Geokinematics of Central Europe from GPS data

Alessandro Caporali[1] and Janusz Śledziński[2]

[1]University of Padova

[2]Politechnic of Warsaw

Goals

- Distribution in space and time of geodetically derived strain rate in Central Europe

Motivation

- A strain rate map is expected to correlate with the geometry and activity of seismogenic faults
- Changes of strain rate with time should affect the probability that a fault activates in the short term
- Post seismic creep should be visible by combining geodetic/GPS and D-InSAR data

Context

- CERGOP 2 (5. FP UE)

Data sources

SINEX files: typically represent a quantitative picture of a network at an epoch: coordinates, covariance, constraints

Some SINEX files are homogeneous and compatible as to data processing standards (IGS/EPN recommendations)

- EUREF (EUR<GPSwk>.SNX) from 860 to 1366 (~10 years)
- Italian network (UPA<GPSwk>.SNX) from 1000 to 1366 (~ 7 years)
- Austrian network (GP_<GPSwk>.SNX) from 995 to 1366 ~ 7 years)

SINEX data files from CEGRN/CERGOP Campaigns in Central Europe 1994 - 2003

Additional velocity estimates (values are given ‘as such’):

- Epoch and permanent stations from Serpelloni McClusky - Hollenstein (particularly Central Southern Italy):

Data Analysis: weekly combination

Weekly combination with Program ADDNEQ of Bernese v. 4.2: EUREF+UPA+GP_ in a unique file. EUREF overweighted relative to UPA e GP_:

FILE	FILE NAME	RMS (SINGLE DIFFERENCE)
1	C:\STORICRD\OUT\EUR13667.NEQ	0.0020
2	C:\STORICRD\OUT\UPA13667.NEQ	0.0020
3	C:\STORICRD\OUT\GP_13667.NEQ	0.0012

Default weight in SINEX

FILE	FILE NAME	VALUE	RMS	GRP
1	C:\STORICRD\OUT\EUR13667.NEQ	1.0000	0.000000	EUR
2	C:\STORICRD\OUT\UPA13667.NEQ	0.0100	0.000000	UPA
3	C:\STORICRD\OUT\GP_13667.NEQ	0.0100	0.000000	GP_

Relative weight assigned to each solution

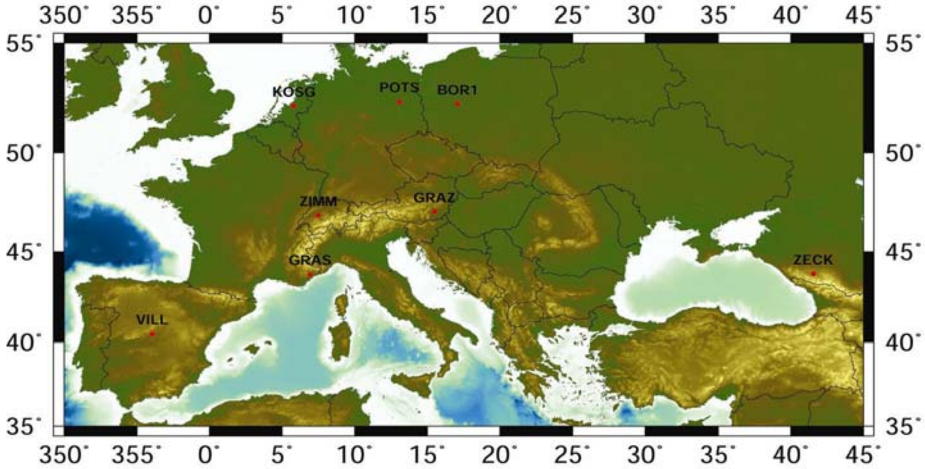
TOTAL NUMBER OF STATIONS:	258				1	2	3
123 HFLK 11006S003	3	N	0.1		0.1	-0.1	0.0
		E	0.3		0.0	-0.2	0.3
		U	0.5		0.1	0.6	-0.4
802 RTMN 11037S001	2	N	0.2			-0.1	-0.2
		E	0.1			0.0	-0.1
		U	0.5			0.5	0.0

This site only in the regional solutions

Data Analysis: time series

– Constraints to IGS/ITRF2000 values

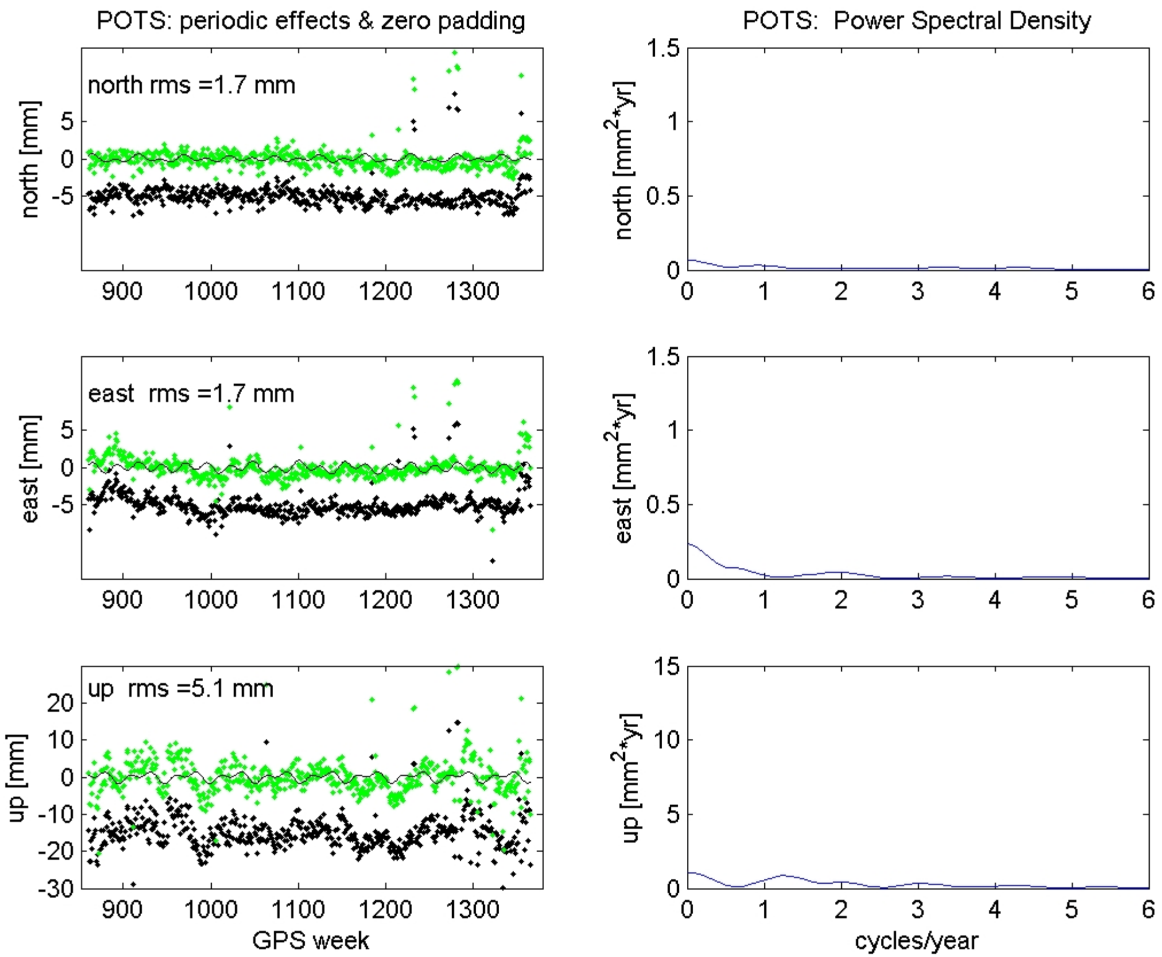
• BOR1 12205M002	POS	
• KOSG 13504M003	POS	
• ZIMM 14001M004	POS	VEL
• POTS 14106M003	POS	VEL
• GRAS 10002M006	POS	VEL
• GRAZ 11001M002	POS	
• VILL 13406M001		VEL
• ZECK 12351M001		VEL



STATISTIC OF SOLVED FOR PARAMETERS	#PARAMETERS	#PRE-ELIMINATED
STATION COORDINATES	1116	2706 (BEFORE INV)
STATION VELOCITIES	1053	0
NUMBER OF SOLVE FOR PARAMETERS	2169	2706

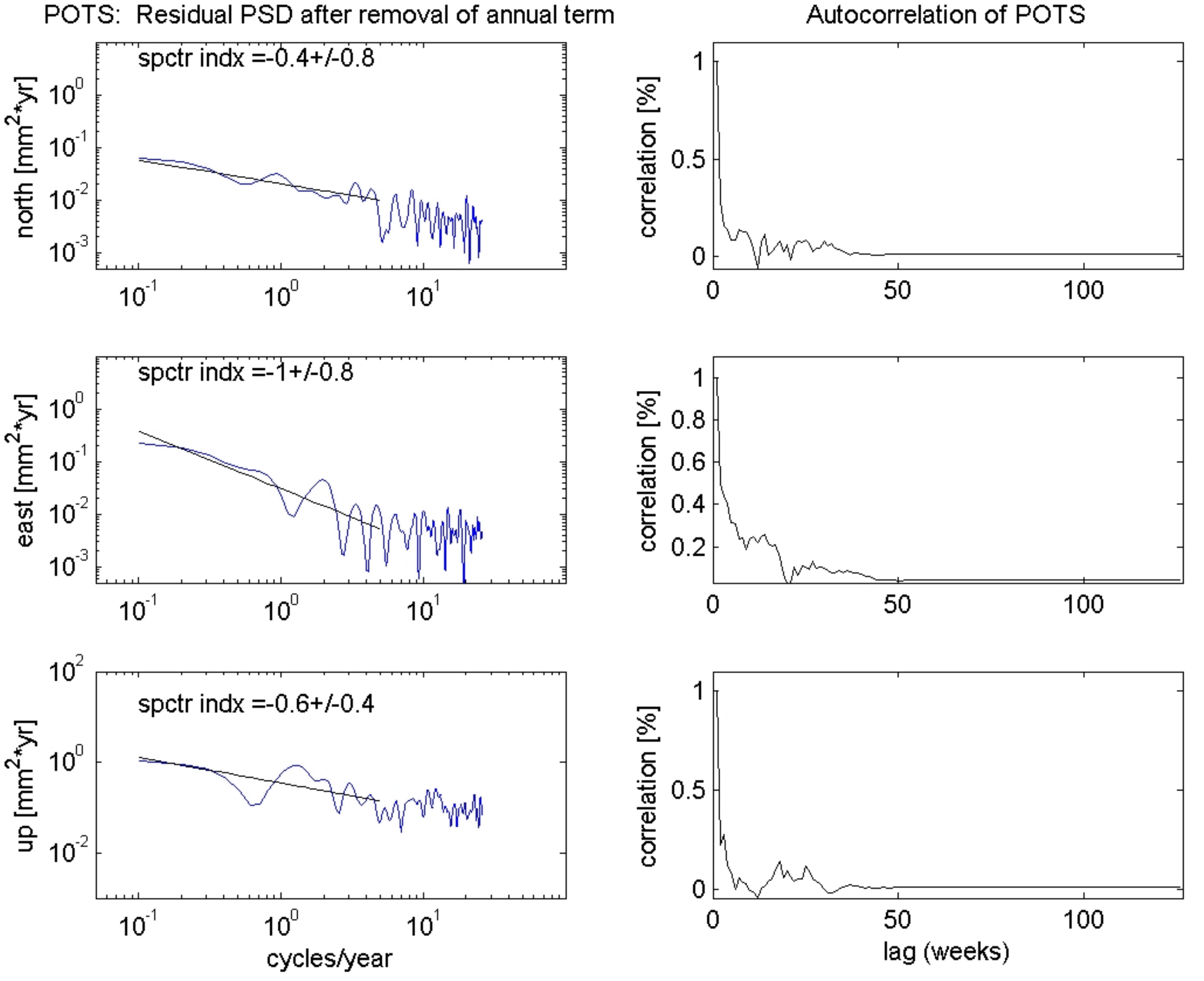
TOTAL NUMBER OF PARAMETERS	: 35894517
TOTAL NUMBER OF OBSERVATIONS	: > 53806263
NUMBER OF SINGLE DIFF. FILES	: 34758
A POSTERIORI SIGMA OF UNIT WEIGHT	: 0.0034 m
TOTAL NUMBER OF STATIONS	: 372

Statistical analysis on time series: 1. Identification of periodic signals

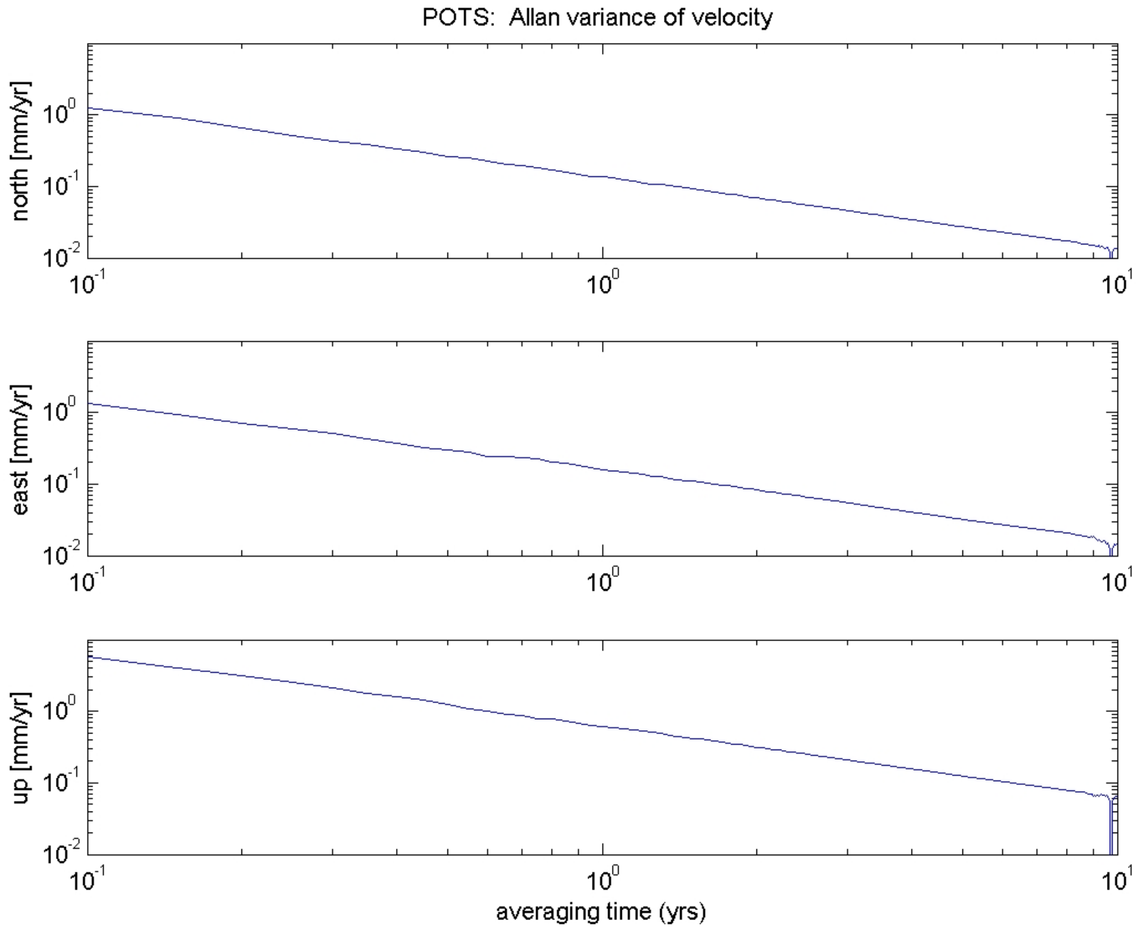


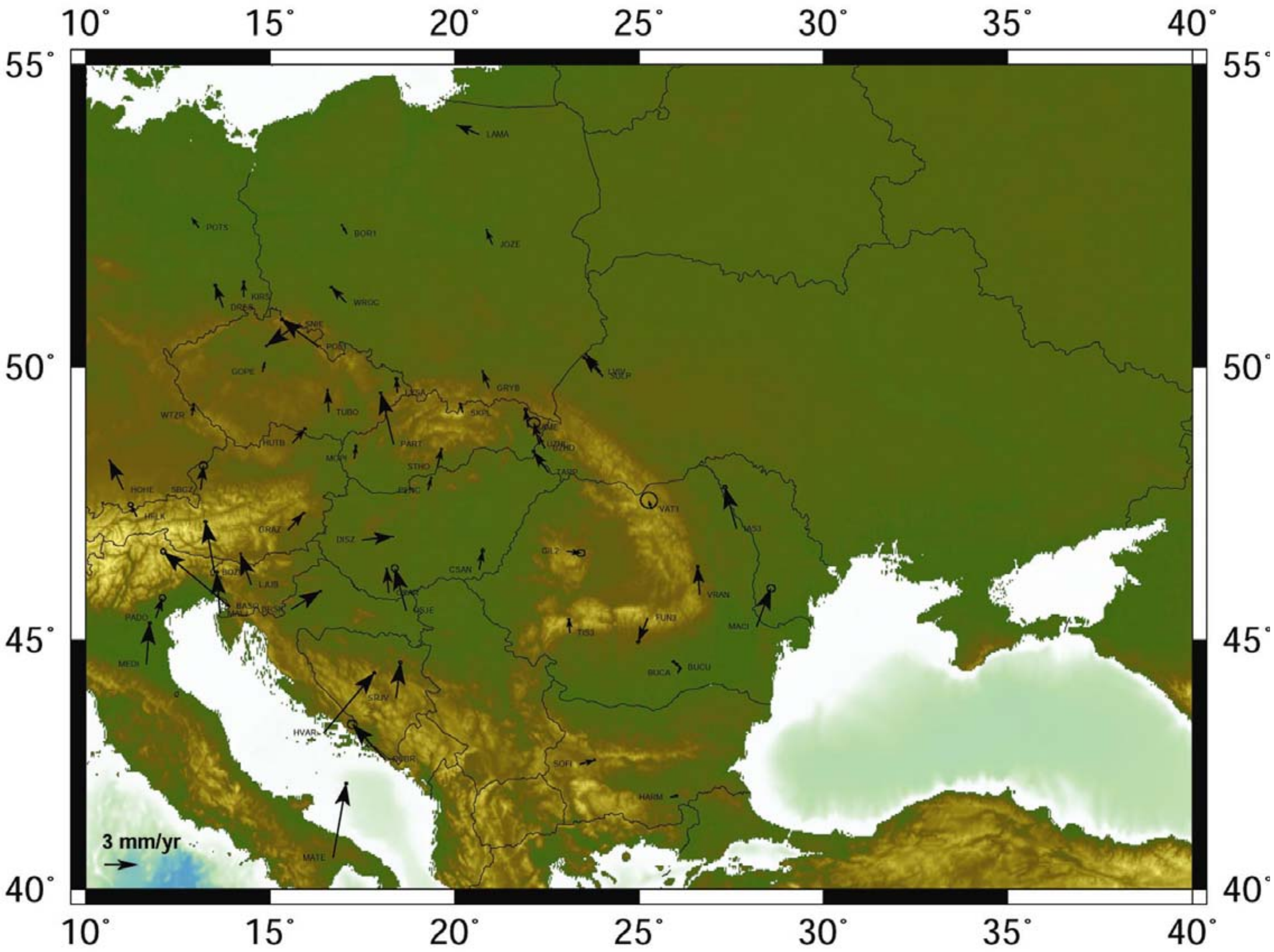
Statistical analysis on time series:

2. Noise profile and statistical independence of samples



Statistical analysis on time series:
3. Evolution of velocity uncertainty in the sense of Allan variance

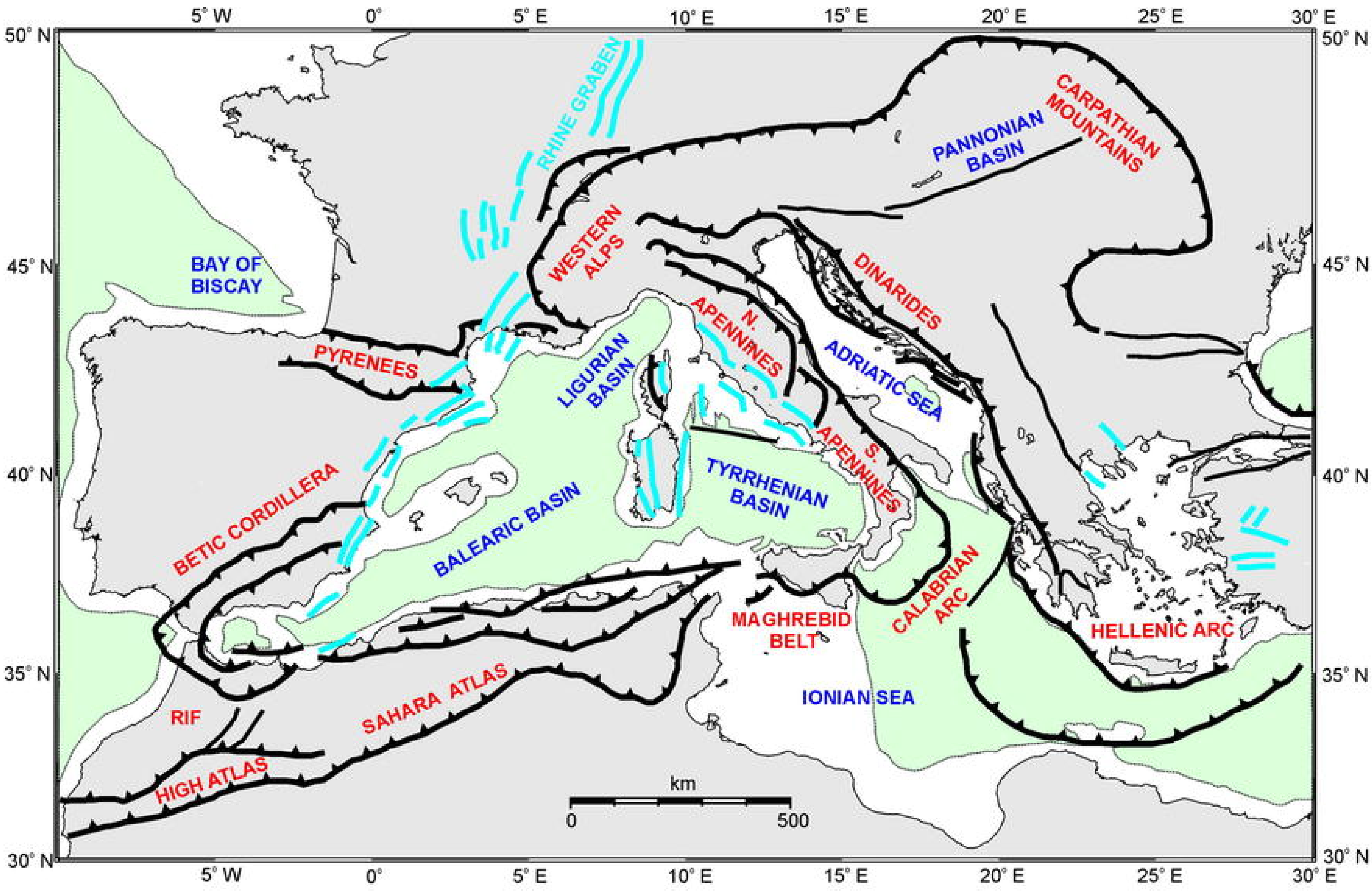




Velocity in Central Europe (CERGOP data set)

Structural setting and active tectonics

after Jolivet, L., and Faccenna, C., 2000, Mediterranean extension and the Africa-Eurasia collision: Tectonics, 19, 1095–1106.

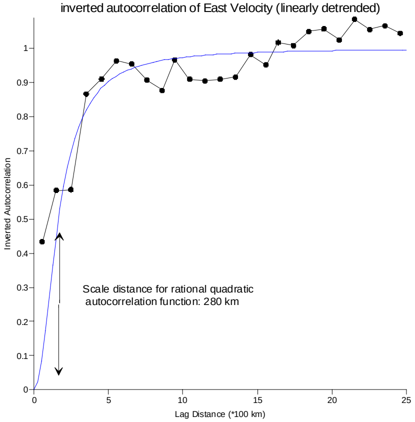


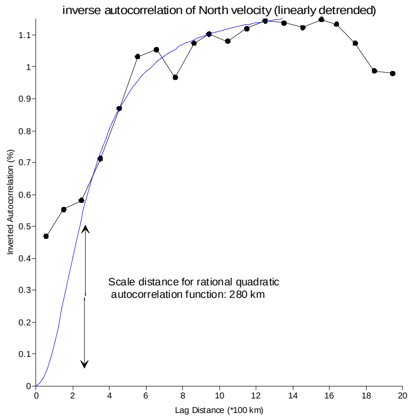
Interpolation of velocity vectors with least squares collocation, a minimum variance algorithm

- Variogram analysis: length of decorrelation d_0 =290 km (correlation drop of 50%)
- Isotropic correlation function defined consistently:

$$C_{ij}(d) = \frac{C_{ij}(0)}{1+\left(d/d_0\right)^2} \quad i, j = e(ast), n(orth);$$

$$C(d) = \begin{bmatrix} C_{nn} & C_{en} \\ C_{en} & C_{ee} \end{bmatrix}$$





$$\begin{bmatrix} v_n \\ v_e \end{bmatrix}_{grid-node} = \sum_{s} C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'} \qquad s, s' = station \quad indeces$$

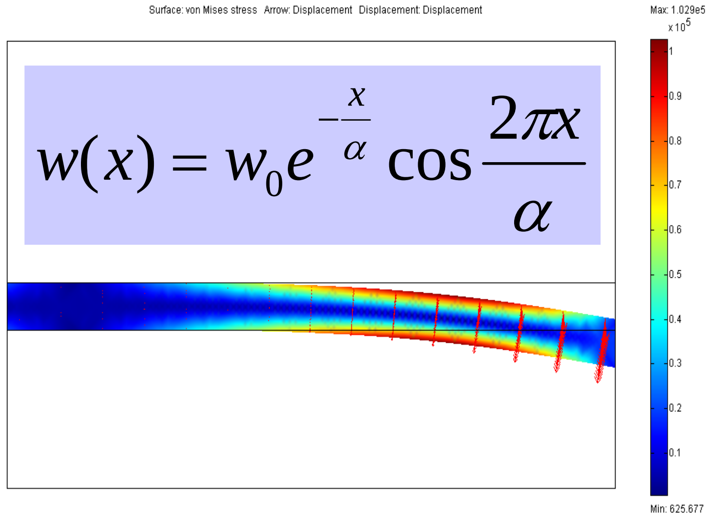
$$\begin{bmatrix} \sigma_{nn} \\ \sigma_{ee} \end{bmatrix}_{grid-node} = \left\{ \left[\sum_{s} C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \right]^T E^{-1}{}_{s's'} \left[\sum_{s} C(d_{grid-node,s}) \sum_{s'} C^{-1}(d_{s,s'}) \right] \right\}^{-1}$$

- E is a diagonal matrix with elements equal to the variance of each velocity component, e.g. in the sense of Allan variance.

Why 290 km? Possible interpretation using an isostatic flexural model of an elastic plate

$$D\frac{d^4w}{dx^4}+(\rho_m-\rho_c)gw=0$$

$$D=\frac{Eh^3}{12(1-\nu^2)} \qquad \alpha=\left[\frac{4D}{(\rho_m-\rho_c)g}\right]^{1/4}$$



$$w(x)=w_0e^{-\frac{x}{\alpha}}\cos\frac{2\pi x}{\alpha}$$

- If E=70 Gpa, ν=0.25, density contrast 600 kg/m^3 and plate thickness ~ 27 km, then the flexural parameter α ~ 290 km

From velocity to horizontal strain rate

Eigenvectors of the 2D strain rate tensor are computed at those permanent GPS sites such thatthere exist at least 4 other stations in the four quadrants within d$_0$ (= 290 km)

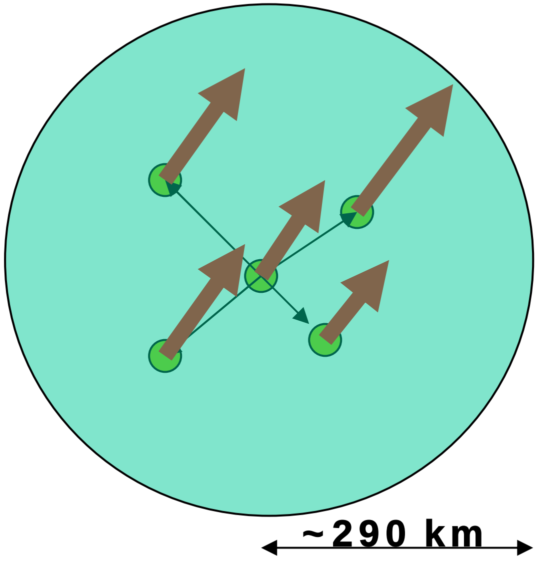
$$\begin{bmatrix} v_{n,n} & v_{n,e} \\ v_{e,n} & v_{e,e} \end{bmatrix}_P = \sum_s \begin{bmatrix} \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \\ \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \end{bmatrix}_{P,s} \sum_{s'} \left[C(d_{s,s'}) + W_{ss'}\right]^{-1} \cdot \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'} \qquad s, s' = station \quad indeces$$

$$\varepsilon_1 = \frac{v_{n,n} + v_{e,e}}{2} + \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\varepsilon_2 = \frac{v_{n,n} + v_{e,e}}{2} - \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\sin 2\theta = \frac{v_{e,n} + v_{n,e}}{\varepsilon_2 - \varepsilon_1}; \cos 2\theta = \frac{v_{e,e} - v_{n,n}}{\varepsilon_1 - \varepsilon_2}$$

- Link to strain rate map for North Center Italy (EUR+UPA+GP_ combination)
- Link to strain rate for Center South Italy (data base of E. Serpelloni)
- Comparison of the two velocity data base



Estimating a formal strain rate uncertainty

Step 1: Mapping by collocation the velocity uncertainties into strain rate uncertainties, expressed in geographical coordinates

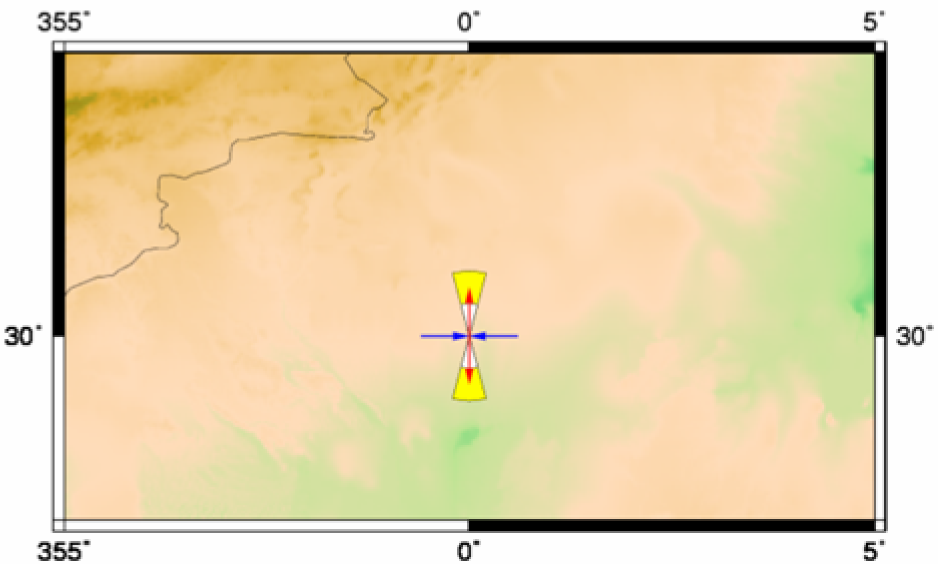
$$\begin{bmatrix} dv_{n,n} & dv_{n,e} \\ dv_{e,n} & dv_{e,e} \end{bmatrix}_P = \sum_s \begin{bmatrix} \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \\ \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \end{bmatrix}_{P,s} \sum_{s'} \left[C(d_{s,s'}) + W_{ss'} \right]^{-1} \cdot \begin{bmatrix} \sigma_n \\ \sigma_e \end{bmatrix}_{s'} \quad s, s' = station \quad indeces$$

Step 2: Linear propagation of the strain rate uncertainty from geographical axes to principal axes:

$$\varepsilon_1 = \frac{v_{n,n} + v_{e,e}}{2} + \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\varepsilon_2 = \frac{v_{n,n} + v_{e,e}}{2} - \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

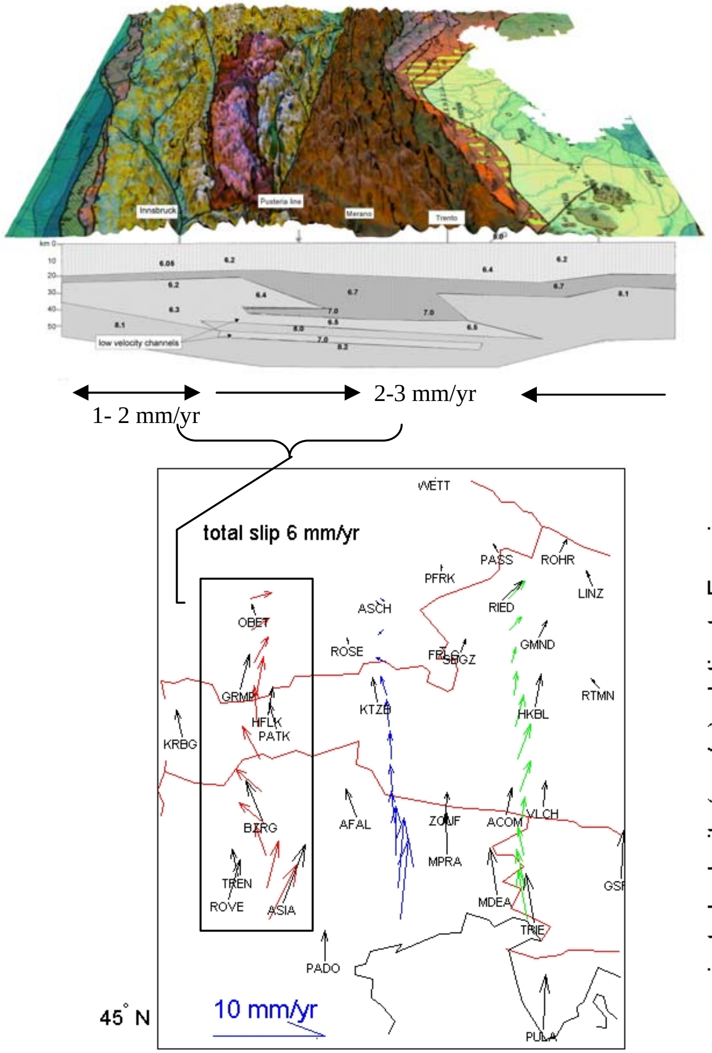
$$\sin 2\theta = \frac{v_{e,n} + v_{n,e}}{\varepsilon_2 - \varepsilon_1}; \cos 2\theta = \frac{v_{e,e} - v_{n,n}}{\varepsilon_1 - \varepsilon_2}$$

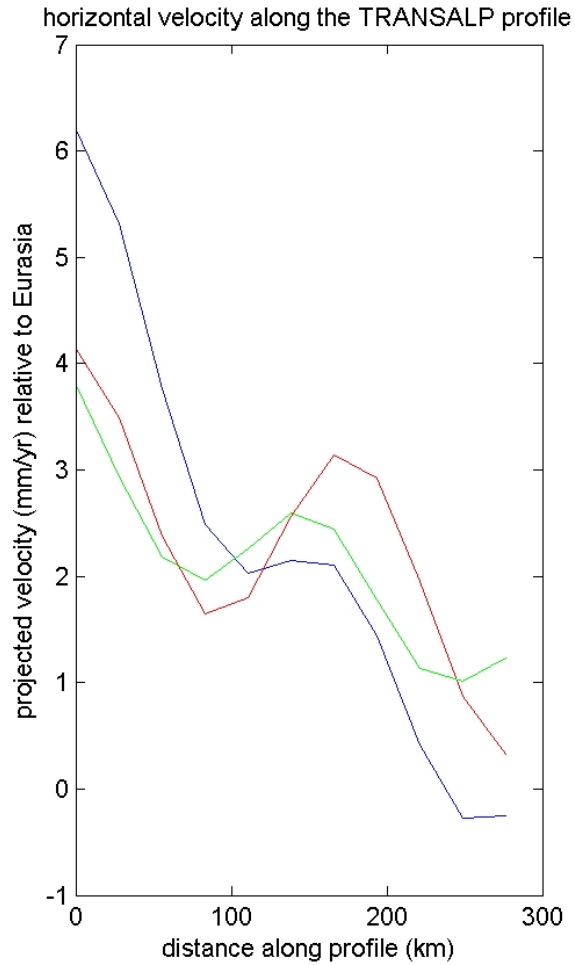


$$d\varepsilon_{1,2} = \frac{dv_{n,n} + dv_{e,e}}{2} \pm \frac{\frac{(v_{e,e} - v_{n,n})(dv_{e,e} - dv_{n,n})}{2} + 2\varepsilon_{e,n} d\varepsilon_{e,n}}{2\sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + (\varepsilon_{e,n})^2}}$$

$$d\theta = \cos^2 2\theta \left[\frac{d\varepsilon_{e,n}}{v_{e,e} - v_{n,n}} \right] - \frac{\varepsilon_{e,n}(dv_{e,e} - dv_{n,n})}{(v_{e,e} - v_{n,n})^2}$$

Slip Profiles in the Eastern Alps





- Velocities are interpolated to a profile (left) and their projection onto the profile is plotted against space (right)
- A shortening of up to ~ 6 mm/yr is implied across the 300 km profile, or 20 nstrain/year. Locally can be higher, to ~ 40 nstrain /yr
- Divergent pattern in parallel profiles across the Tauern window may imply a squeezing and hence lateral extrusion

Conclusions

- **We have presented a systematic analysis of time series of coordinates of permanent, high quality GPS stations belonging to the EPN, CEGRN and national networks, spanning up to 10 years**
- **Velocities have been computed rigorously by staking the normal equation of the merged networks. Rigorous noise analysis and estimate of velocity uncertainty. Statistical analysis of the ensemble of velocities yields a correlation length of 290 km**
- **Strain rates and interpolated velocities along seismic profiles have been computed by least squares collocation**
- **We find slip rates of up to 6 mm/yr in the Eastern Alps (TRANSALP), and strain rates of the order of 40-50 nstrain /yr.**
- **Data in Central Europe are very sparse. Strain rate appears to be very small wherever it can be computed with the chosen reliability standards**