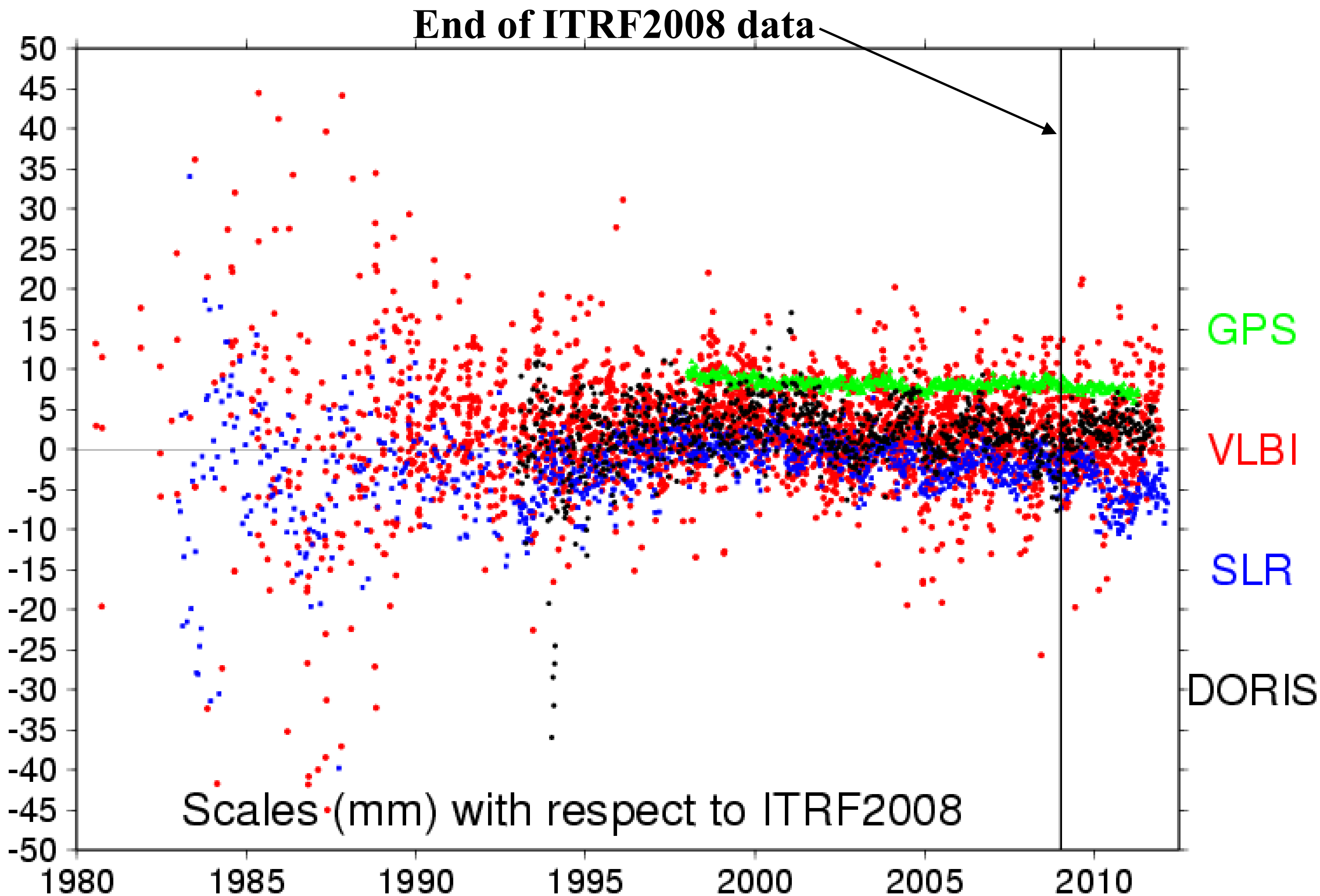
Origin components wrt ITRF2008



Scale factors wrt ITRF2008



Scale factors wrt ITRF2008



Revisit the weighting btw local ties and SG solutions

- **Difficulties:**
  - Velocity disagreements btw techniques for some sites
  - Large "tie" discrepancies for 50% of sites
  - Epochs of ties and discontinuities (?)
  - Local tie accuracy (?)
- **Procedure: Estimate variance factors (VF) for SG solutions via velocity fields combination**
  - Add local tie SINEX files and iterate (re-evaluate tie VF) until convergence ==> unit weight close to 1.
- **15 test combinations, by varying floor sigmas of:**
  - Local Ties (1, 2, 3) mm
  - Velocity constraints (0.01, 0.05, 0.1, 0.5, 1.0) mm/yr

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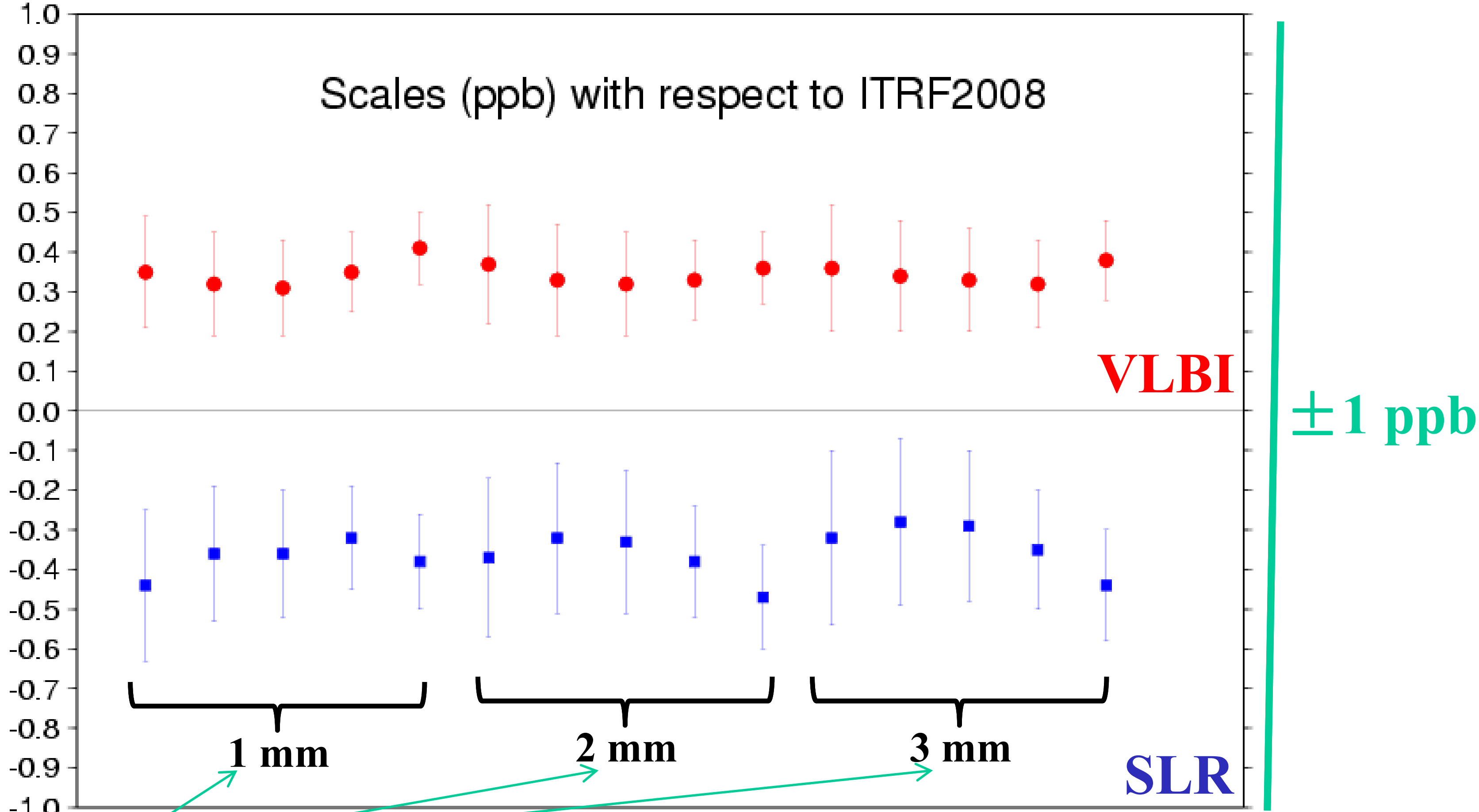
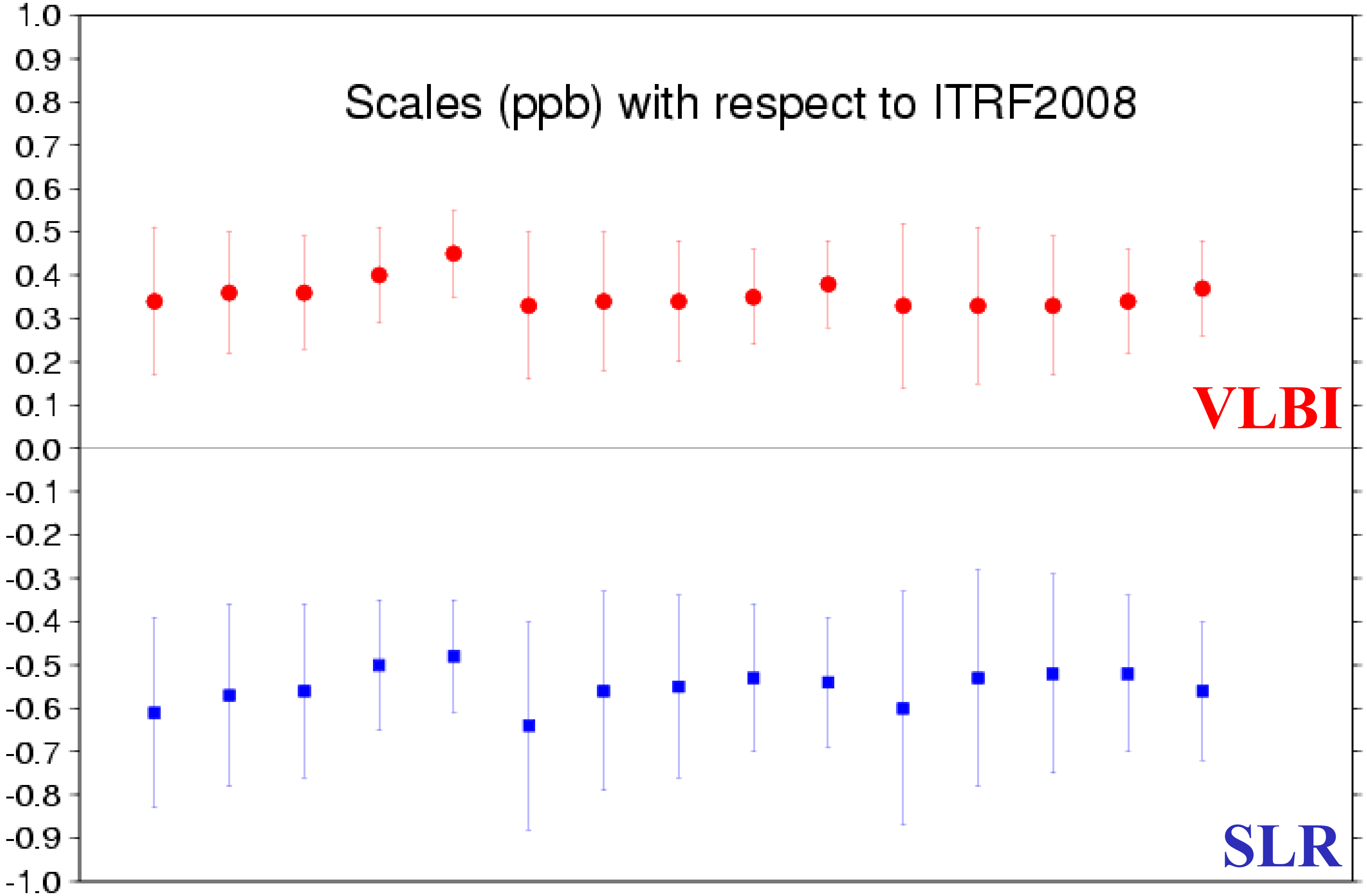
Scale factors wrt ITRF2008



Tests : Floor σ Ties (1, 2, 3 mm), and σ Velocity (0.01, 0.05, 0.1, 0.5, 1 mm/yr)

Scale factors wrt ITRF2008

Uncalibrated Radome Sites Excluded



Tests : Floor σ Ties (1, 2, 3 mm), and σ Velocity (0.01, 0.05, 0.1, 0.5, 1 mm/yr)

Scale Difference (VLBI-SLR) amplified by 0.2 ppb

Uncalibrated Radomes: Tie Residuals

Site	E (mm)	N (mm)	Up (mm)	Comment
CRO1	**4.9**	**-1.2**	**-1.4**	VLBA, seems OK
FORT	**1.7**	**-3.8**	**1.9**	VLBI, but tie corrected by J. Ray
GODE	**-3.0**	**5.2**	**-6.8**	SLR
MDO1	**1.8**	**-3.0**	**17.0**	SLR
MDO1	**4.3**	**-10.0**	**7.0**	VLBI
NLIB	**-0.4**	**1.9**	**-8.5**	VLBI
ONSA	**6.7**	**-1.3**	**-1.6**	VLBI
SHAO	**1.7**	**-6.8**	**-17.2**	SLR: probably GPS problem in N
SHAO	**-2.8**	**-6.8**	**-0.5**	VLBI: probably GPS problem in N
TIDB	**0.0**	**2.2**	**3.3**	VLBI, seems OK
TSKB	**2.2**	**2.1**	**0.9**	VLBI, seems OK
WTZZ	**-0.5**	**4.6**	**2.3**	VLBI: probably GPS problem in N
WTZZ	**0.1**	**4.6**	**8.1**	SLR: probably GPS problem in N
YARR	**4.0**	**-2.1**	**17.2**	SLR

Examples of "velocity tie" problems

Site	E mm	N mm	Up mm	Comment
GODE	**-3.0** **-1.5**	**5.2** **3.2**	**-6.8** **-3.0**	SLR: Total residuals at tie epoch Due to velocity discrepancy
MDO1	**1.8** **0**	**-3.0** **0**	**17.0** **3.5**	SLR: Total residuals at tie epoch Due to velocity discrepancy
MDO1	**4.3** **0**	**-10.0** **-2.0**	**7.0** **1.3**	VLBI: Total residuals at tie epoch Due to velocity discrepancy
NLIB	**-0.4** **-1.6**	**1.9** **2.8**	**-8.5** **-3.6**	VLBI: Total residuals at tie epoch Due to velocity discrepancy
MEDI	**-0.5** **0.6**	**-2.6** **-0.6**	**9.4** **2.0** **-8.9**	VLBI: Total residuals at tie epoch Due to velocity discrepancy Effect of VLBI antenna sag (P. Sarti)

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Summary of the extended analysis

- **Scale (at 2005.0):**
  - Agreement btw SLR&VLBI : between 0.7 & 1 ppb
  - GPS : N/A
  - DORIS : in between SLR and VLBI
- **Scale rate wrt ITRF2008 in ppb/yr :**
  - SLR, VLBI & DORIS : between -0.03 & 0.03 (± 0.02)
  - GPS : -0.02
- **Origin wrt ITRF2008 (at 2005.0):**
  - SLR : 0 (±1) mm
  - GPS : up to 10 mm in Z
  - DORIS : unreliable in Z
- **Origin rate with respect to ITRF2008 :**
  - SLR : (-0.3, 0, 0) (±0.1) mm/yr
  - GPS : 0.7 mm/yr in Z
  - DORIS : unreliable in Z
- **Uncalibrated radome effect** : 0.2 ppb

Conclusion

- **ITRF current accuracy: ~1cm over its time-span**
- **Results of extended analysis:**
  - **Consistent with ITRF2008**
  - **Persistent scale factor between VLBI & SLR : 0.7 to 1. ppb**
  - **Scale drift could be minimized at the level of ± 0.02 ppb/yr**
  - **==> ITRF2013 scale may be fixed to ITRF2008**
- **Impact of uncalibrated radomes: ~ 0.2 ppb (undesirable)**
  - **GPS & VLBI might have the same (opposite) error (e.g. Tsukuba)**
- **TC solutions to be submitted to ITRF2013:**
  - **New reprocessed solutions**
  - **Solutions with Loose/removable constraints or NEQ**
  - **NT-ATML: to be decided after the evaluation of the solutions with & without corrections**

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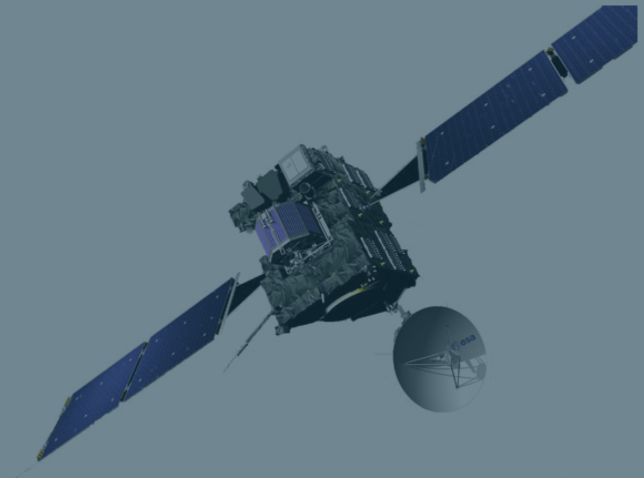
A REFERENCE FRAME FOR GEOPHYSICS AND RELATIVISTIC GEODESY



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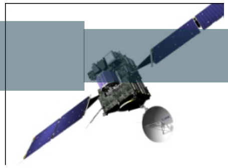
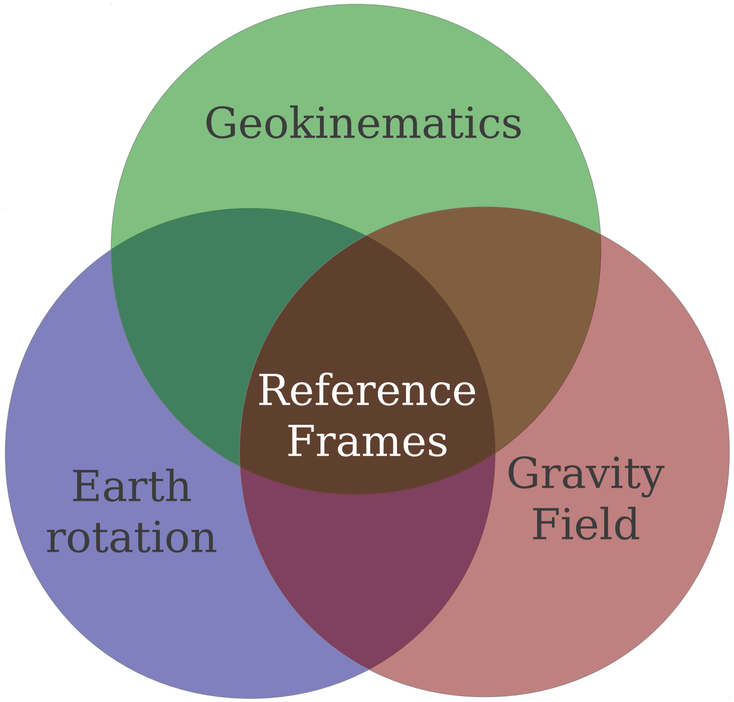
Pacôme DELVA

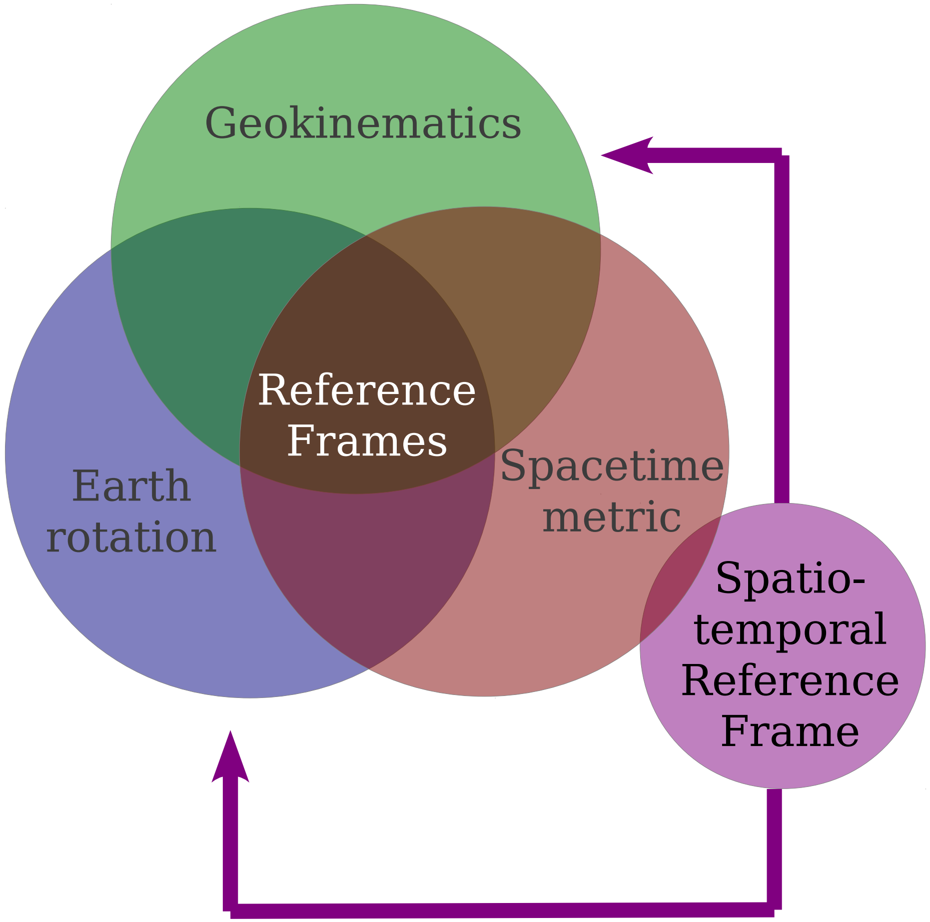
SYRTE / UPMC / Paris Observatory





the « three pillars » of GGOS

- Non relativistic framework
- High intricacy of problems
  - parameters degeneracy
  - Huge variety of observation types makes difficult a common framework model
  - Coherency of multi-technique schemes ?
- Heavy and dedicated infrastructure (VLBI, tracking stations, satellites…)



- Disentangle as much as possible the realisation of the reference frame from the other problems
- Relativistic framework:
  - Time is just the fourth coordinate → realisation of a spatio-temporal reference frame
  - Space-time is dynamic: geodetic reference frame + gravity field → spacetime metric solution of Einstein equation
  - Geoid → relativistic definition
- Inter-connected clocks in Earth orbit:
  - spatio-temporal reference system
  - Dynamical and quasi-inertial
  - Relativistic Positioning System (RPS)

ESA/ACT Ariadna Studies (2009-2010)

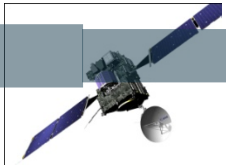
- « Mapping the Spacetime metric with a Global Navigation Satellite System »
  → self consistent definition of reference frame using the GNSS clocks and inter-satellite links

ESA/PECS Study (2011-2014):

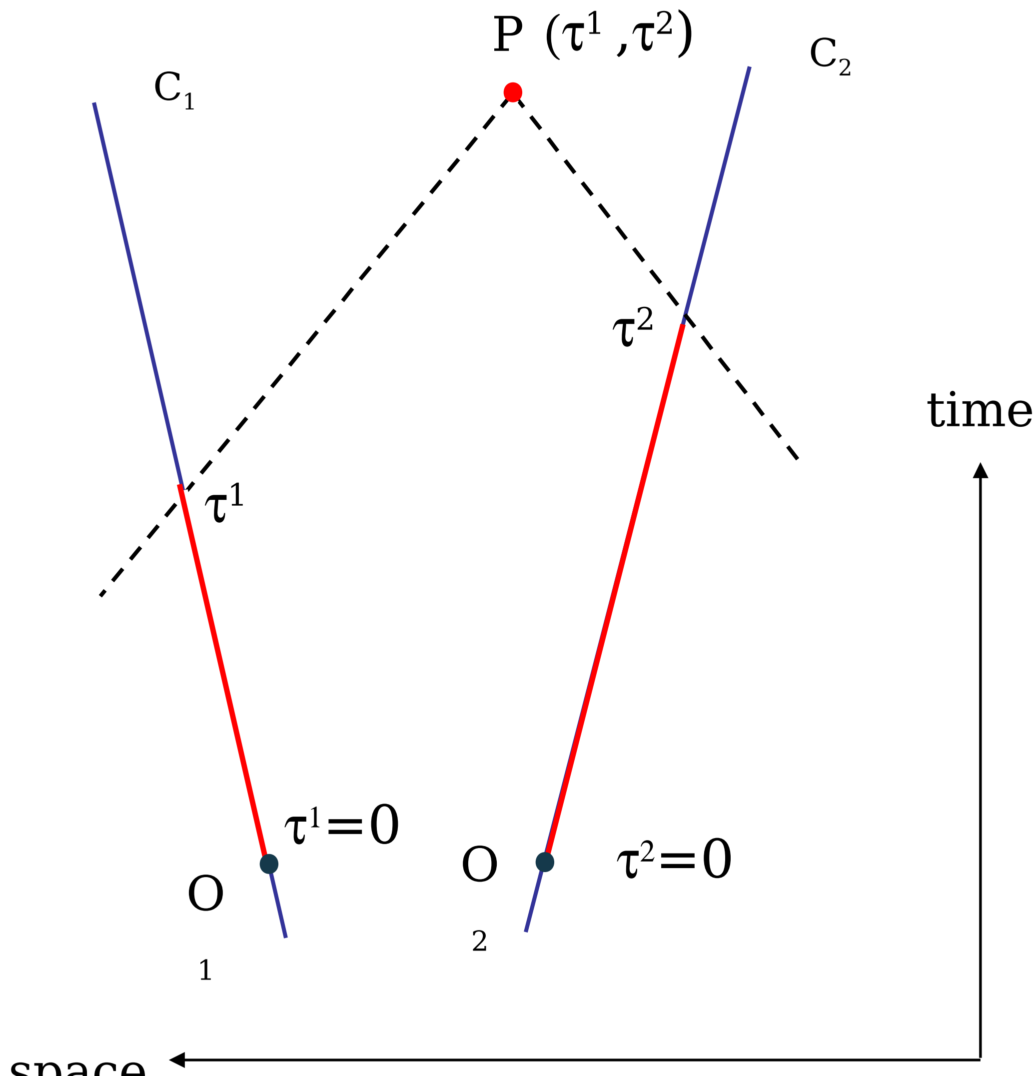
- Relativistic Global Navigation System (RGNSS)
- University of Ljubljana (M. Horvat, U. Kostic, A. Gomboc), ESA / Advanced Concepts Team (S. Carloni, L. Summerer), Syrte/UPMC/CNRS (P. Delva, E. Richard)

GSAC Recommendations (2012)

- « Provide a **net of inter-satellite links** (optical or microwave) in the entire Galileo constellation, which will provide major improvements in the determination of the Galileo clocks and orbits. »
- « Deploy an **« ACES-like » payload** on a small number of Galileo satellites to provide a new type of links between Galileo satellites and ground stations, and a demonstrator for a general-purpose time and frequency transfer system (microwave). »



- General relativity + 4 test particles, whose time-like trajectories C_α are exactly known and parameterized with proper times τ^α.
- Given a point P, its past light cone intersects the four trajectories at proper times τ^1,τ^2,τ^3 and τ^4.
- Then $(\tau^1,\tau^2,\tau^3,\tau^4)$ are the coordinates of point P → **emission coordinates**



Rovelli, PRD **65** (2002)
Coll & Pozo, CQG **23** (2006)

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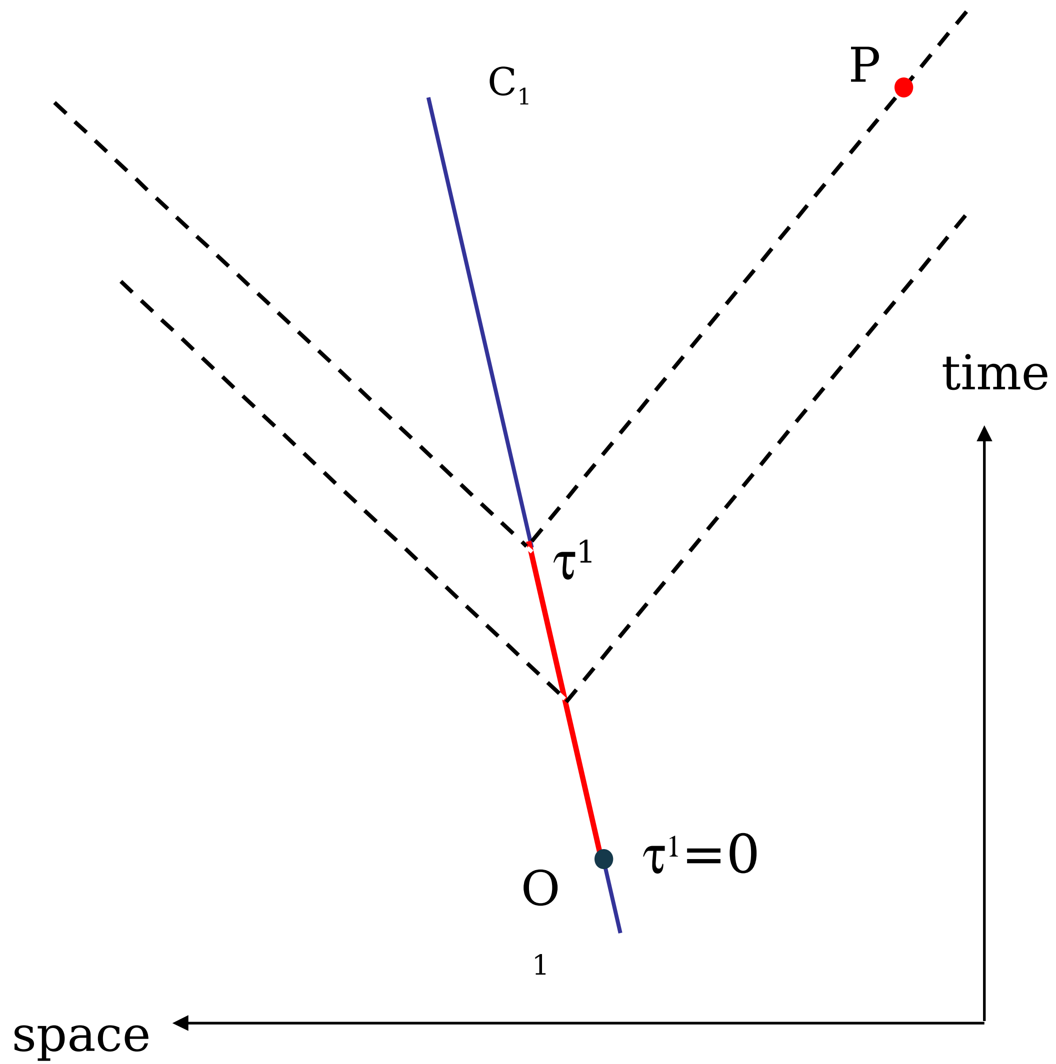
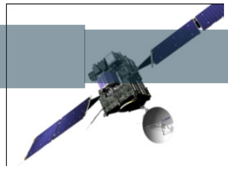
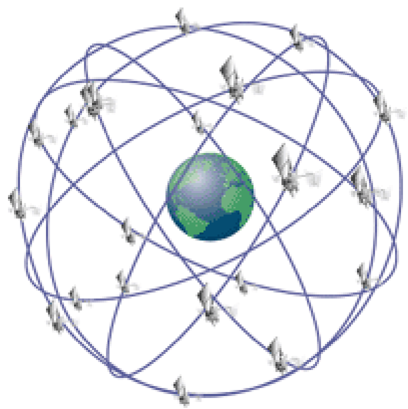


From emission to local coordinates





Satellite tracking

post-processing

Satellites constants of motion

Emission coordinates

User

Coordinate transformation to the ABC Reference Frame

From emission to local coordinates

- Main ingredient: Hamiltonian to describe dynamics

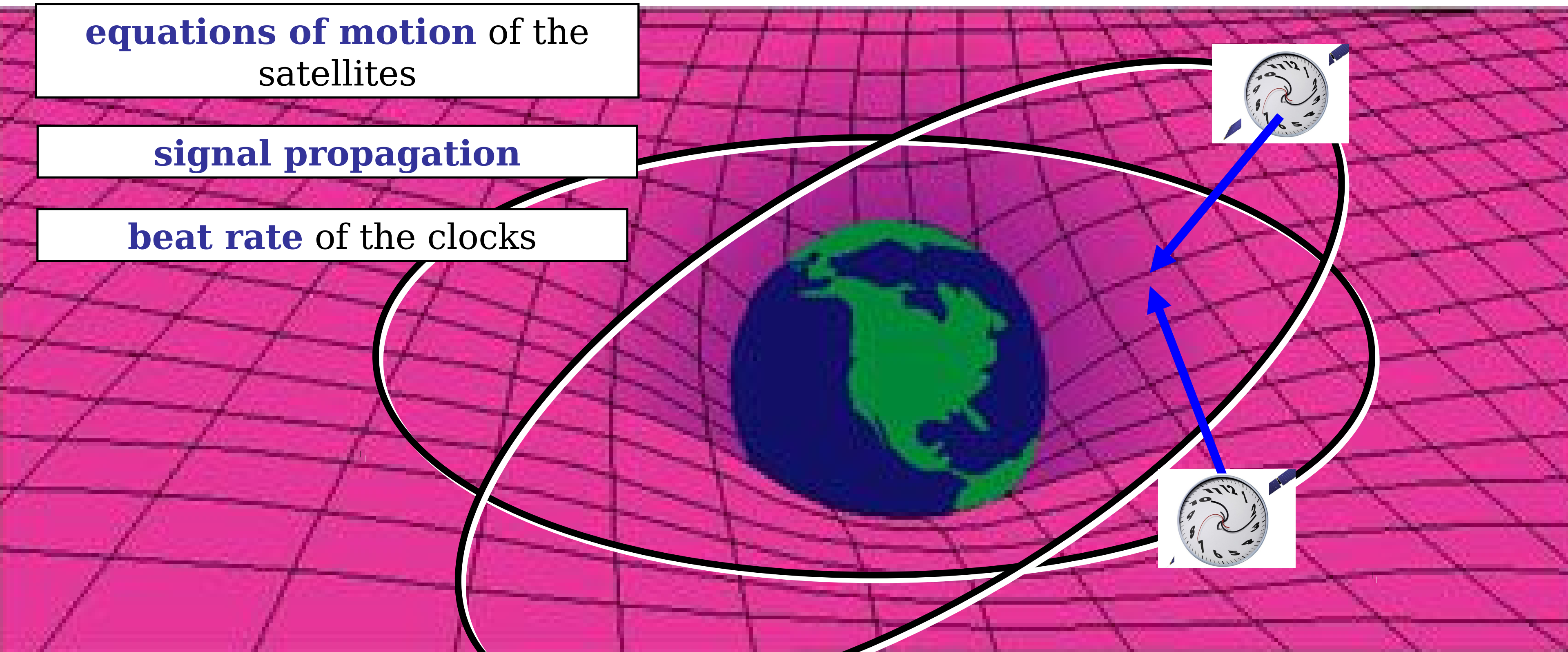
$$H = \frac{1}{2}\left[-\frac{1}{1-\frac{2M}{r}}\, p_t^2 + \left(1-\frac{2M}{r}\right) p_r^2 + \frac{1}{r^2}\left(p_\theta^2 + \frac{1}{\sin^2\theta}\, p_\phi^2 \right)\right]$$

Background geometry

equations of motion of the satellites

signal propagation

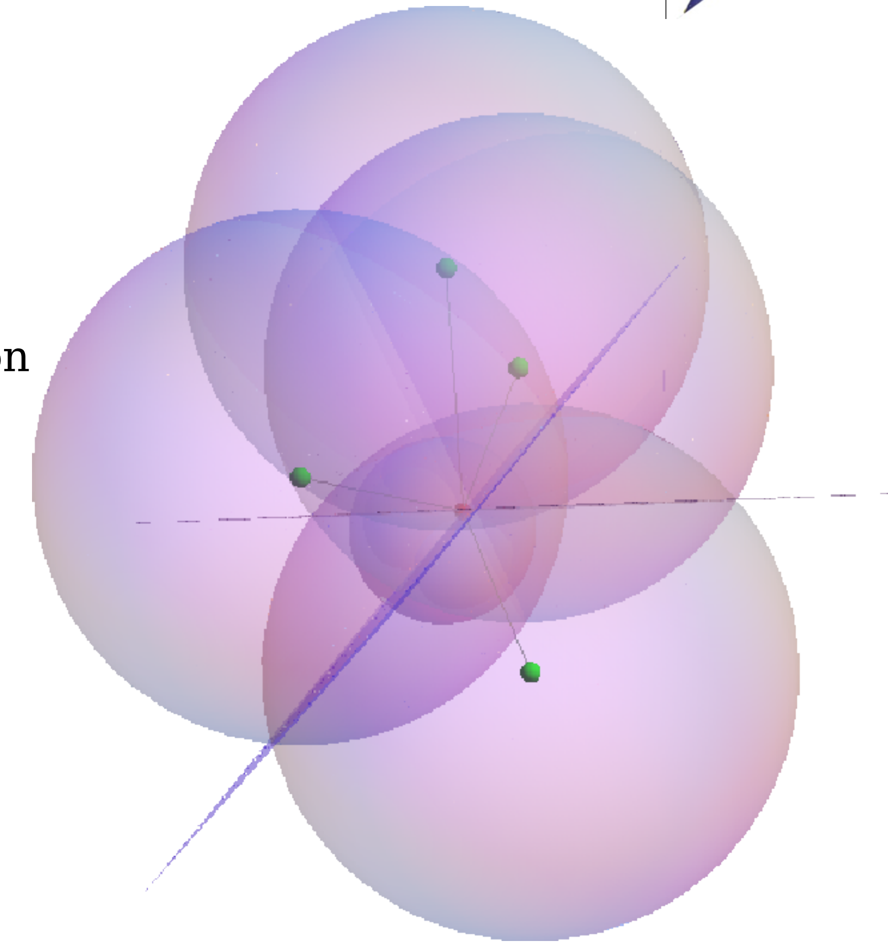
beat rate of the clocks



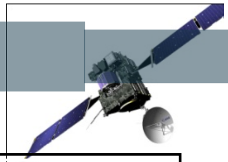
- **Solve** the set of non-linear differential equations describing the satellites and the light (ISL) geodesics

- **Numerical code**
  - coordinate transformations from emission to local coordinates (and the inverse problem)
  - constellation of N satellites, known constants of motions

- Effects of **non-gravitational perturbations** on the positioning system
  - clocks errors, drag, micro-meteorites

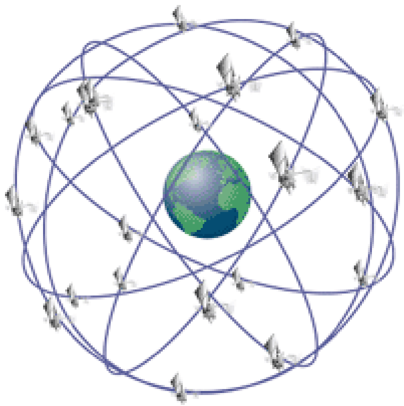


Inter-Satellite Links



Inter-Satellite Links (ISL)

Emission coordinates



- **Autonomous constellation →** defines a dynamical (ABC) Reference Frame
- Orbital periods are used to **correct the satellites clocks**

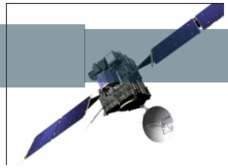
~~Satellite tracking from Earth~~

Satellites constants of motion

Emission coordinates

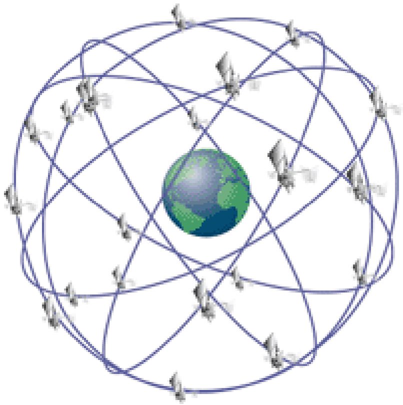
User

Coordinate transformation to the ABC Reference Frame



Inter-Satellite Links (ISLs)

Emission coordinates



Clock correction and data reduction

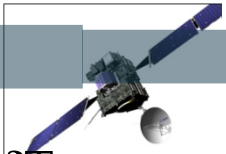
Realization of the ABC reference frame

Satellites constants of motion

Emission coordinates

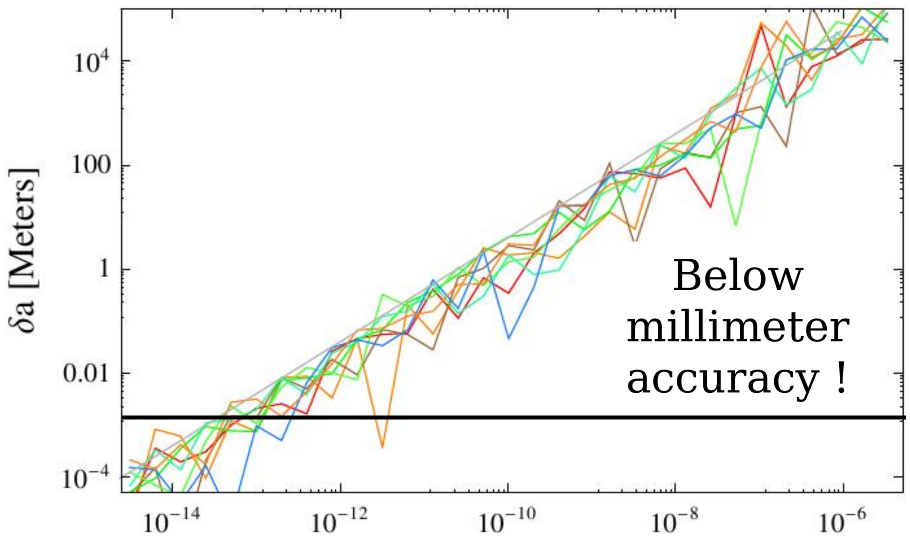
User

Coordinate transformation to the ABC Reference Frame



- **Simulation** of data pairs (τ*,τ)_{ij} with additional random noise δT
- **Robustness** of recovering constants of motion with respect to noise in the data
- **Consistency** of description with redundant number of satellites
- Possibility to use the constellation as a clock with **long term stability**
- Possibility to use perturbation theory to refine the Hamiltonian toward a better **long term dynamical prediction → ESA/PECS project**

GALILEO
~1 ns/day



Allan deviation of the clocks @ 1 day

Technical reports (http://www.esa.int/act)

Čadež, A., Kostić, U., Delva, P., *Mapping the Spacetime Metric with a Global Navigation Satellite System*, **Advanced Concepts Team**, **2011**, European Space Agency

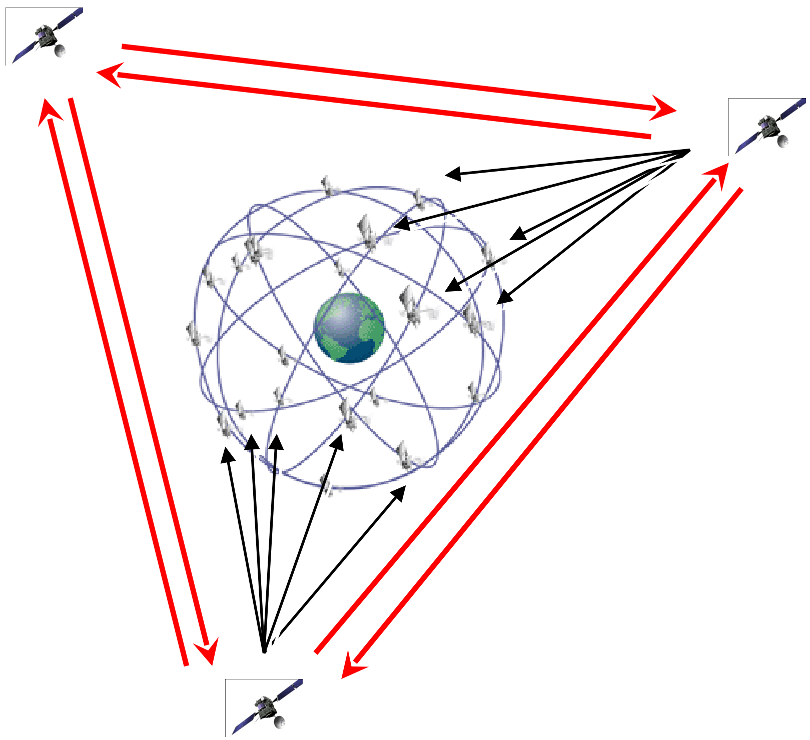
Čadež, A., Kostić, U., Delva, P., and Carloni, S., 2011, *Mapping the Spacetime Metric with a Global Navigation Satellite System - Extension of study: Recovering of orbital constants using inter-satellites links*, **Advanced Concepts Team**, **2011**, European Space Agency

Peer-reviewed article

Delva, P., Kostić, U., Čadež, A., *Numerical modeling of a Global Navigation Satellite System in a general relativistic framework*, **Advances in Space Research**, **2011** (Special Issue on Galileo)

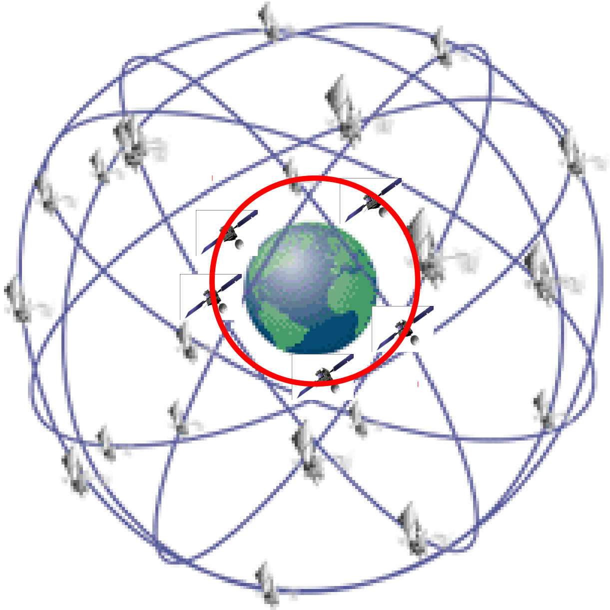
Proceeding

Delva, P., Čadež, A., Kostić, U., and Carloni, S., *A relativistic and autonomous navigation system*, **Proceedings of the Rencontres de Moriond and GPHYS colloquium**, **2011** (http://arxiv.org/abs/1106.3168)



Geostationnary constellation for time dissemination

LEO constellation for Earth gravitational field determination



Toward relativistic geodesy

Ground clock network linked to the constellation of satellites:

- Realisation of a relativistic equipotential → where clocks beat at the same rate (in the ABC frame) → 10 cm accuracy with optical clocks
- Measurement of static and time-varying gravitational field by comparing clocks at different locations
- First demonstration of relativistic geodesy: ACES/PHARAO experiment

Conclusion

- Turn non-dedicated satellites to a **powerful scientific instrument** for experimental gravitation ("Riemannian gravimeter"), reference systems, geophysics, high precision positioning

- Data sets and dynamics treated in a coherent frame, independent of Earth internal dynamics and atmosphere → **high stability and accuracy**

- Operation of the experiment for many decades, with continuous data flow, constantly refining the dynamical model (Hamiltonian)

- Very few studies on **inter-satellites links**, that do not take advantage of the autonomy and the dynamics of the constellation

- Going further:

  - how inter-satellite links ameliorate existing systems through the study of spatio-temporal positioning for different type of users

  - Study different technologies and system configuration (secondary constellation, …)

  - Organization of a workshop in september in Ljubljana (Slovenia) around scientific uses of Inter-Satellite Links

RELATIVISTIC POSITIONING SYSTEMS AND THEIR SCIENTIFIC APPLICATIONS

Brdo near Kranj, Slovenia, 19-21 September 2012

We are pleased to announce that a three-days workshop on relativistic positioning systems and their scientific applications will be held at Brdo near Kranj, Slovenia, on 19-21 September 2012.

The workshop is organized by the Faculty of Mathematics and Physics of the University of Ljubljana (UL) and ESA (Advanced Concepts Team). The goal of the workshop is to bring together those interested in the development of Relativistic Positioning Systems (RPS) and, in particular, to share ideas and establish future lines of research and collaborations.

The deadline for abstract submission is 1st July 2012.

More information can be found on http://rgnss.fmf.uni-lj.si/workshop

Topics of the workshop include:

- Formulation of relativistic positioning systems and properties of emission coordinates
- Application to GNSS, relativistic reference frames, pulsar-based navigation and localization
- Inter-satellite links and autonomous GNSS
- Relativistic celestial mechanics (coordinate systems, Hamiltonian techniques...)
- Application to Earth sciences, astronomy and metrology.

Also other contributions in line with the aims of the workshop will be considered.

Scientific Organizing Committee:

Bertram Arbesser-Rastburg (ESA)
Sante Carloni (ESA)
Pacôme Delva (Obs. Paris)
Clovis Jacinto de Matos (ESA)
Rune Floberghagen (ESA)
Uroš Kostić (UL)
Leopold Summerer (ESA)

Local Organizing Committee:

Andreja Gomboc (UL), Martin Horvat (UL), Uroš Kostić (UL)

Institute of Information Theory and Automation,
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CZ-250 66 Zdiby 98, e-mail: Milan.Talich@vugtk.cz

Creation of strain maps from velocity field of deformation by on-line tools

Milan Talich

Space Geodesy and Earth System, August 18-21, 2012, Shanghai, China

What is Strain Analysis:

- **based on continuum mechanics, describes the change in shape and dimensions of the monitored object**
- **is more objective dynamic indicator in the researched area than the only calculus and representation of point displacement vectors.**

Strain Analysis:

- Geodetic methods applications is based on repeated measurement and comparison of results of individual epochs of measurements. The vector of point displacement is expressed as a function of coordinates

$$\mathbf{x}_i^o - \mathbf{x}_i^t = \mathbf{d}_i = (u_1, u_2, u_3)_i^T = \mathbf{u}(\mathbf{x}) = (u_1(\mathbf{x}), u_2(\mathbf{x}), u_3(\mathbf{x}))^T, \quad \mathbf{x} = (x, y, z)^T$$

- Where $\mathbf{x}_i^o$ (resp. $\mathbf{x}_i^t$) is the vector of P_i point coordinates of fundamental (resp. actual in t-time) epoch.
- The strain tensor in P_i is defined as a gradient of the function in this point:

$$\mathbf{E}_i = \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{pmatrix}_i = \mathrm{grad}(\mathbf{d}_i) = \begin{pmatrix} \frac{\partial u_1}{\partial x} & \frac{\partial u_1}{\partial y} & \frac{\partial u_1}{\partial z} \\ \frac{\partial u_2}{\partial x} & \frac{\partial u_2}{\partial y} & \frac{\partial u_2}{\partial z} \\ \frac{\partial u_3}{\partial x} & \frac{\partial u_3}{\partial y} & \frac{\partial u_3}{\partial z} \end{pmatrix}_i$$

Strain Analysis:

e.g. for displacements projected to XY of the local coordinate system
(min. 3 points with displacements vectors are needed):

$\Delta = e_{11} + e_{22}$ - total dilatation,

$\gamma = \sqrt{\gamma_1^2 + \gamma_2^2}$ - total shear,

$\gamma_1 = e_{11} - e_{22}$ - shear strains,

$\varepsilon_1 = \frac{1}{2}(\Delta + \gamma)$ - axis of maximum strain,

$\gamma_2 = 2e_{12}$ - shear strains,

$\varepsilon_2 = \frac{1}{2}(\Delta - \gamma)$ - axis of minimum strain,

$$\varphi = \frac{1}{2}\operatorname{arctg}\left(\frac{\gamma_2}{\gamma_1}\right)$$ - direction of axis of maximum strain,

$\psi = \varphi + \frac{1}{4}\pi$ for $\omega_{12} > 0$ - direction of shear strain,

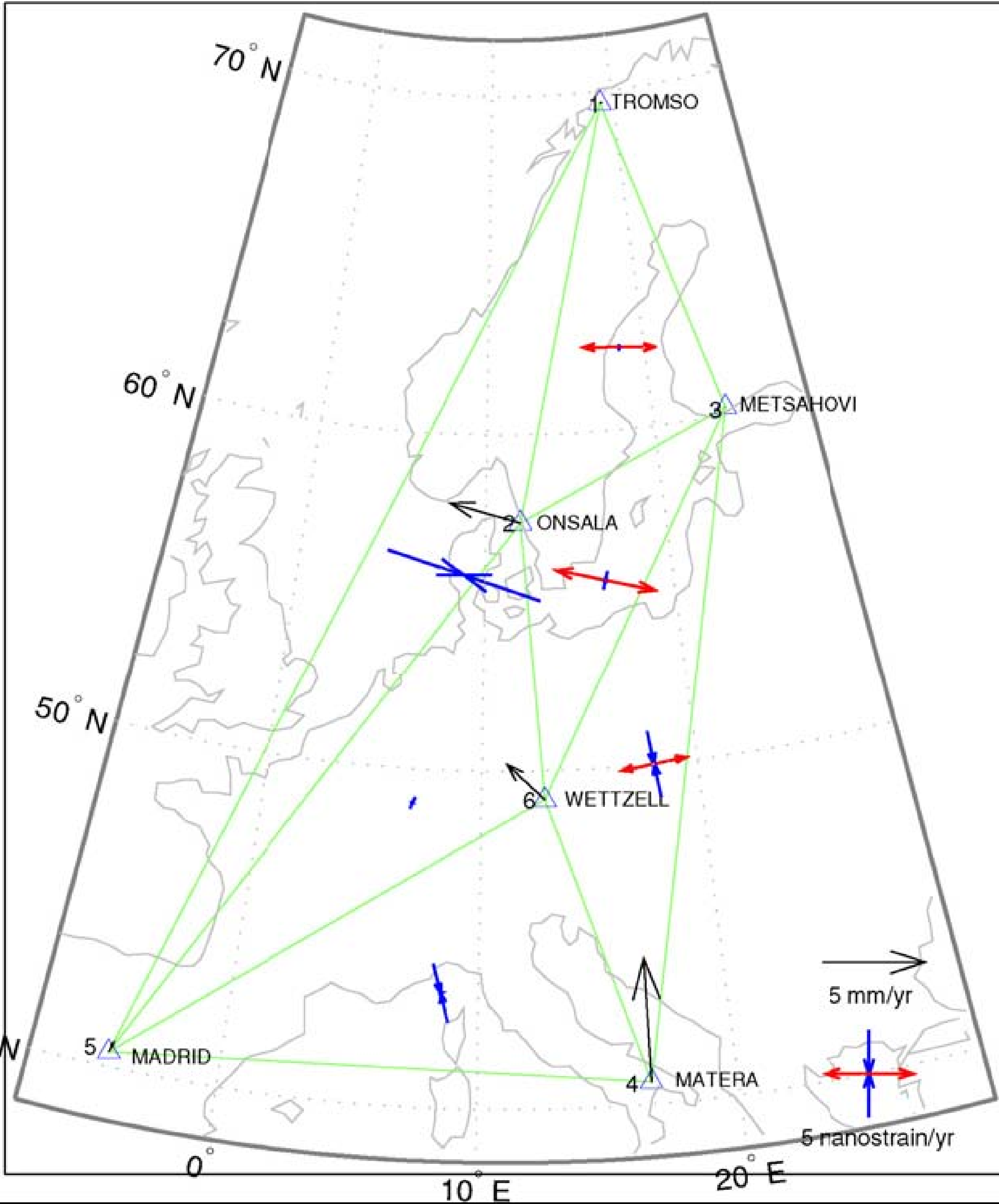
$\psi = \varphi - \frac{1}{4}\pi$ for $\omega_{12} < 0$ - direction of shear strain.

How to determine of Strain tensors from geodetic repeated measurements:

- First step is determination of displacements of selected points on the object in question (standard task)
  - After it determination of displacement field in continuous form by their interpolation (generalized task) can follow
- The second step is determination of deformations parameters by geometric analysis of continuum mechanics (strain analysis), usually two ways are used:
  - Splitting of the geodetic net in triangles and computation of the strain tensors within each triangle (hypothesis of homogeneous strain field in each triangle self),
  - Computation of global strain field from all displacements in the investigated area (hypothesis of homogeneous strain field in the whole area),

Determination of displacements (first step):

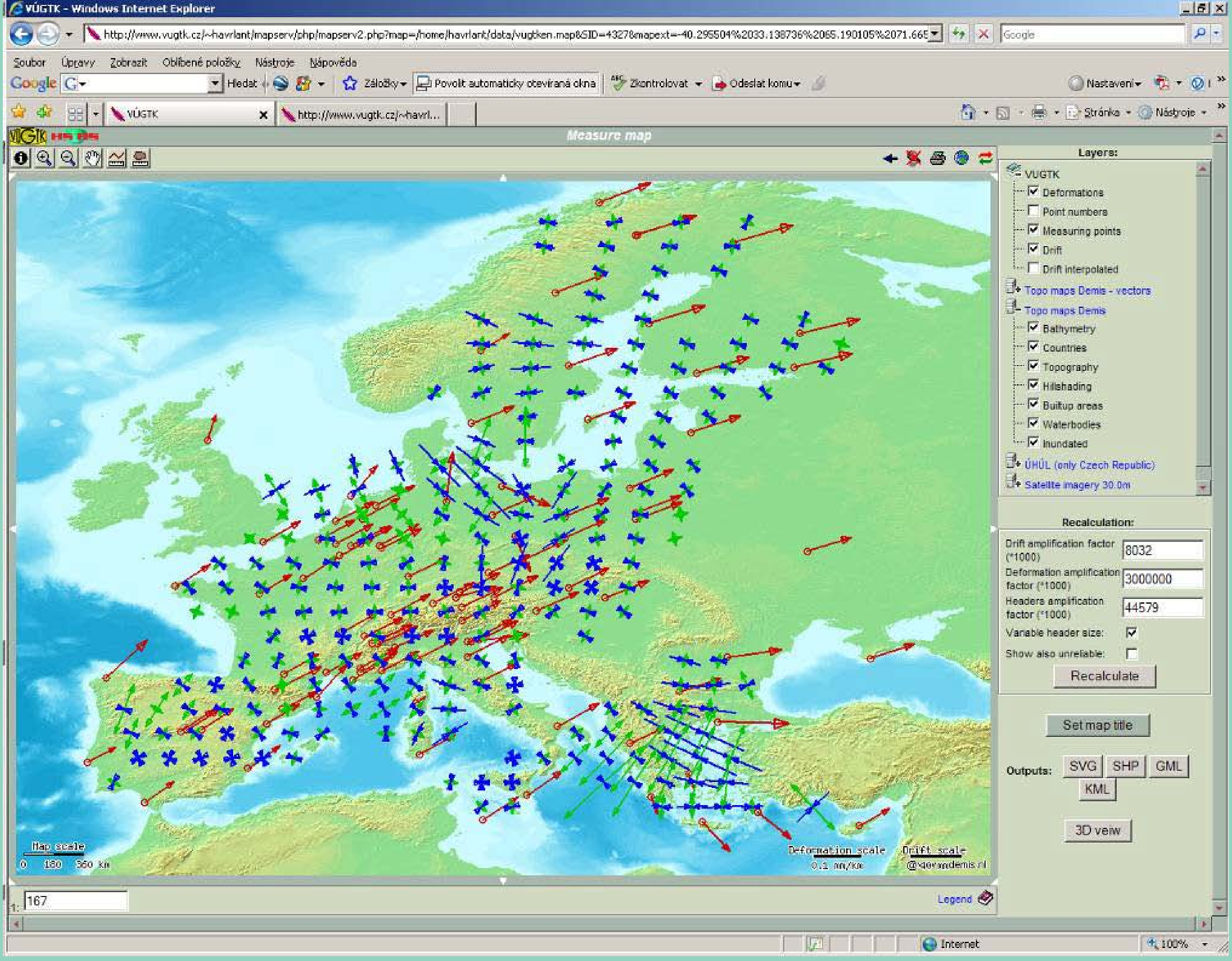
- **The resulting character of displacements is given by the conditions for geodetic network placing in the coordinate frame.**
- **The first condition is to computing the net adjusting as free network.**
- **Usually selected points that are expected to be in the stable part of location are chosen like fiducial points.**
- **But: we are never quite sure that our hypothesis about points stability are correct – Everything is moving.**



Determination of deformations (second step)

Strain field by using Delaunay triangulation

(Cai and Grafarend, 2007)



Strain field

Benefits resulting from Strain Analysis (second step):

- **All deformation parameters (strain tensors) are independent on used coordinate frame and insensitive to translation and rotation (excepting direction of axis)**

Practical benefits:

- => It is not necessary to deal with conditions of placing the geodetic network in the coordinate frame (fiducial points declaration by free net adjustment).

- => To the practical using this means elimination of the errors obtained due to false (erroneous) hypothesis about stability of fiducial points that we consider as stable during repeated measurement.

Practical benefits:

- => practical example can be GPS antenna exchange (change of phase centre of a new antenna against the old one) of a permanent station at fiducial point of the GPS net (if this point is not included into calculation of the field of displacements and deformation).

Practical benefits:

- => it is not necessary to transform displacements given e.g. in coordinates frame ITRF into ETRF, or to reduce displacements in ITRF by movements of tectonic plate according to some of geodynamic models as APKIM2000 or NNR-NUVEL

Practical benefits:

- => it is possible to deduce the real geodynamic activities based on determined deformation parameters (location of faults,…).
- Above all, the real situation is disclosed.

Practical benefits:

- Strain analysis can be used as technological and scientific base for communication between specialists of different professions because such information is used to further studies, physical interpretations and determining causative factors. Especially if we wont to better understand the processes and their interaction within the Earth system.

How practically to determine of Strain tensors from geodetic repeated measurements ?

- **For computation of strain tensors can everybody use on-line application :**

www.vugtk.cz/~deformace

Deformation Analysis - Windows Internet Explorer

http://www.vugtk.cz/~deformace/pgm/index.php

Favorites | Deformation Analysis | Page | Safety | Tools

VÚGTK
www.vugtk.cz

RESEARCH INSTITUTE OF GEODESY, TOPOGRAPHY AND CARTOGRAPHY

Deformation Analysis

www.vugtk.cz/~deformace

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About application

- Input data formats
- Output data
- Examples
- Help

RUN APPLICATION

Deformation Analysis

- Registration of a new user
- Terms and Conditions
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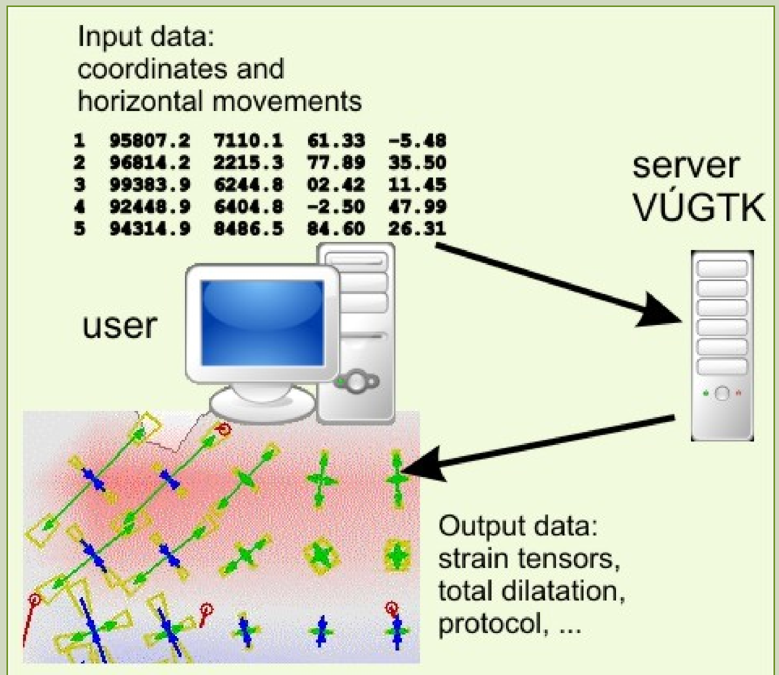
- Publications

Deformation Analysis

Web Application to on-line calculation of deformations derived from repeated geodetic plane survey. Parameters of deformation field (strain tensors, total dilatation, ...) are determined in a grid covering the area in question.



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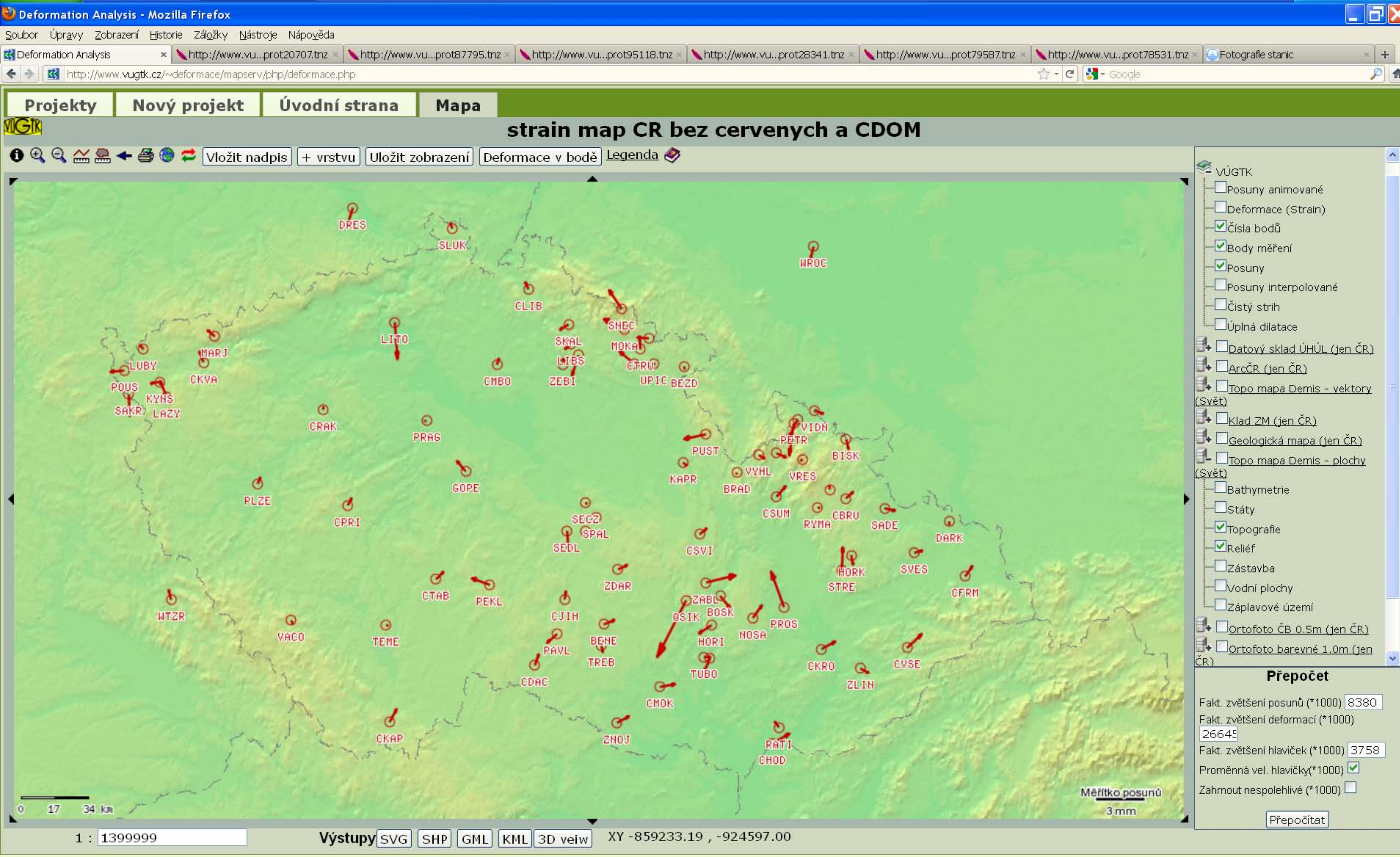

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Projekty
Nový projekt
Úvodní strana
Mapa
strain map CR bez cervenych a CDOM
Vložit nadpis
+ vrstvu
Uložit zobrazení
Deformace v bodě
Legenda
VÚGTK
Posuny animované
Deformace (Strain)
Čísla bodů
Body měření
Posuny
Posuny interpolované
Čistý strih
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Státy
Topografie
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Fakt. zvětšení posunů (*1000) 8380
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Fakt. zvětšení hlaviček (*1000) 3758
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CMBO
UPIC
BEZD
SAKR
LAZY
CRAK
PRAG
VIDN
PETR
PUST
BISK
KAPR
VYHL
VRES
BRAD
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SADE
SECZ
SPAL
SEDL
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CTAB
PEKL
ZDAR
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WTZR
CJIH
OSIK
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TEME
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TUBO
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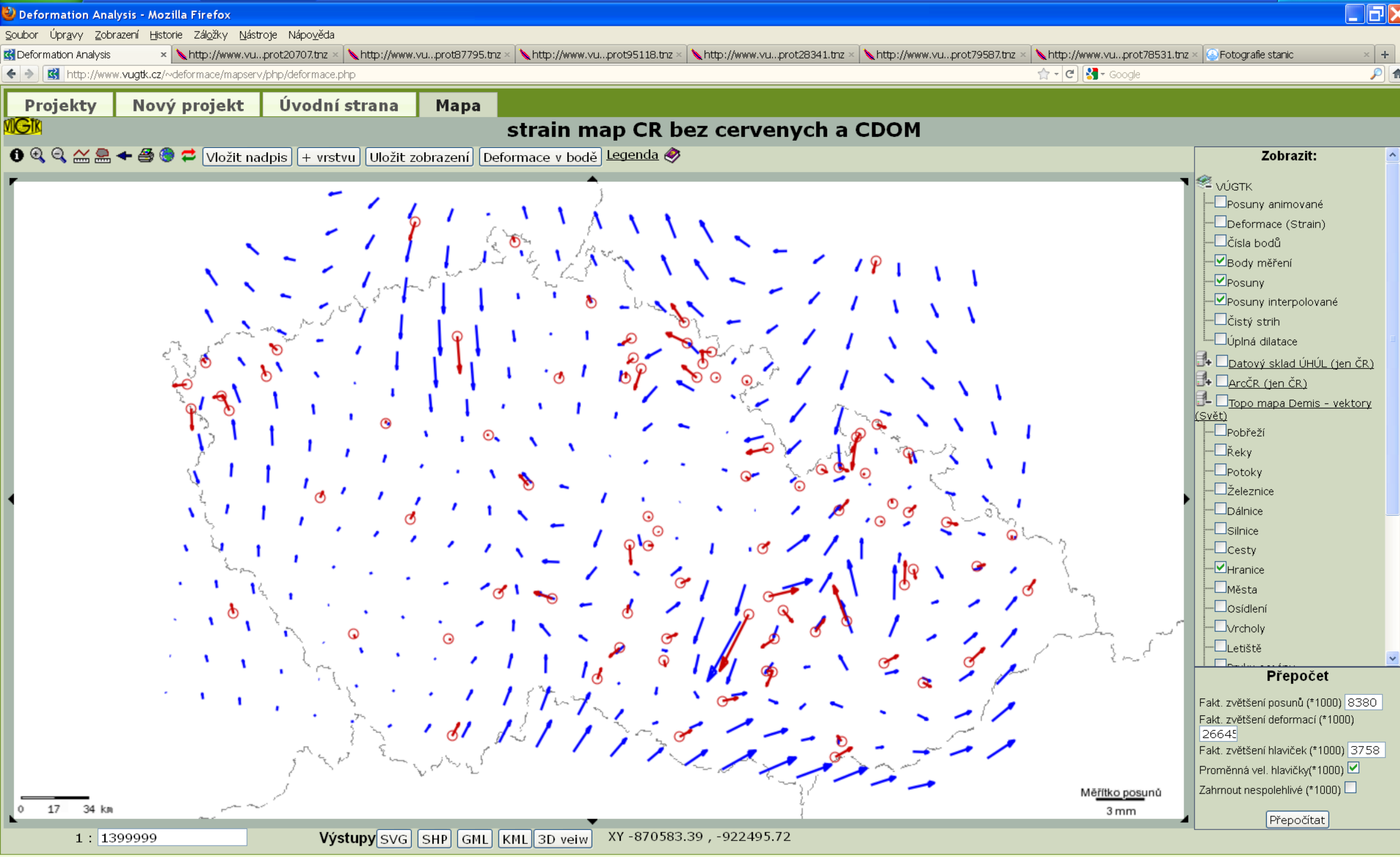
0 17 34 km
Měřítko posunů
3 mm
1 : 1399999
Výstupy SVG SHP GML KML 3D veiw
XY -859233.19 , -924597.00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Fotografie stanic
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Projekty
Nový projekt
Úvodní strana
Mapa
strain map CR bez cervenych a CDOM
Vložit nadpis
+ vrstvu
Uložit zobrazení
Deformace v bodě
Legenda
Zobrazit:
VÚGTK
Posuny animované
Deformace (Strain)
Čísla bodů
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Čistý strih
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Pobřeží
Řeky
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Zahrnout nespolehlivé (*1000)
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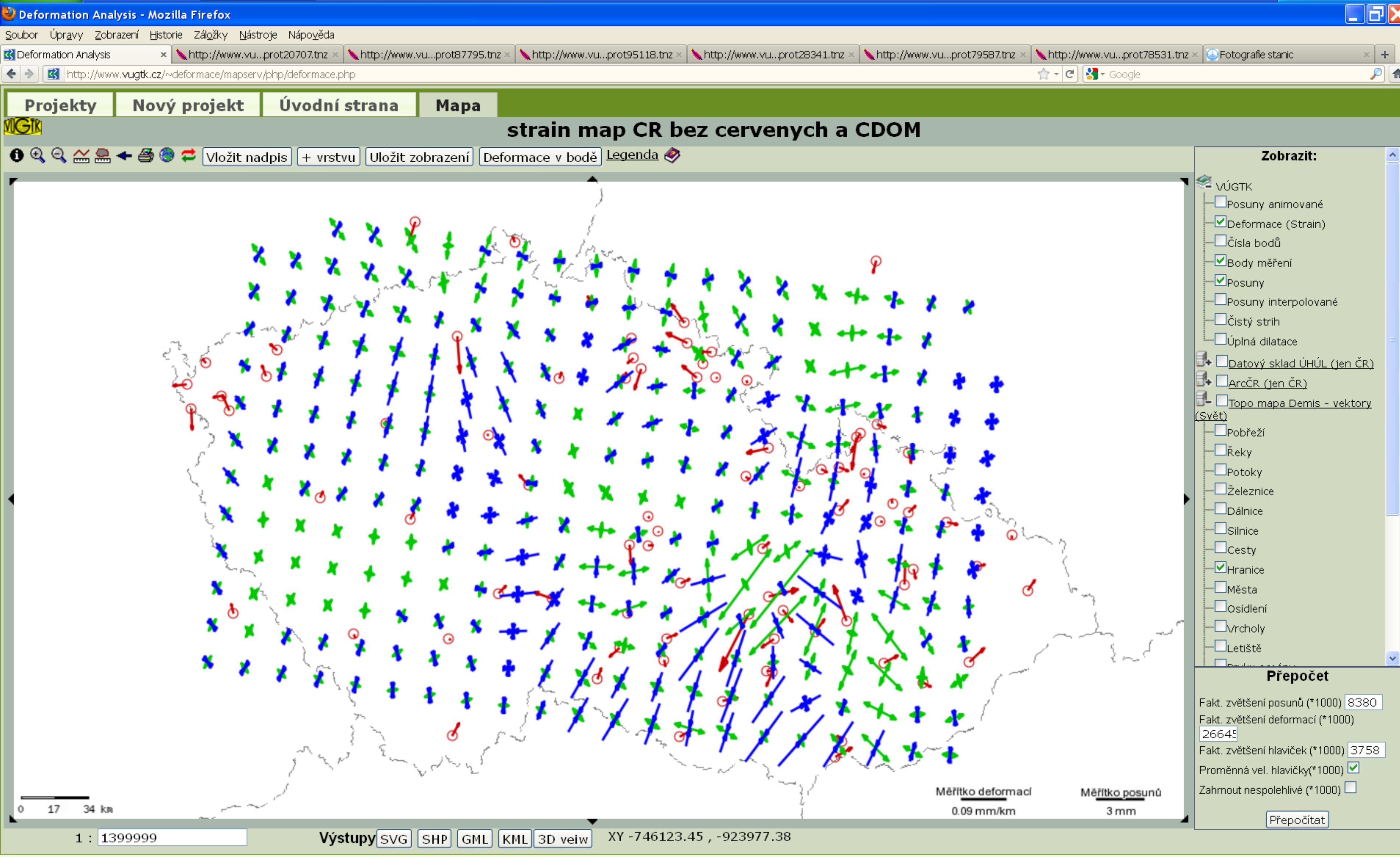
3 mm
1 : 1399999
Výstupy SVG SHP GML KML 3D veiw
XY -870583.39 , -922495.72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Nový projekt
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Zahrnout nespolehlivé (*1000)
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0 17 34 km
Měřítko deformací
0.09 mm/km
Měřítko posunů
3 mm
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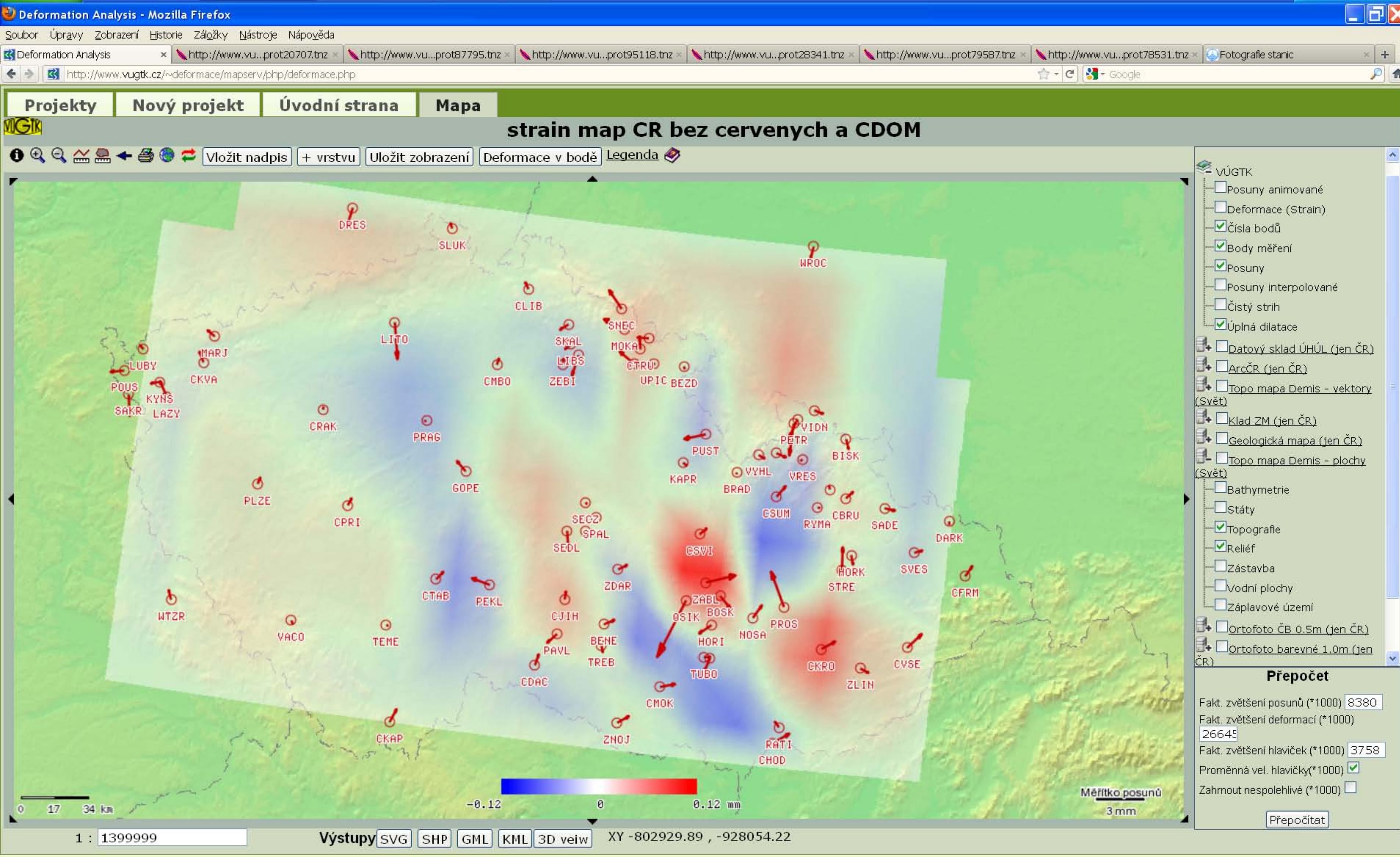
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+ vrstvu
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Legenda
VÚGTK
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Body měření
Posuny
Posuny interpolované
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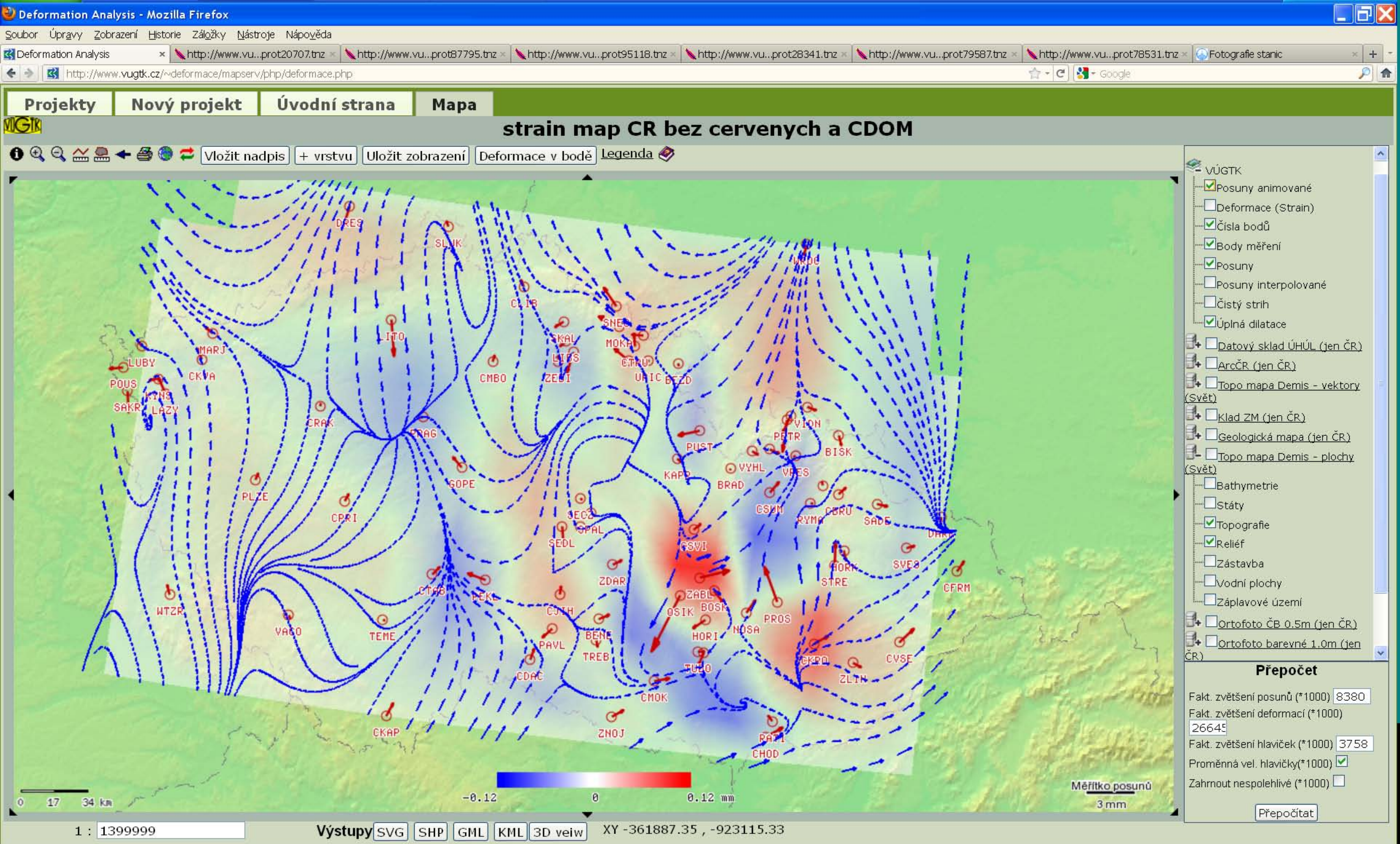
Proměnná vel. hlavičky(*1000)
Zahrnout nespolehlivé (*1000)
Přepočítat
-0.12
0
0.12 mm
Měřítko posunů
3 mm
0 17 34 km
1 : 1399999
Výstupy SVG SHP GML KML 3D veiw
XY -802929.89 , -928054.22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VÚGTK
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Body měření
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Zahrnout nespolehlivé (*1000)
Přepočítat
-0.12
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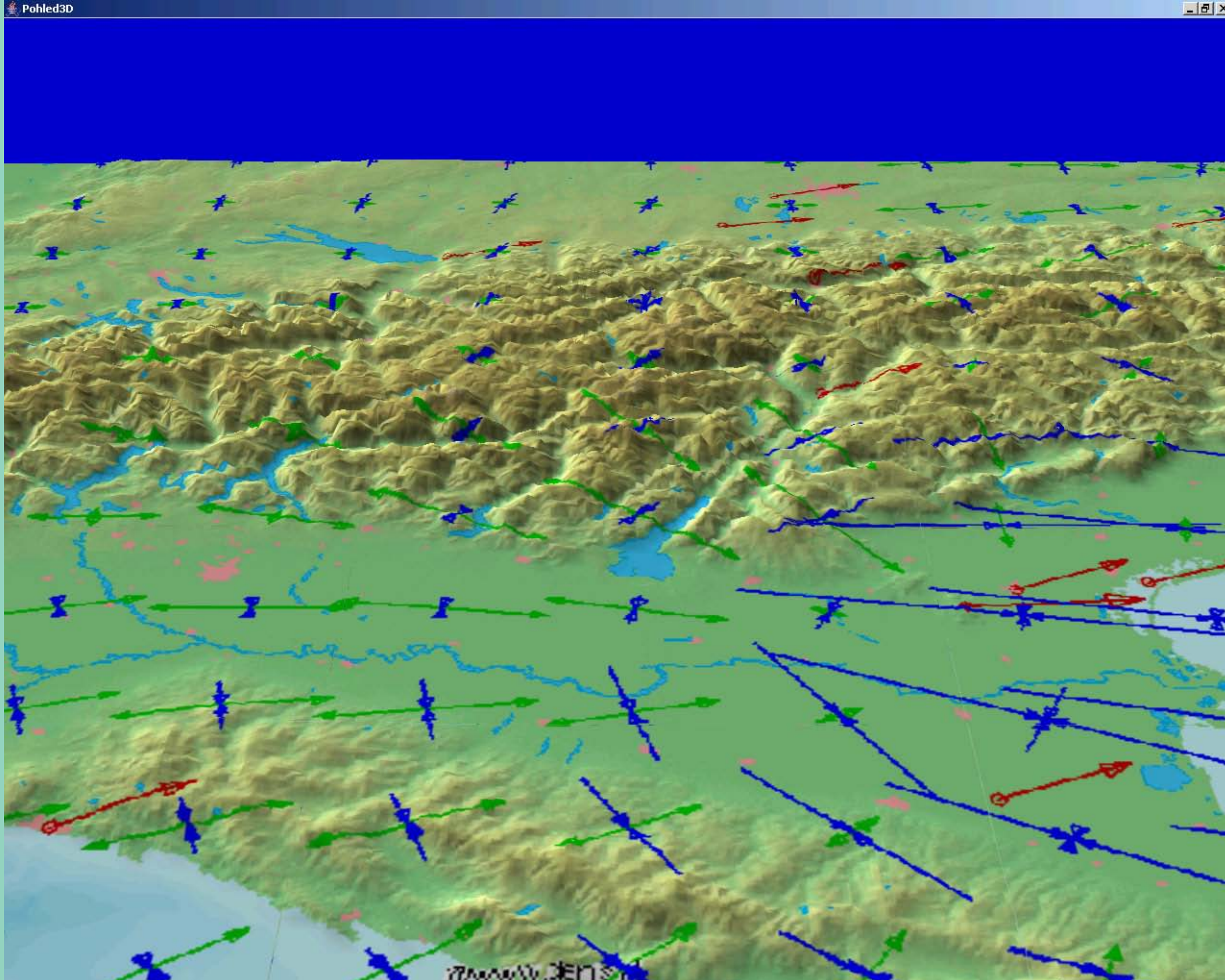
0.12 mm
0 17 34 km
Měřítko posunů
3 mm
1 : 1399999
Výstupy SVG SHP GML KML 3D veiw
XY -361887.35 , -923115.33


Pohled3D

We can help you with processing of your data.

We need your help with next progress of our application for deformation analysis (your remarks, proposals, experience,…).

Thank you for your attention

Milan.Talich@utia.cas.cz

www.vugtk.cz/~deformace

Diurnal Variation of Ground-based GPS-PWV under Different Solar Radiation Intensity in Chengdu Plain

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August 2012

Key word: ground-based GPS; precipitable water vapor; radiation intensity; diurnal cycle

Introduction

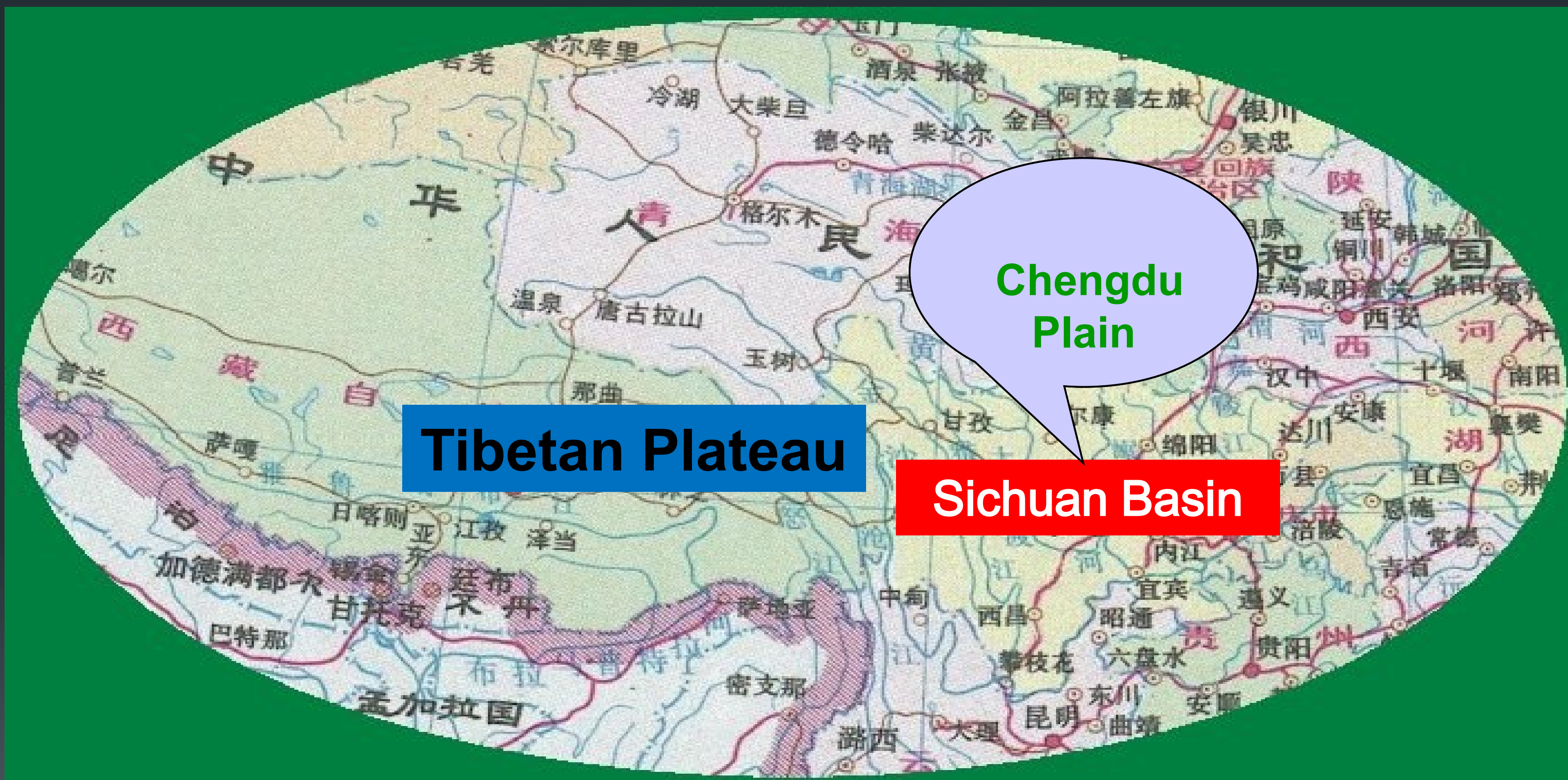
- Water vapor is essential for convective activity.
- Temporal variation of atmospheric water vapor is very important in forecasting regional weather and for understanding of local circulation system.
- Global positioning system (GPS) technology is typically used for geodesy and precise geographic positioning.

- High spatial resolution of GPS network can also estimate GPS-derived precipitable water vapor (GPS-PWV).

- PWV is defined as a column integrated amount of water vapor above the surface.

- Regional GPS network has a great potential for studying atmospheric water vapor variations in high temporal and spatial resolution.

Background of research areas



The geographical distribution of the GPS monitoring stations in Chengdu Plain

Data

- Surface meteorological elements : pressure, air temperature, precipitation ,solar radiation and sunshine.
- Raw GPS data with a time interval of 30 second was obtained from regional GPS measurement.
- 30-minute mean zenith total delay (ZTD) is estimated using the GPS analytic software.

Steps of GPS Analysis

1. GPS raw data TD

2. zenith hydrostatic delay (ZHD) by SA model

$$ZHD = 10^{-6}\frac{k_1 R p_s}{g_m M_d}$$

3. zenith wet delay (ZWD)

$$ZWD = ZTD - ZHD$$

4.GPS-derived precipitable water vapor –Businger's formula

$$PWV = \Pi$$

non-dimensional parameter of portionality

$$\Pi = \frac{10^6}{\rho R_v (k_2' + k_3 / T_m)}$$

coefficients determined from laboratory experiments

$$k_2' = k_2 - m \cdot k_1$$

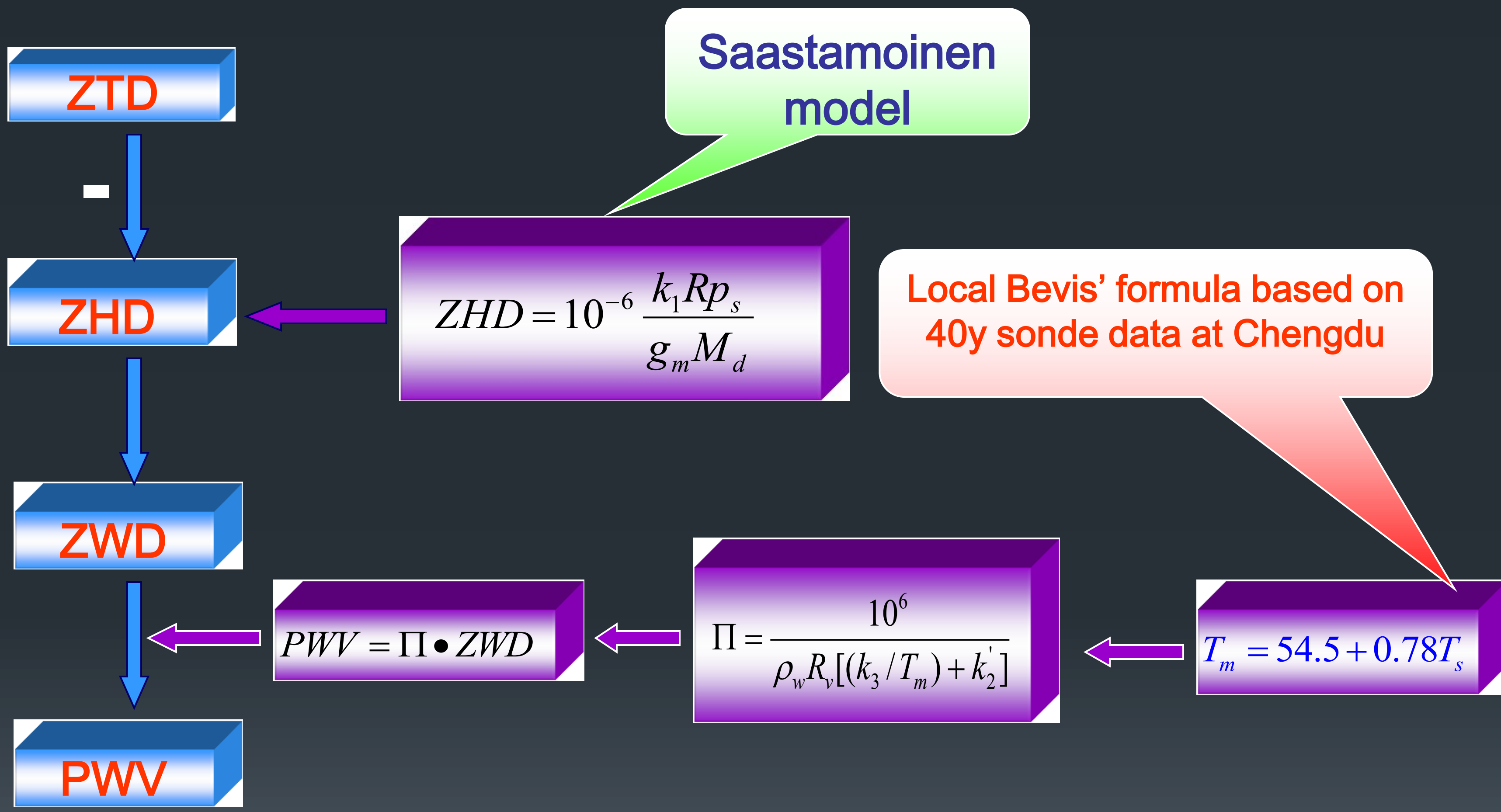
refractivity

$$N = k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} + k_3 \frac{P_v}{T^2}$$

mean weighted temperature-Bevis's regression formula

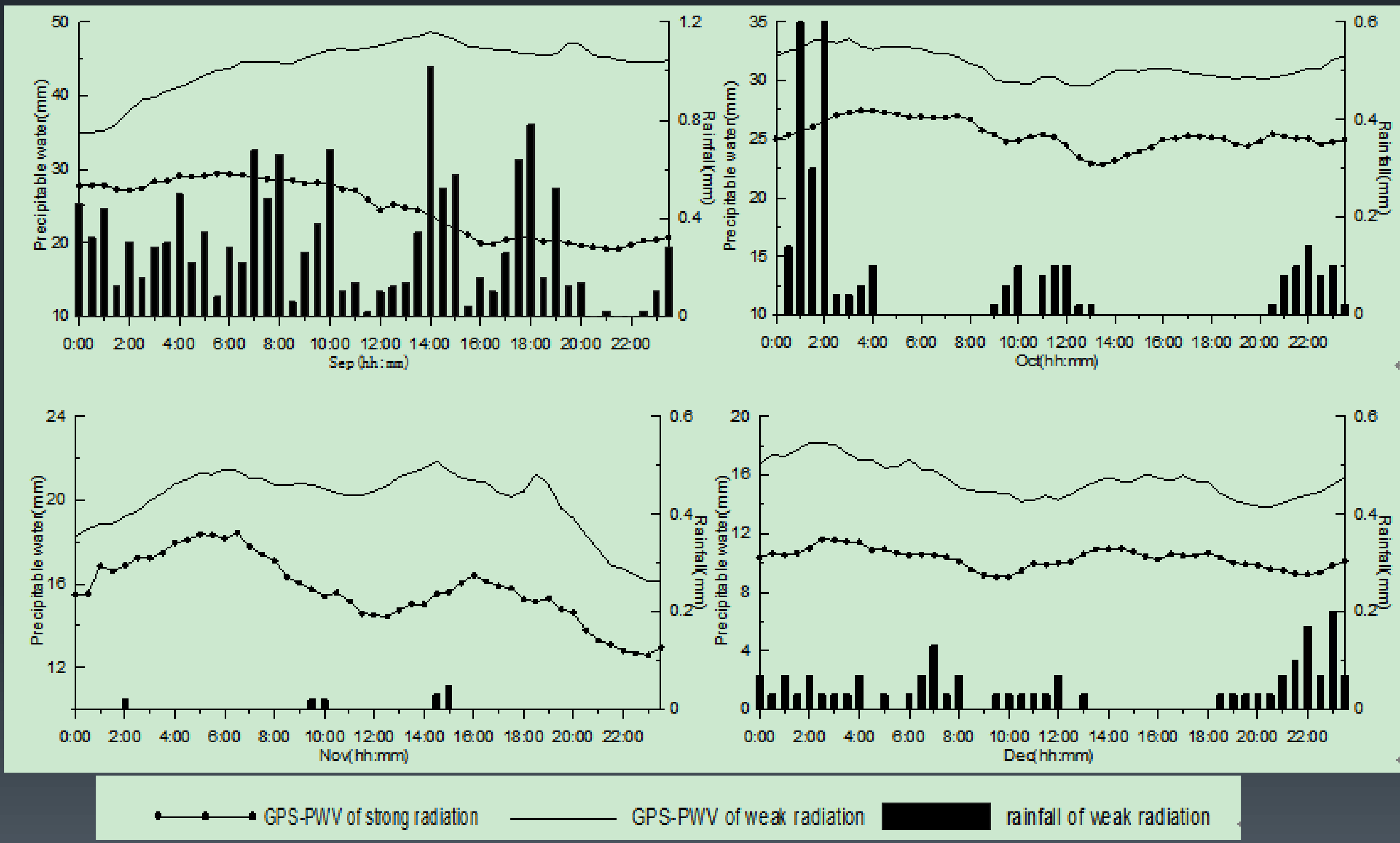
$$T_m = a + bT_s$$

PWV derived from ground-based GPS



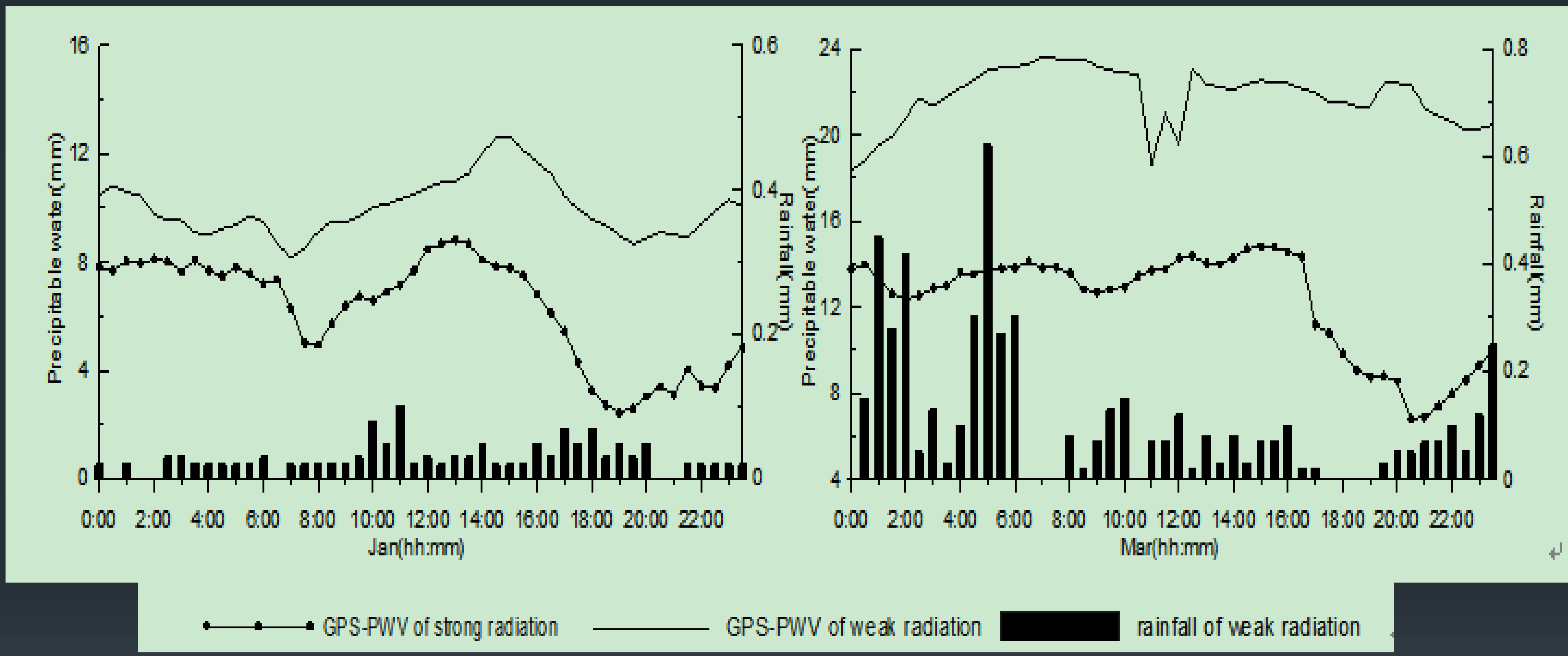
GPS-PWV of strong radiation

Diurnal Variation of Ground-based GPS-PWV under Different Solar Radiation

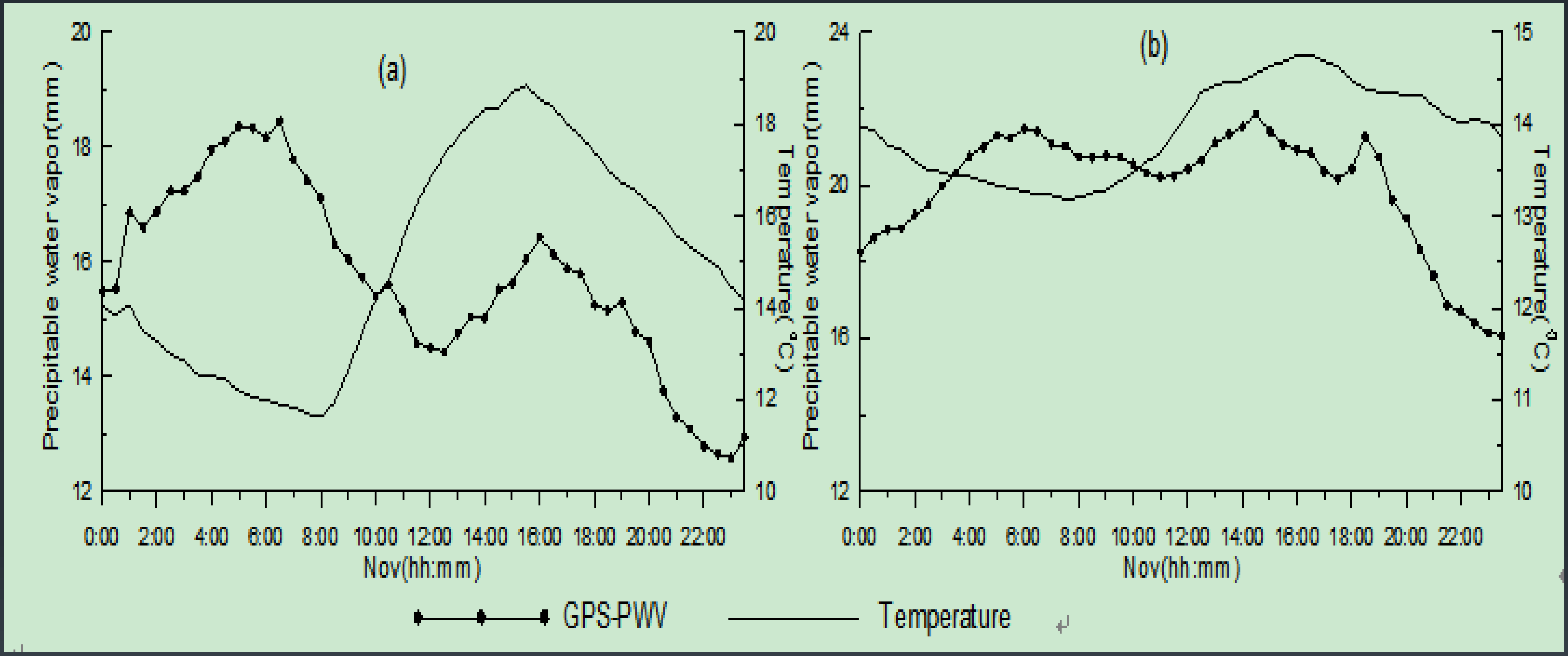


Diurnal of GPS-PWV under strong and weak radiation from September 2007 to March 2008 at Chengdu station

GPS-PWV of strong radiation



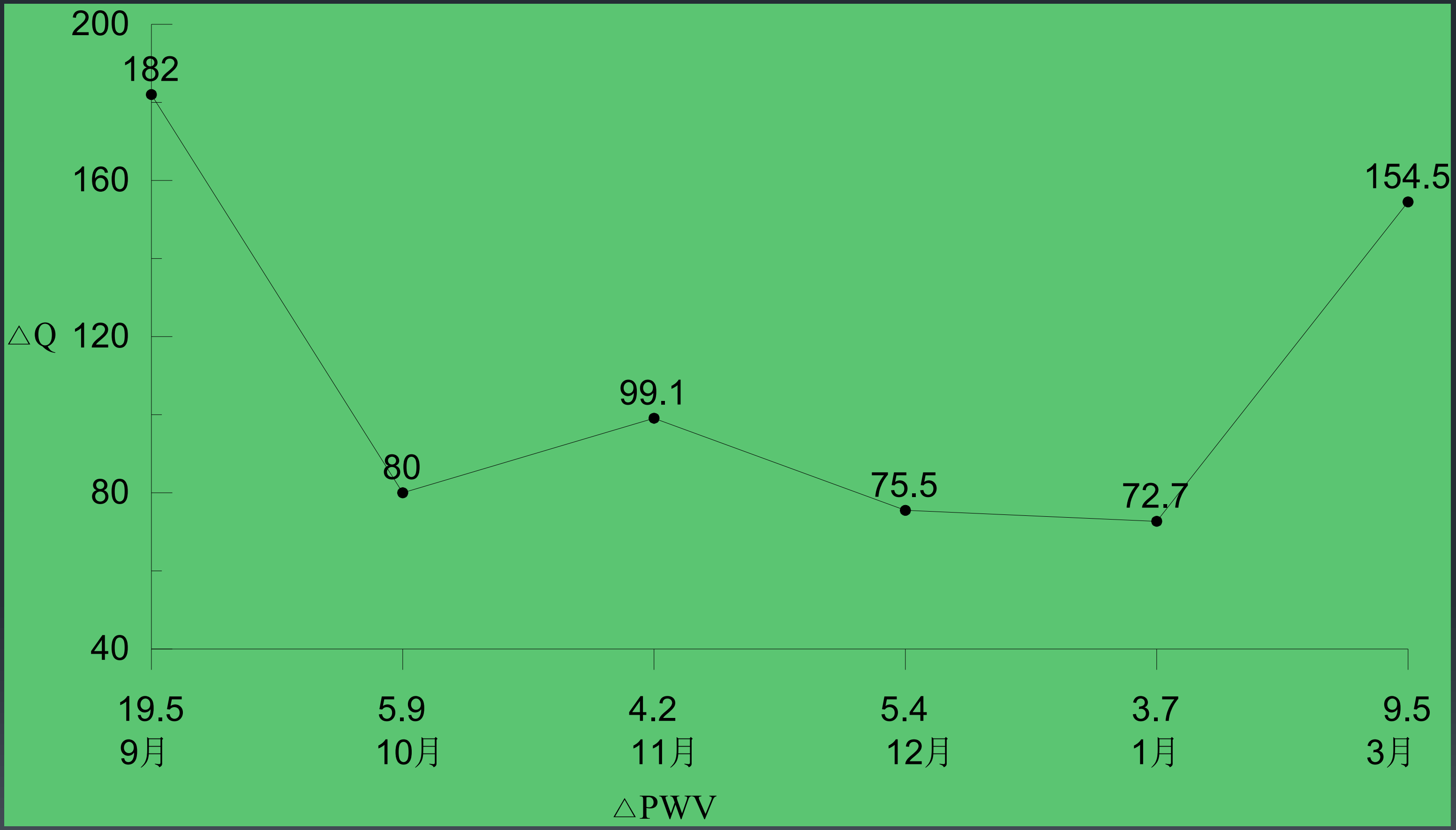
Diurnal of GPS-PWV under strong and weak radiation from September 2007 to March 2008 at Chengdu station



Diurnal of GPS-PWV and temperature in strong and weak radiation day in November 2007 at Chengdu station

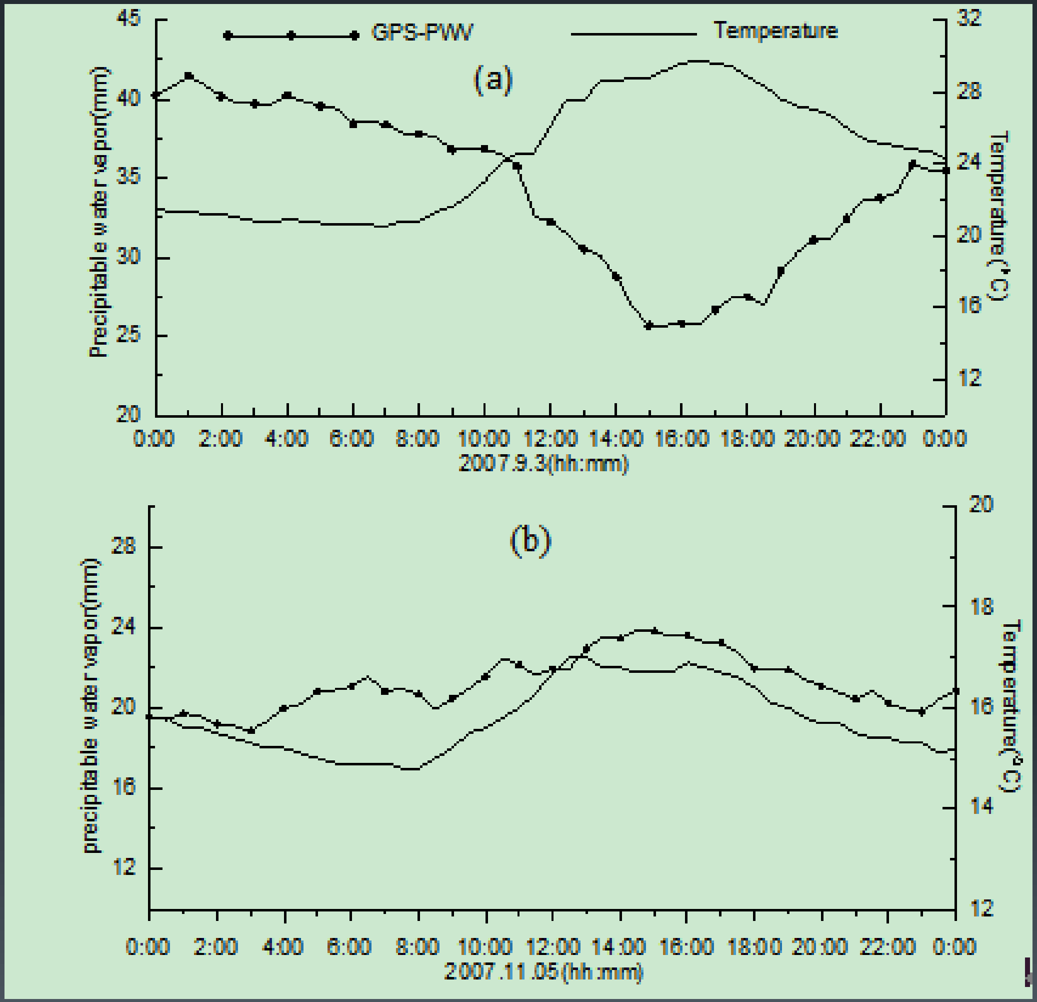
Values of global radiation and GPS-PWV in strong and weak radiation day

	Daily global radiation (Q) (M•J/m^2)		GPS-PWV (mm)	
	Strong radiation day	weak radiation day	Strong radiation day	weak radiation day
SEP, 2007	198.1	16.1	24.711	44.208
OCT, 2007	95.6	15.6	25.388	31.293
NOV, 2007	115.0	15.9	15.737	19.968
DEC, 2007	81.6	6.1	10.304	15.688
JAN, 2008	85.4	12.7	6.276	10.011
MAR, 2008	172.4	17.9	12.274	21.777



The relation figure of △Q （M•J/m²）and △PWV（mm）

Relationship between GPS-PWV and temperature in strong and weak radiation day



The time series of GPS-PWV and temperature in strong (a) and weak (b) radiation in Chengdu Plain

Summary

- The estimates of total zenith delay are available based on GPS data from the ground-based GPS station at Chengdu by using GPS analytic software package.

- The estimates of every 30min precipitable water vapor (PWV) derived from GPS are obtained by jioning meteorological data from automatic weather station (AWS).

- Combined with daily data of solar radiation and sunshine, the characteristics of GPS-PWV in the strong and weak solar radiation are analyzed.

- The relationship of GPS-PWV with surface air temperature in strong and weak radiation intensity is researched. It showed that the GPS-PWV of weak radiation is higher than strong radiation.
- The relationship between △PWV and △Q (daily global radiation) is positive correlation.
- Without considering the rainfall, the difference of GPS-PWV in strong and weak radiation day respectively appears in the daytime.

- The main decreasing of GPS-PWV appears after sunrise, and while temperature is maximum, the GPS-PWV is minimum.
- In the daytime of strong radiation day（fine day）, GPS-PWV is negative correlation to temperature.
- In daytime of the weak radiation day (overcast), the relationship between GPS-PWV and temperature is positive correlation.

- With the increasing of temperature after sunrise, GPS-PWV is growing gradually.
- However, there is a time lag between variation of GPS-PWV and temperature due to greenhouse effect of atmospheric water vapor.

Thank You All

The Rotational and Gravitational Signature of Recent Great Earthquakes

Richard S. Gross

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109–8099, USA

International Symposium on Space Geodesy and Earth System

August 18–21, 2012
Shanghai, China

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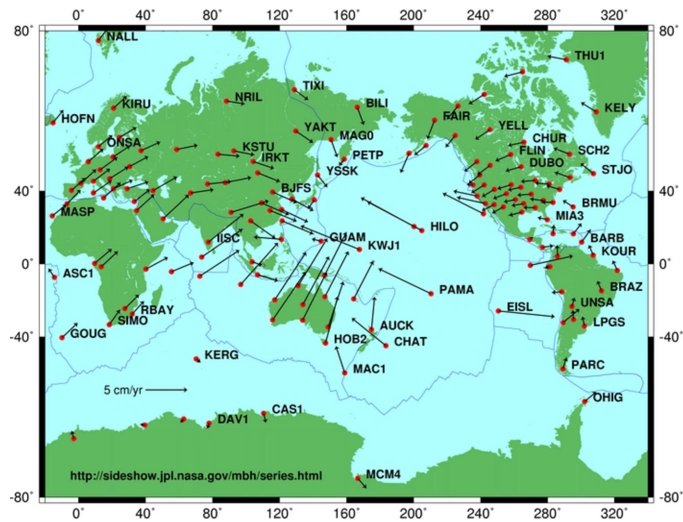
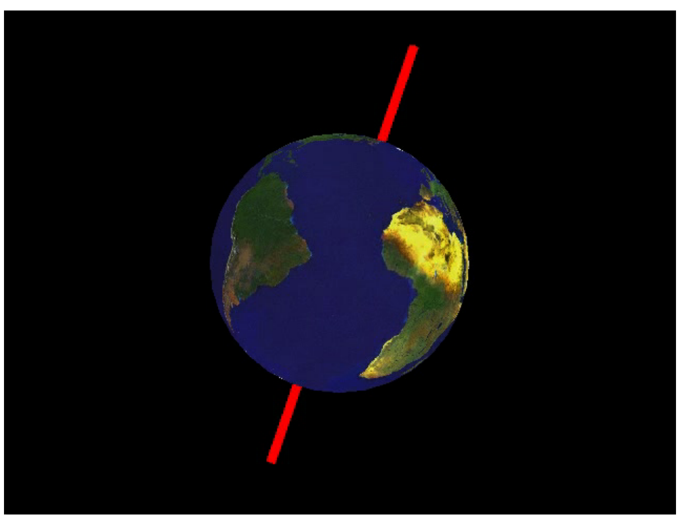
The Three Pillars of Geodesy

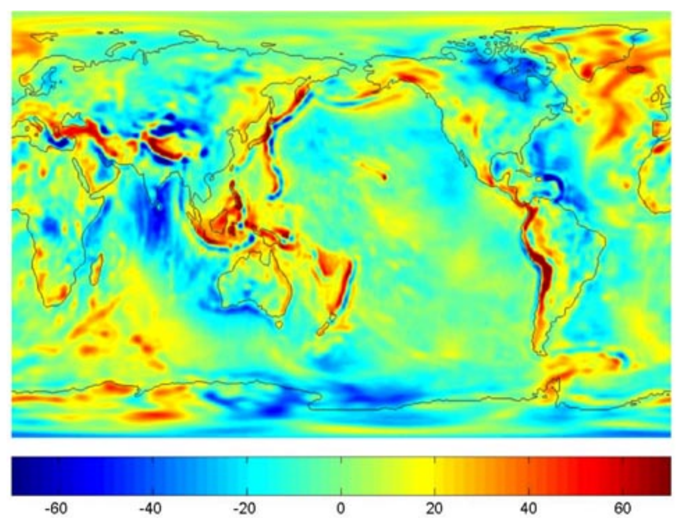


Shape & Deformation

Earth Rotation



Gravity & Geoid



Introduction

- The three pillars of geodesy
  - Geometric shape, rotation, and gravity
    - Static and time varying
- Are related by common observing systems
  - Examples: SLR, GPS, DORIS, VLBI (shape and rotation)
- Are related by common sources of excitation
  - Examples: atmosphere, oceans, hydrology, earthquakes, GIA
- But are sometimes modeled separately
  - Example: flat Earth models for earthquake displacements, spherical Earth models for rotation
- A unified modeling approach
  - Allows excitation process to be studied using all geodetic data
  - Example: earthquakes

Geodetic Effects of Earthquakes

- Flat Earth models
  - Commonly used to model site displacements
  - May or may not include effects of layering
  - Do not include effects of sphericity
    - Important for great earthquakes having rupture lengths of 1000 km (10°) or more
- Spherical Earth models
  - Commonly used for rotation effects
  - Often used for gravity effects
- A unified mode sum approach
  - Based on a realistic Earth model (PREM)
  - Automatically accounts for effects of sphericity, layering, self-gravitation

Data Sets

- Observed length-of-day & polar motion excitation
  - COMB2010 combined EOP series
    - Combination of optical astrometric, LLR, SLR, VLBI, & GPS observations
    - Polar motion rate observations not used (contaminated by tidal artifacts)
    - Daily values at midnight spanning January 20, 1962 to July 15, 2011
    - Degree-6 polynomial fit to & removed from LOD−AAM to remove decadal signal
- Helmholtz Centre Potsdam – GFZ
  - Consistent estimates of AAM, OAM, & HAM computed at GFZ
    - AAM computed from European Centre for Medium-Range Weather Forecasts
    - OAM computed from Ocean Model for Circulation and Tides (OMCT)
    - HAM computed from Land-Surface Discharge Model (LSDM)
    - Ocean and hydrology models driven by ECMWF fields
    - Global atmosphere/oceans/hydrology mass conservation imposed
    - AAM, OAM, HAM from operational ECMWF fields starting 1 Jan 2001 used here

Site Displacements

- Equation of motion

$$\nabla \cdot \tau + \mathbf{f_g} + \mathbf{f_s} = \rho(\mathbf{r}) \frac{\partial^2 \mathbf{u}}{\partial t^2}$$

- Solve by expanding displacement field

$$\mathbf{u}(\mathbf{r},t) = \sum_k a_k(t)\, \mathbf{u}_k^*(\mathbf{r})$$

  - Normal mode eigenfunctions

$$\mathbf{u}_k(\mathbf{r}) = {}_nU_l(r)\, Y_{lm}(\theta,\lambda)\, \hat{\mathbf{r}} + {}_nV_l(r) \frac{\partial Y_{lm}}{\partial \theta}\, \hat{\boldsymbol{\theta}} + {}_nV_l(r) \frac{1}{\sin\theta} \frac{\partial Y_{lm}}{\partial \lambda}\, \hat{\boldsymbol{\lambda}}$$

  - Expansion coefficients (static limit)

$$a_k(\infty) = \frac{M_o}{\omega_k^2}\, \hat{\mathbf{M}} : \boldsymbol{\varepsilon}_k(\mathbf{r_s})$$

- Normal mode eigenfrequencies and eigenfunctions
  - Computed using MINOS program provided by Guy Masters

Earth Rotation

- Conservation of angular momentum
  - Earthquakes are internal to the Earth (no load Love numbers)
  - Earthquakes occur suddenly (motion effects neglected)
- Length of day

$$\frac{\Delta\Lambda(t)}{\Lambda(t)} = \frac{\Delta I_{zz}(t)}{I_{zz}^{(m)}}$$

- Polar motion excitation

$$\Delta\chi_x(t) + i\,\Delta\chi_y(t) = \frac{1.61}{I_{zz} - I_{xx}}\left[\Delta I_{xz}(t) + i\,\Delta I_{yz}(t)\right]$$

- Inertia tensor

$$\mathbf{I} = \int \rho(\mathbf{r})\left[(\mathbf{r}\cdot\mathbf{r})\,\mathbf{I} - \mathbf{r}\,\mathbf{r}\right]dV$$

- Perturbed inertia tensor $(\mathbf{r} \Rightarrow \mathbf{r} + \mathbf{u})$

$$\Delta\mathbf{I} = \int \rho_o(\mathbf{r})\left[2\,(\mathbf{r}\cdot\mathbf{u})\,\mathbf{I} - (\mathbf{u}\,\mathbf{r} + \mathbf{r}\,\mathbf{u})\right]dV$$

Gravitational Field

- Gravitational potential of Earth

$$U(\mathbf{r}) = \frac{GM}{r}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\left(\frac{a}{r}\right)^{l}\left[C_{lm}\cos m\lambda + S_{lm}\sin m\lambda\right]\tilde{P}_{lm}(\cos\theta)$$

- Stokes coefficients

$$C_{lm} + i\,S_{lm} = \frac{N_{lm}}{Ma^{l}}\int_{V_o} r^{l}\,Y_{lm}(\theta,\lambda)\,\rho(\mathbf{r})\,dV$$

- Perturbed Stokes coefficients $(\mathbf{r} \Rightarrow \mathbf{r} + \mathbf{u})$

$$\Delta C_{lm} + i\,\Delta S_{lm} = \frac{N_{lm}}{Ma^{l}}\int_{V_o} r^{l-1}\,\mathbf{u}\cdot(\hat{\mathbf{r}}\,l + \nabla_h)\,Y_{lm}(\theta,\lambda)\,\rho(\mathbf{r})\,dV$$

Earth Rotation & Gravitational Field

- Related via the inertia tensor
  - Elements of inertia tensor are related to the degree-2 Stokes coefficients

$$I_{xz} = -\sqrt{5/3}\, M a^2 C_{21}$$

$$I_{yz} = -\sqrt{5/3}\, M a^2 S_{21}$$

$$I_{zz} = \frac{1}{3}\left[T - \sqrt{20}\, M a^2 C_{20}\right]$$

- Trace of inertia tensor

$$T = 2\int \rho(\mathbf{r})\, r^2\, dV$$

- Perturbed trace of inertia tensor $(\mathbf{r} \;=>\; \mathbf{r} + \mathbf{u})$

$$\Delta T = 4\int \rho_o(\mathbf{r})\, \mathbf{r}\cdot\mathbf{u}\, dV$$

Polar Motion Excitation

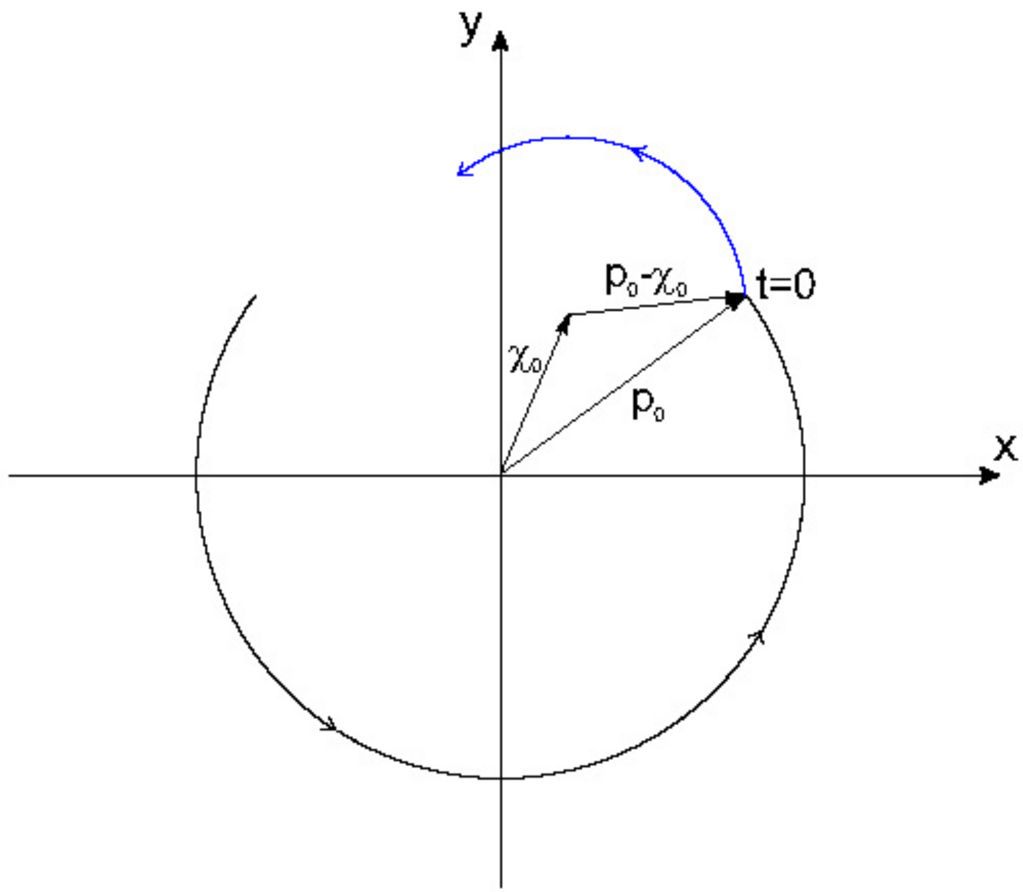


Figure 2: Excitation of polar motion by the step function.

(Brzezinski, 2005)

Recent Great Earthquakes

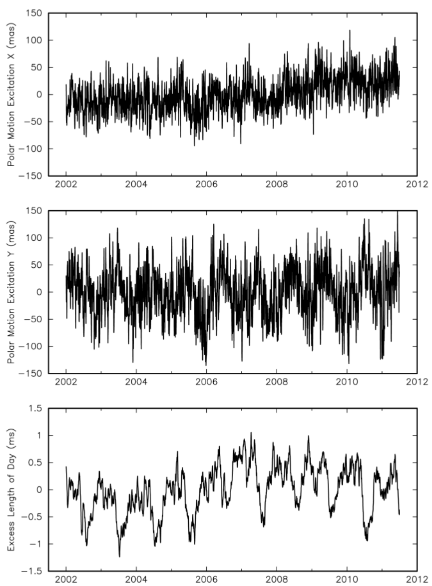
- 2004 Sumatra (M_w = 9.3)
  - 5 sub-event model of *Tsai at al.* (2005)
    - Based on seismic data
- 2005 North Sumatra (M_w = 8.5)
  - Caltech's Tectonics Observatory slip model with 295 patches
    - Based on GPS, seismic, and coral uplift and subsidence data
- 2007 South Sumatra (M_w = 8.4)
  - Caltech's Tectonics Observatory slip model with 203 patches
    - Based on GPS, seismic, and InSAR data
- 2010 Chile (M_w = 8.8)
  - Updated USGS slip model with 166 fault patches slipping
    - Based on seismic data
- 2011 Japan (M_w = 9.0)
  - Updated USGS slip model with 319 fault patches slipping
    - Based on seismic data

Modeled Change in Earth Rotation

	Δlod (μsec)	$\Delta\chi_x$ (mas)	$\Delta\chi_y$ (mas)
Recent great earthquakes			
2004 Sumatra (M_w = 9.3)	–6.77	–1.41	1.85
2005 North Sumatra (M_w = 8.5)	–0.84	–0.25	0.08
2007 South Sumatra (M_w = 8.4)	–0.64	–0.17	–0.07
2010 Chile (M_w = 8.8)	–1.71	–1.38	3.26
2011 Japan (M_w = 9.0)	–1.36	–2.97	3.27
Approximate measurement uncertainty (1σ)	10	5	5
Other great earthquakes			
1960 Chile (M_w = 9.5; Chao & Gross, 1987)	–8.40	–9.53	20.45
1964 Alaska (M_w = 9.2; Chao & Gross, 1987)	6.79	–7.11	–2.31

Observed Residual Excitation
(2002.0 – 20011.5)

observed



Variance (percent reduction)

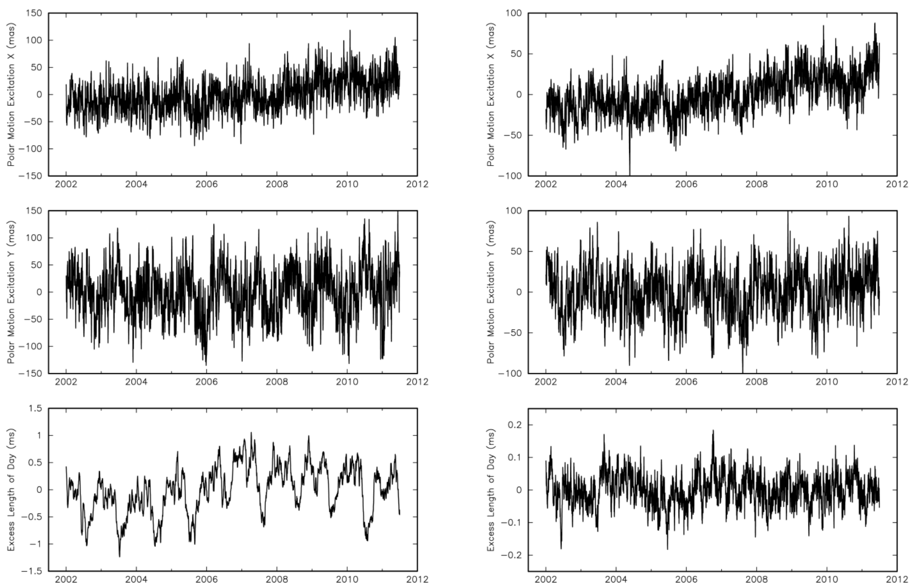
chi-x: 912 mas^2

chi-y: 1978 mas^2

lod: 0.185 ms^2

Observed Residual Excitation
(2002.0 – 20011.5)

observed　　　　　　-atm-poly

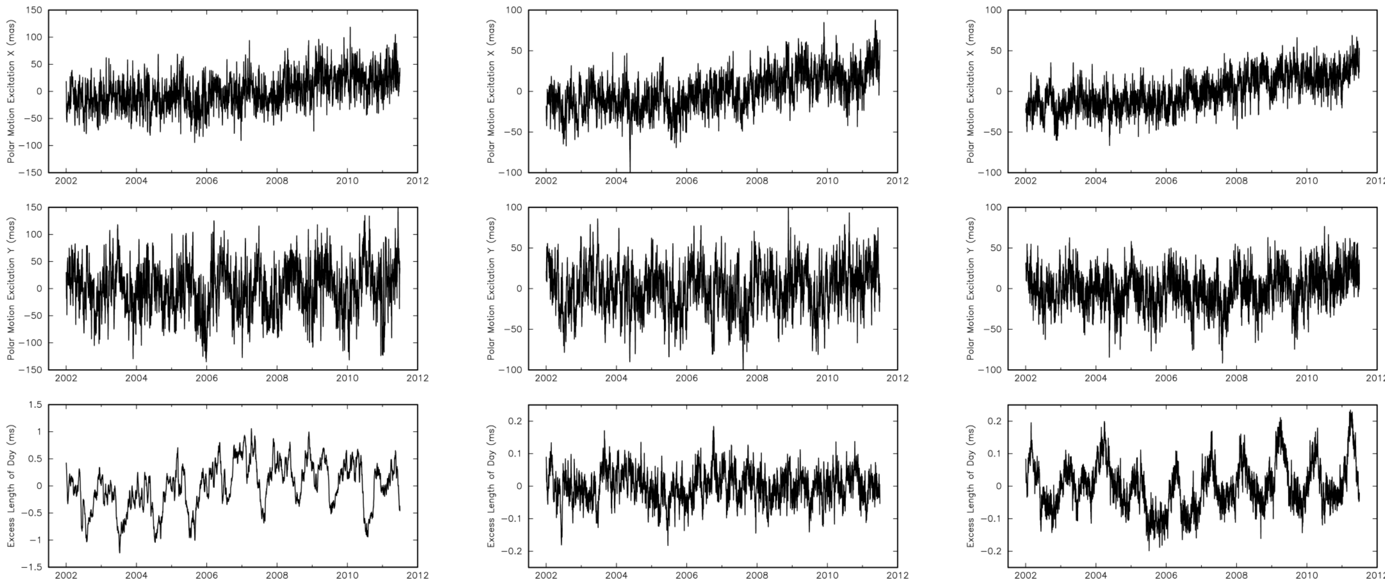


Variance (percent reduction)

	observed	-atm-poly
chi-x:	912 mas^2	564 mas^2 (38%)
chi-y:	1978 mas^2	841 mas^2 (57%)
lod:	0.185 ms^2	0.0025 ms^2 (98.6%)

Observed Residual Excitation
(2002.0 – 20011.5)

observed -atm-poly -atm-poly-ocn

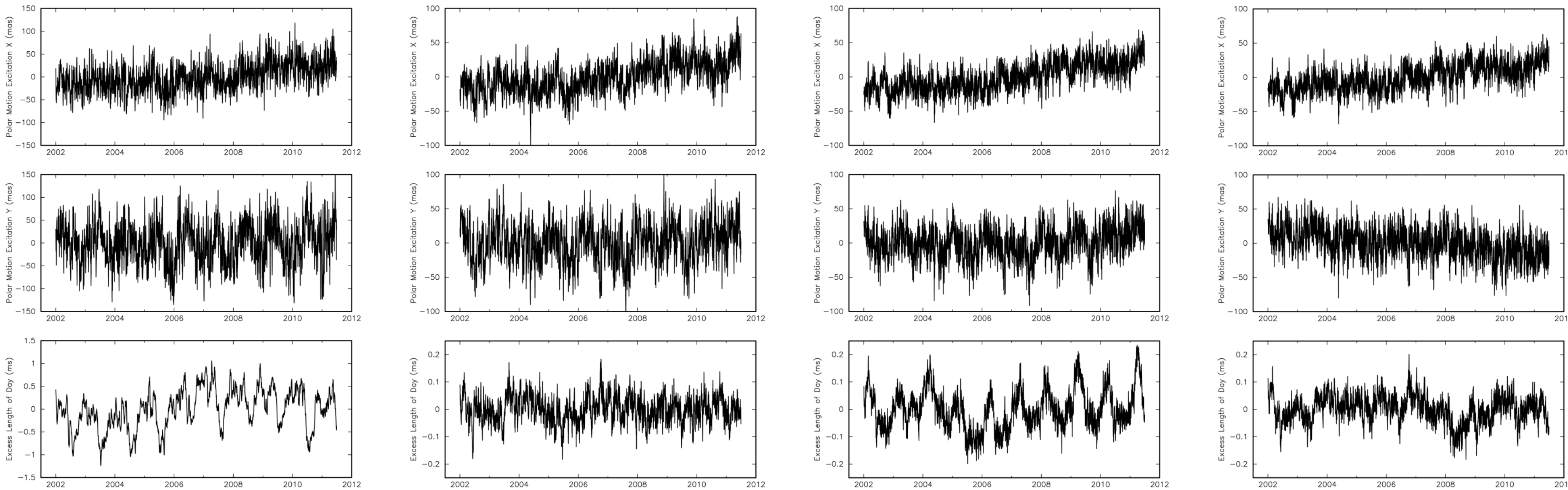


Variance (percent reduction)

chi-x:	912 mas^2	564 mas^2 (38%)	464 mas^2 (49%)
chi-y:	1978 mas^2	841 mas^2 (57%)	532 mas^2 (73%)
lod:	0.185 ms^2	0.0025 ms^2 (98.6%)	0.0053 ms^2 (97.1%)

Observed Residual Excitation
(2002.0 – 20011.5)

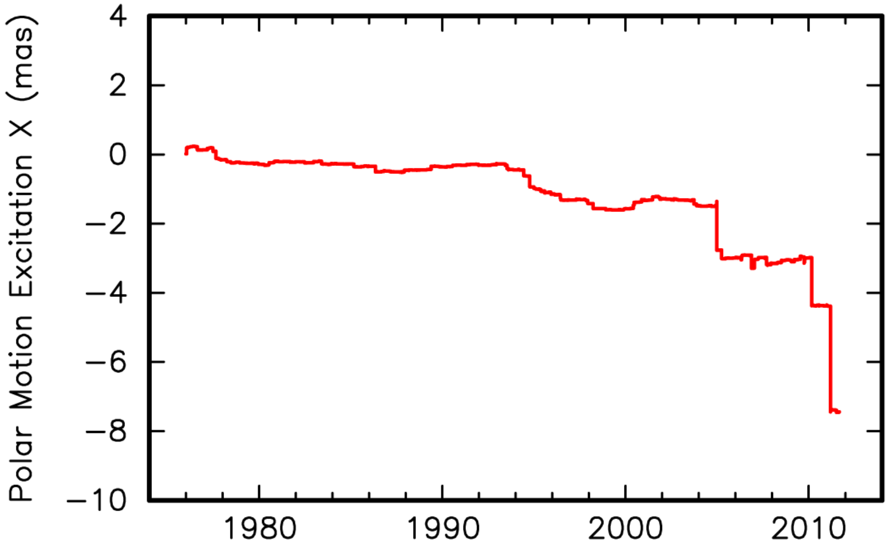
observed	-atm-poly	-atm-poly-ocn	-atm-poly-ocn-hyd

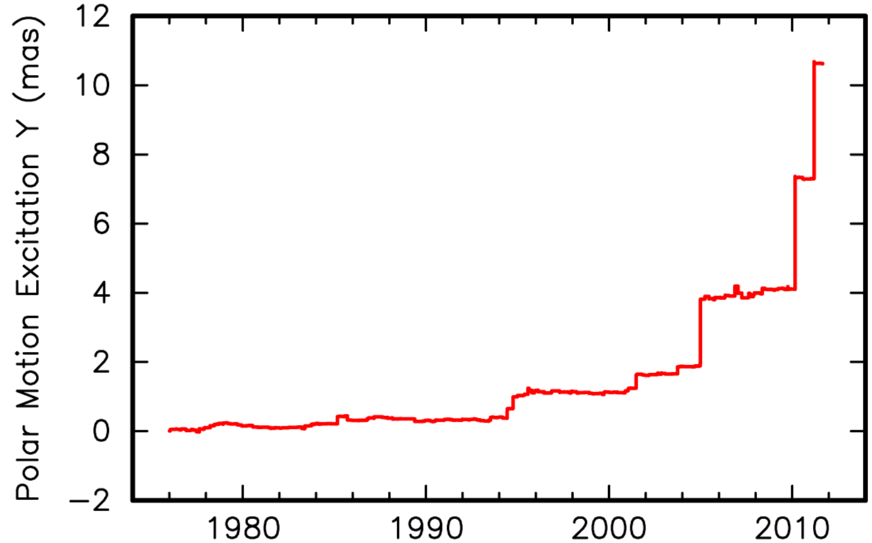


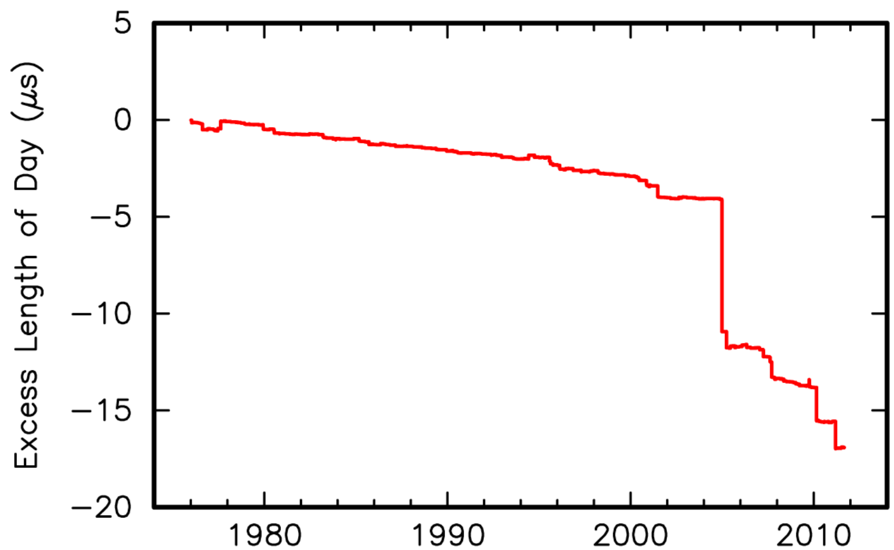
Variance (percent reduction)

chi-x:	912 mas^2	564 mas^2 (38%)	464 mas^2 (49%)	394 mas^2 (57%)
chi-y:	1978 mas^2	841 mas^2 (57%)	532 mas^2 (73%)	503 mas^2 (75%)
lod:	0.185 ms^2	0.0025 ms^2 (98.6%)	0.0053 ms^2 (97.1%)	0.0025 ms^2 (98.6%)

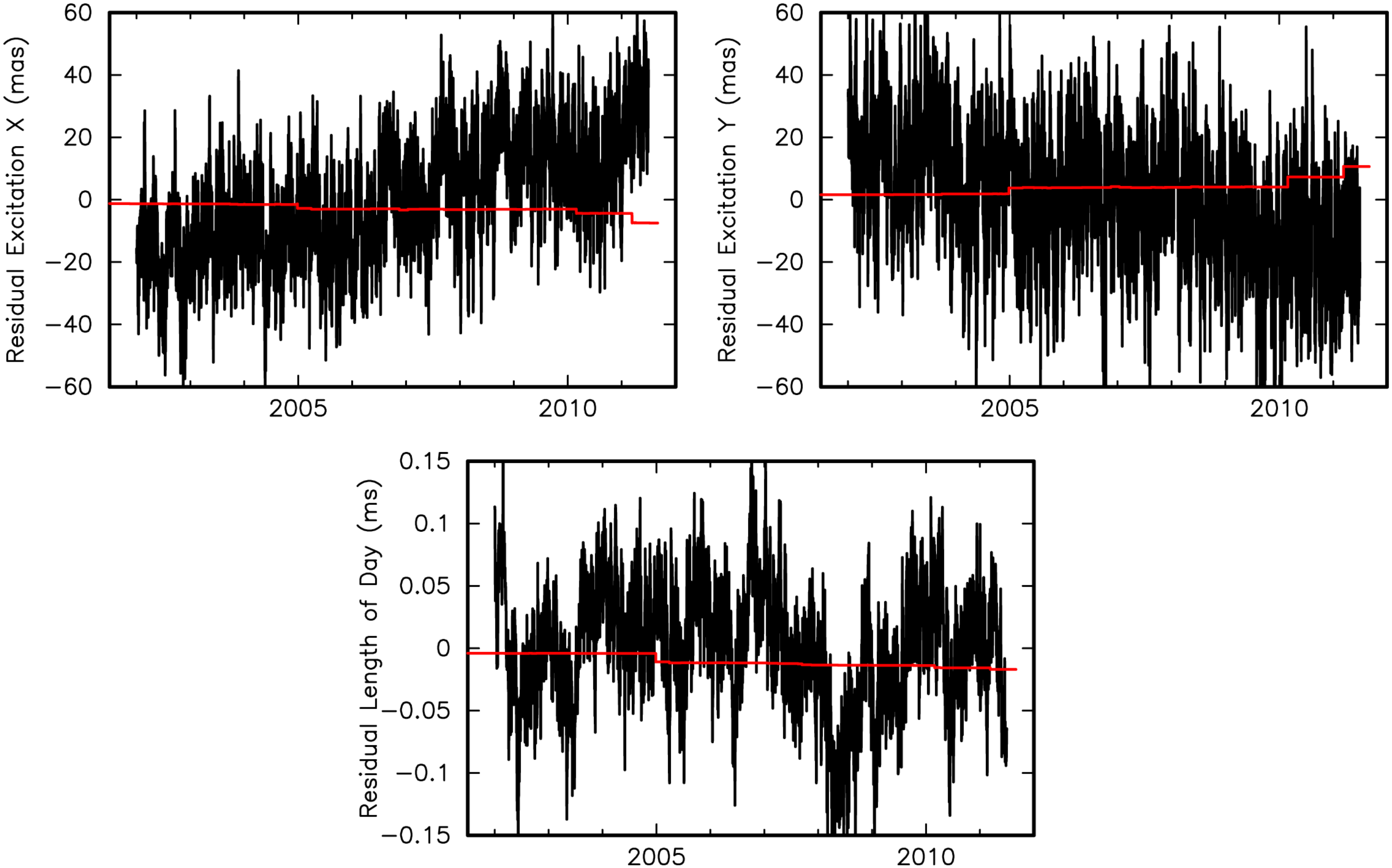
Modeled Change in Earth Rotation





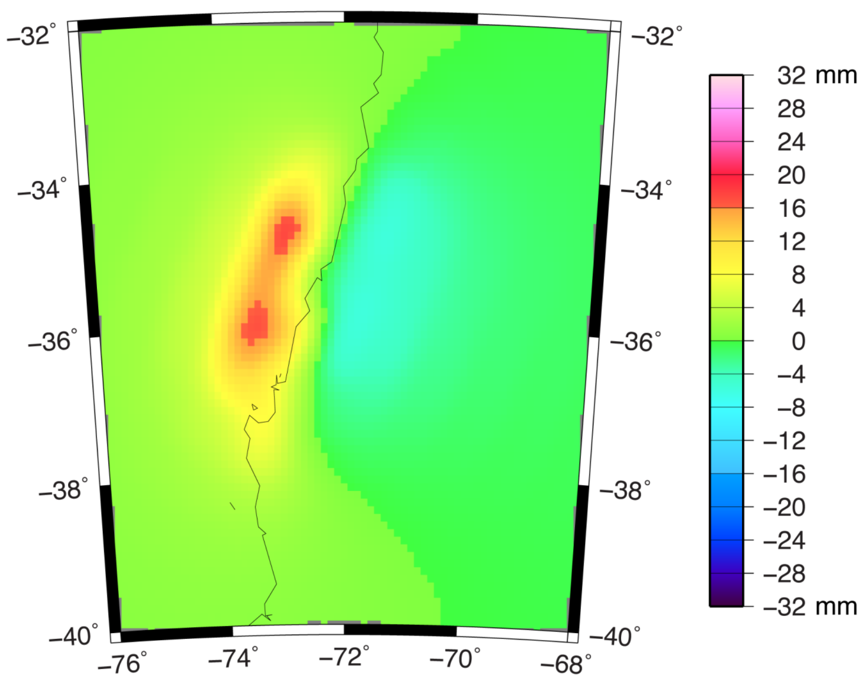


Observed and Modeled Change in Rotation

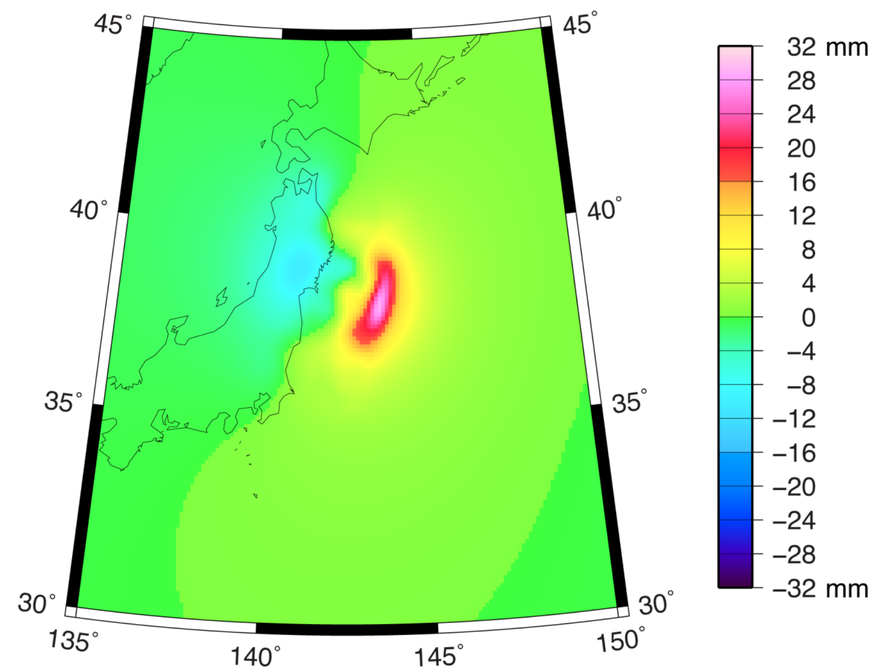


Modeled Change in Geoid

2010 Chile



2011 Japan



Modeled Change in Geopotential

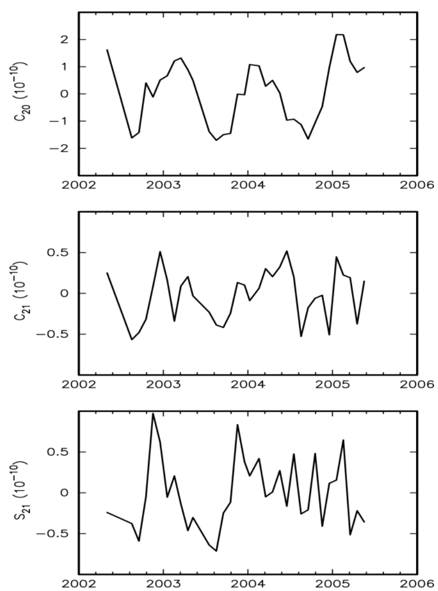
		ΔJ_2 (10^{-11})	ΔJ_3 (10^{-11})	ΔJ_4 (10^{-11})	ΔJ_5 (10^{-11})
2004 Sumatran earthquake					
2004 Sumatra	(M_w = 9.3)	–2.368	–0.621	0.254	0.305
2005 North Sumatra	(M_w = 8.5)	–0.283	–0.043	0.034	0.033
2007 South Sumatra	(M_w = 8.4)	–0.216	0.000	0.031	0.024
2010 Chile	(M_w = 8.8)	–0.302	0.608	–0.263	–0.018
2011 Japan	(M_w = 9.0)	0.006	–0.560	–0.343	–0.116
Approximate SLR measurement uncertainty (1σ)		1.3	1.6	4.9	
Other great earthquakes					
1960 Chilean	(M_w = 9.5; Chao & Gross, 1987)	–0.83	3.29	–1.89	3.64
1964 Alaskan	(M_w = 9.2; Chao & Gross, 1987)	5.25	2.35	1.40	1.62

$$\Delta J_l = -\sqrt{2l+1}\,\Delta C_{l0}$$

Observed Residual Potential Coefficients from Satellite Laser Ranging

(2002.3 – 2005.4)

observed



Variance (percent reduction)

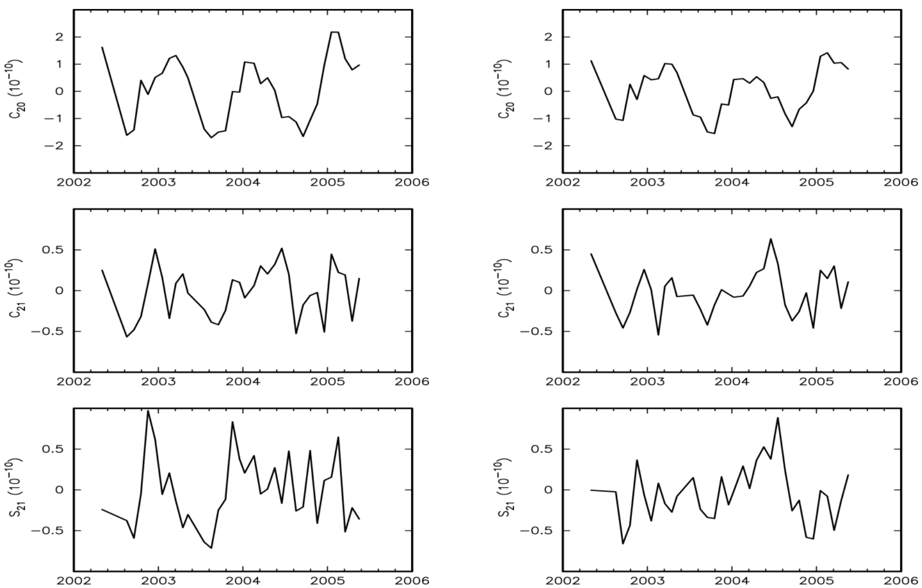
C_{20}:	134.55
C_{21}:	9.73
S_{21}:	18.30

units of variance: 10^{-22}

Observed Residual Potential Coefficients from Satellite Laser Ranging

(2002.3 – 2005.4)

observed　　　obs−(atm+ocn)



Variance (percent reduction)

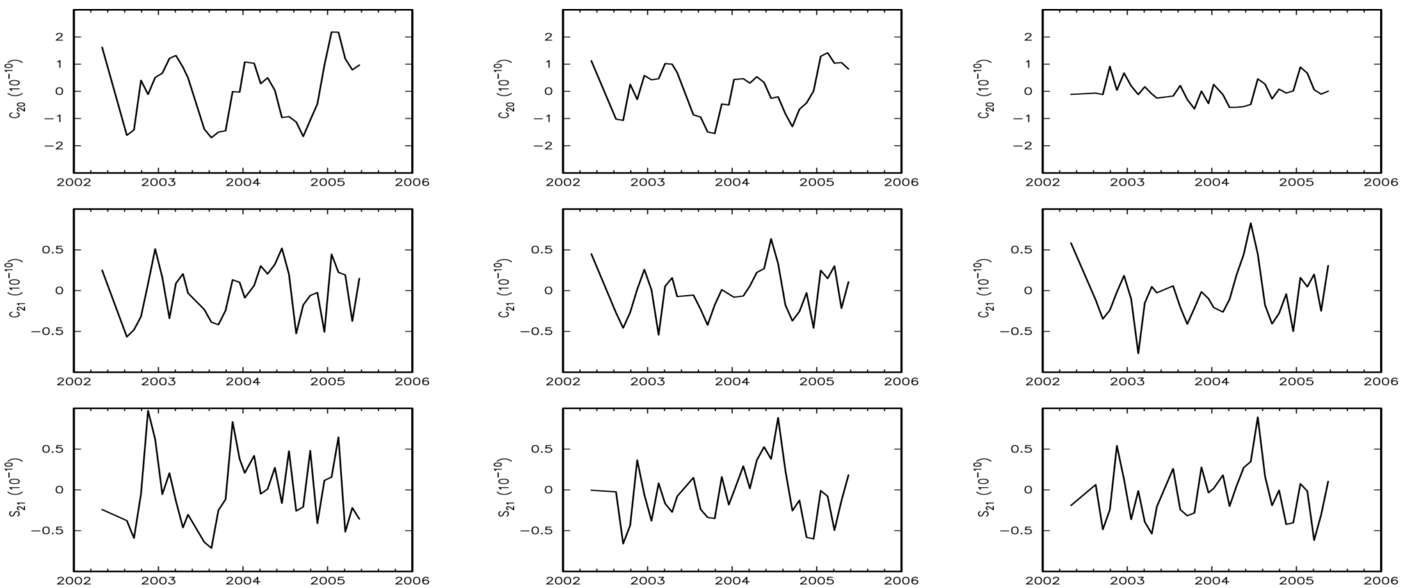
C_{20}:	134.55	72.94 (46%)
C_{21}:	9.73	7.64 (21%)
S_{21}:	18.30	11.70 (36%)

units of variance: 10^{-22}

Observed Residual Potential Coefficients from Satellite Laser Ranging

(2002.3 – 2005.4)

observed | obs−(atm+ocn) | obs−(all surface)



Variance (percent reduction)

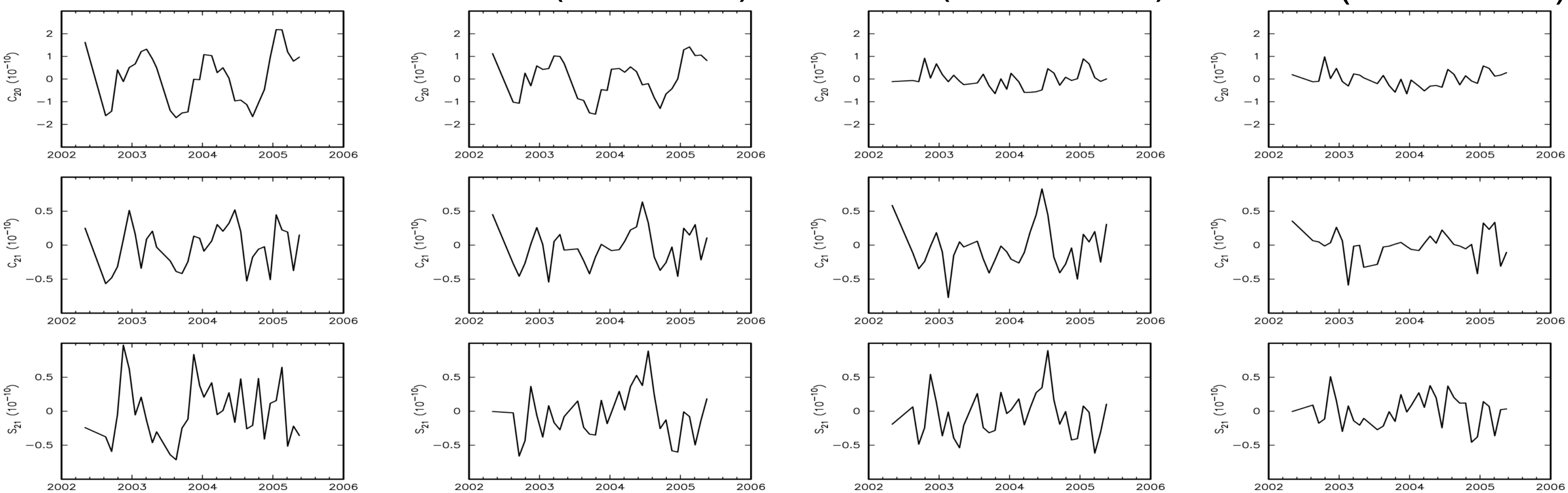
C_{20}:	134.55	72.94 (46%)	15.74 (88%)
C_{21}:	9.73	7.64 (21%)	10.30 (−6%)
S_{21}:	18.30	11.70 (36%)	10.55 (42%)

units of variance: 10^{-22}

Observed Residual Potential Coefficients from Satellite Laser Ranging

(2002.3 – 2005.4)

observed | obs−(atm+ocn) | obs−(all surface) | nonseasonal obs−(all surface)

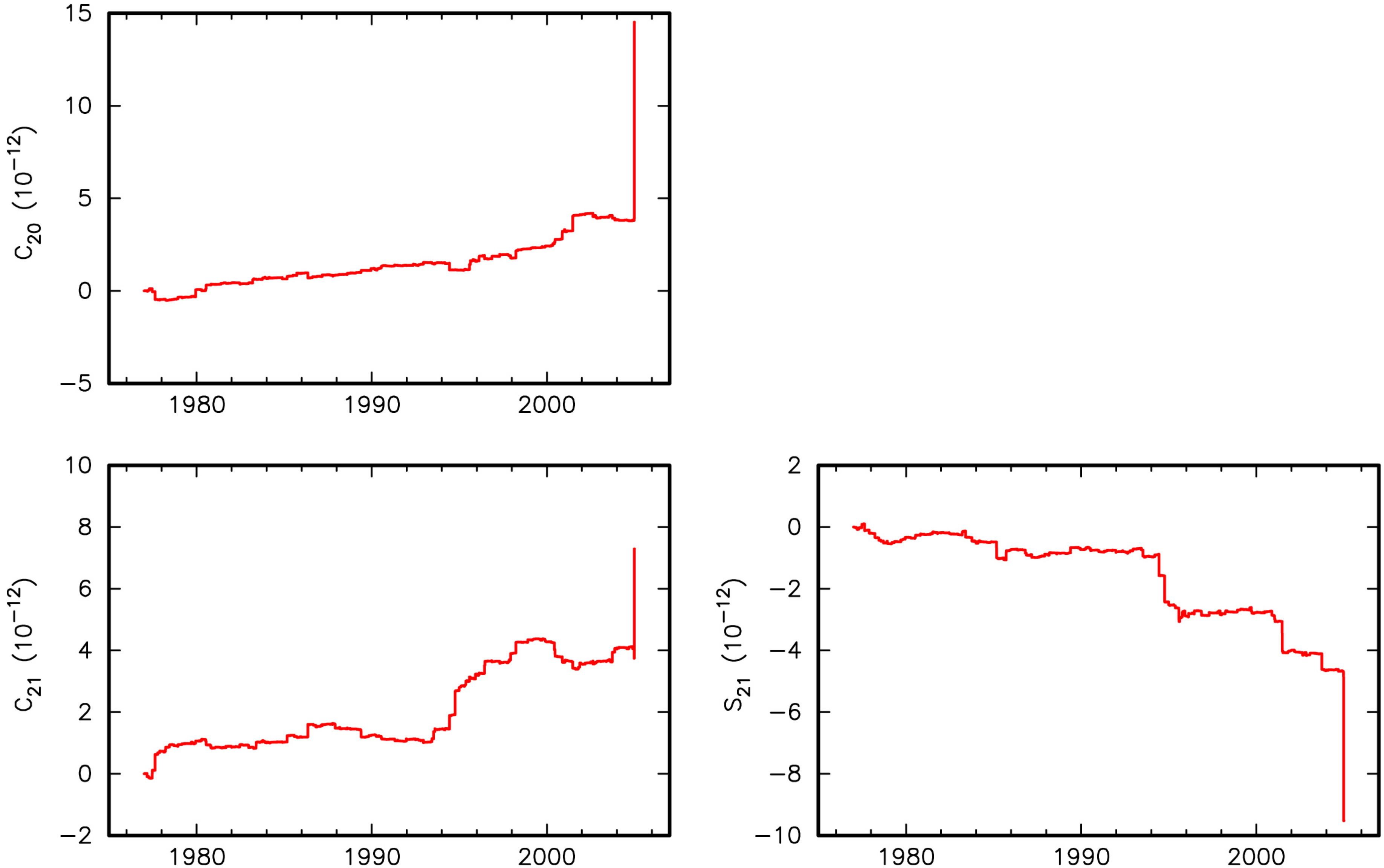


Variance (percent reduction)

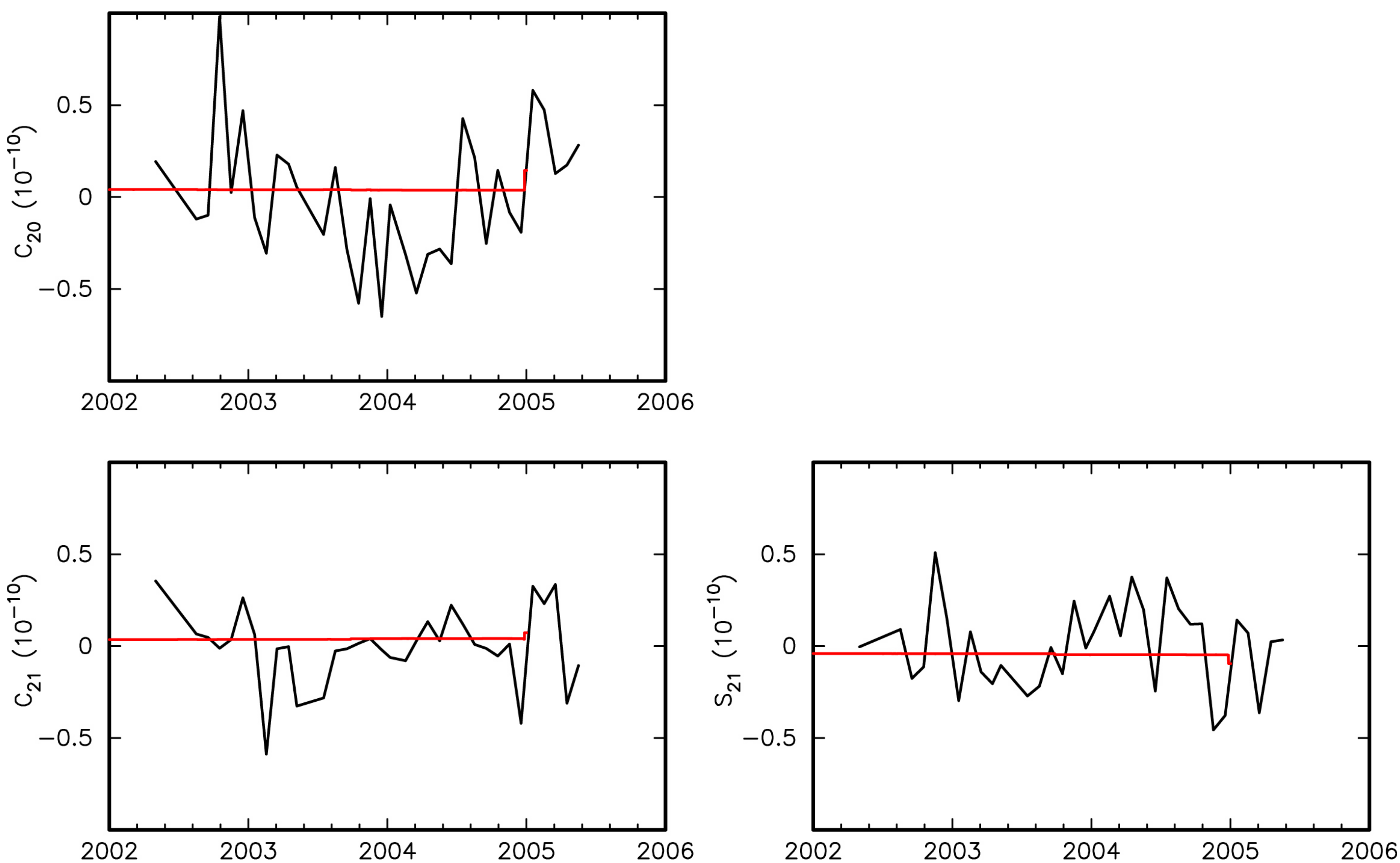
	observed	obs−(atm+ocn)	obs−(all surface)	nonseasonal obs−(all surface)
C_{20}:	134.55	72.94 (46%)	15.74 (88%)	12.32 (91%)
C_{21}:	9.73	7.64 (21%)	10.30 (−6%)	4.22 (57%)
S_{21}:	18.30	11.70 (36%)	10.55 (42%)	5.28 (71%)

units of variance: 10^{-22}

Modeled Change in Geopotential



Observed and Modeled Change in Potential



Summary

- Changes in Earth's shape, rotation, and gravity
  - Are measured by the same observing system
    - SLR, GPS, DORIS, VLBI (shape and rotation)
  - Often have a common cause
    - Atmosphere, oceans, hydrology, earthquakes, global isostatic adjustment
  - But are sometimes modeled separately
    - Flat Earth models for earthquake displacements, spherical for rotation
- Unified model
  - Allows common shape, rotation, and gravity observations to be used to determine model parameters
  - Allows consistent geodetic modeling of
    - Surface change
    - Mass transport and exchange
    - Angular momentum exchange

Summary, cont.

- Earthquakes redistribute the Earth's mass on a global scale
  - Change the Earth's rotation and gravitational field
- Greatest earthquakes have greatest effect
  - 1960 Chile
    - 23 mas change in polar motion excitation
    - 8 μs change in length of day
- Current observing systems are accurate enough to detect changes caused by next great earthquake
  - Polar motion excitation accuracy about 5 mas
  - LOD accuracy about 10 μs