Wrocław University of Environmental and Life Sciences

High-rate GNSS in seismology

Correction of multipath effect for precise point positioning high-rate GNSS data processing in seismic phenomena analysis

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INCREaSE - GEOworkshop

Wrocław, 28.03.2019 r.

Outline

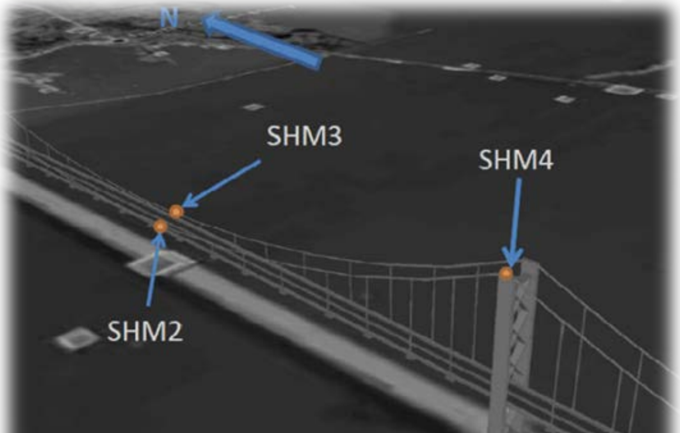
- Motivation
- HR-GNSS in seismology
- Multipath error mitigation
  - Position Domain Sidereal Filtering
  - Multipath Hemispherical Map
  - Digital Filtering
- The application of HR-GNSS in mining tremor analysis

Motivation

HR-GNSS

- high precision
- information on GNSS station location changes in small time intervals

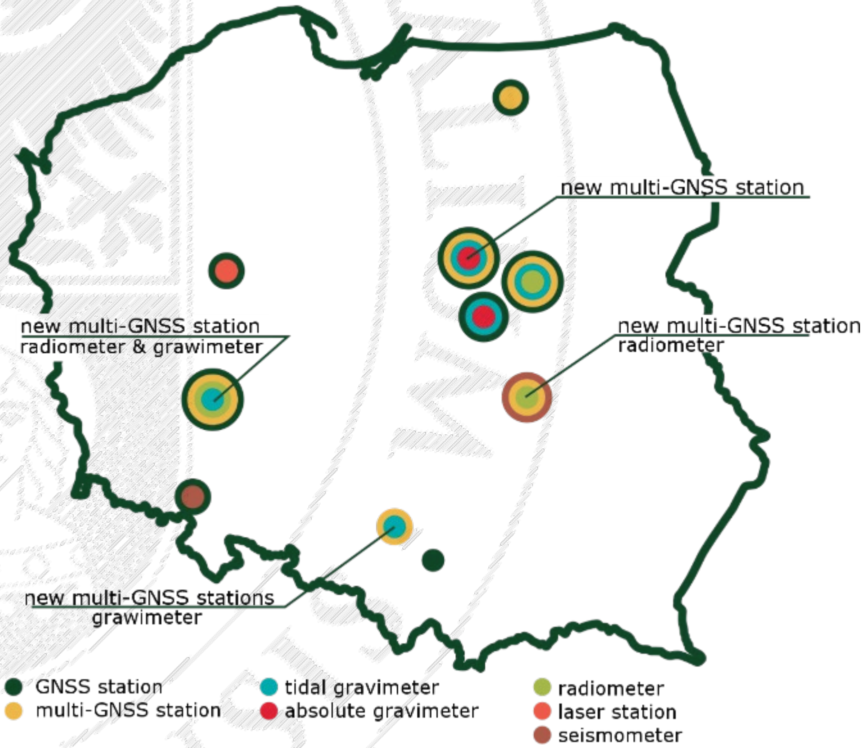
- earthquake analysis, including early warning systems
- structural health monitoring, eg. bridges



(Wang et al., 2017)

EPOS-PL

HR-GNSS network in Poland dedicated to mining deformation analysis with particular emphasis on the area of the Upper Silesian Coal Basin



USCB mining damages

Co-located geophysical and geodetic infrastructure enables to integrate the data.

HR-GNSS in seismology

Differential Positioning (DP)

- in case of earthquakes – the position of reference station may be changed

Precise Point Positioning (PPP)

- empirical analysis showed that HR-PPP in short period of time reaches milimeter precision (Hefty and Gerhátová, 2012; Xu et al., 2013), which is a better result than traditional PPP

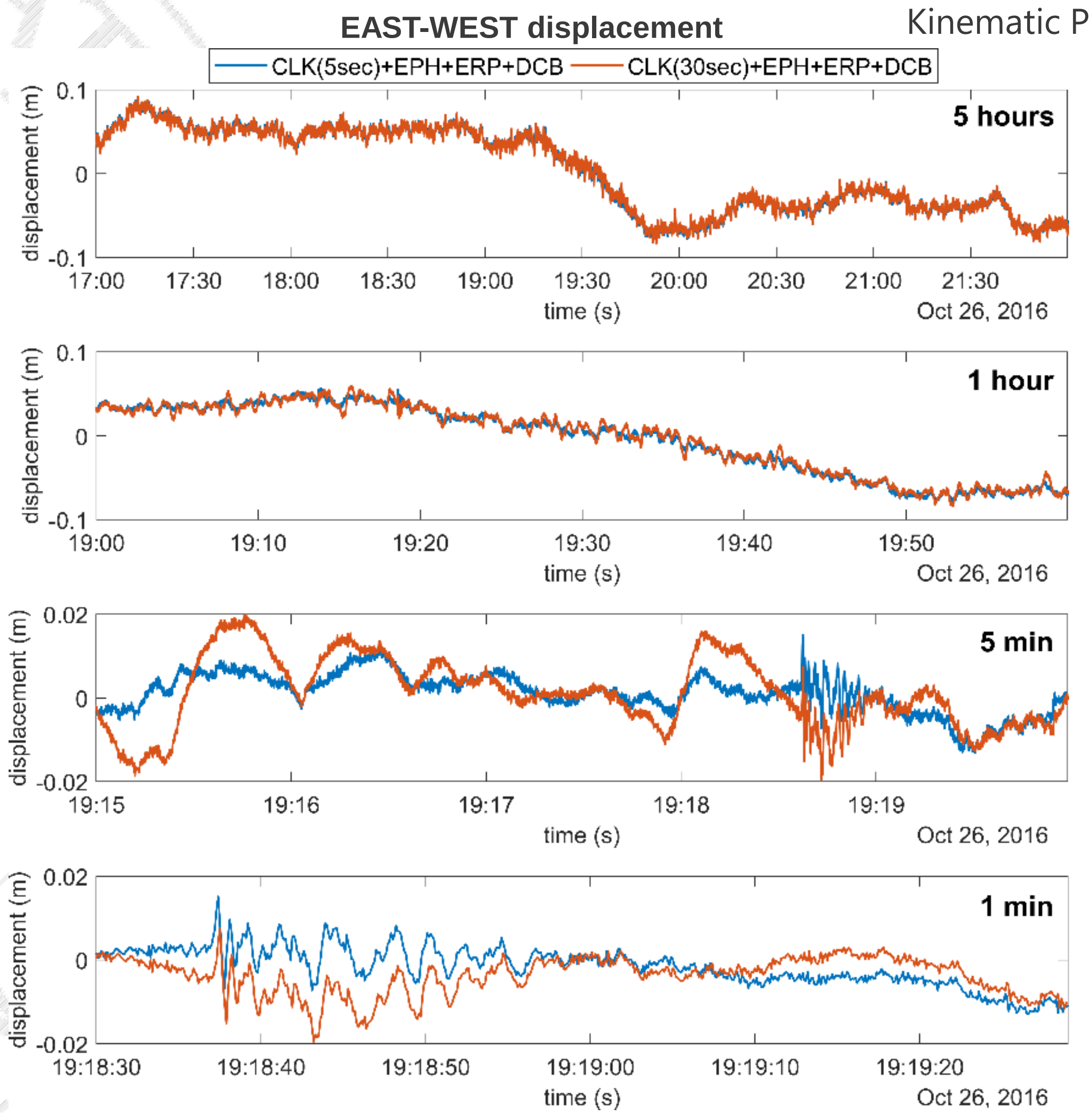
Variometric Approach
(Colosimo et al., 2011; Benedetti et al., 2016)

- Variometric Approach for Displacements Analysis Stand-alone Engine (VADASE)
- the epoch-by epoch displacements (equivalent to inter-epoch mean velocities) are estimated in a global reference frame using the phase observations from the satellites in view in two consecutive epochs
- few-minutes long time series, centimeter accuracy

HR-PPP – the influence of CODE products on time series

Clock data

RTKlib 2.4.3
Kinematic PPP

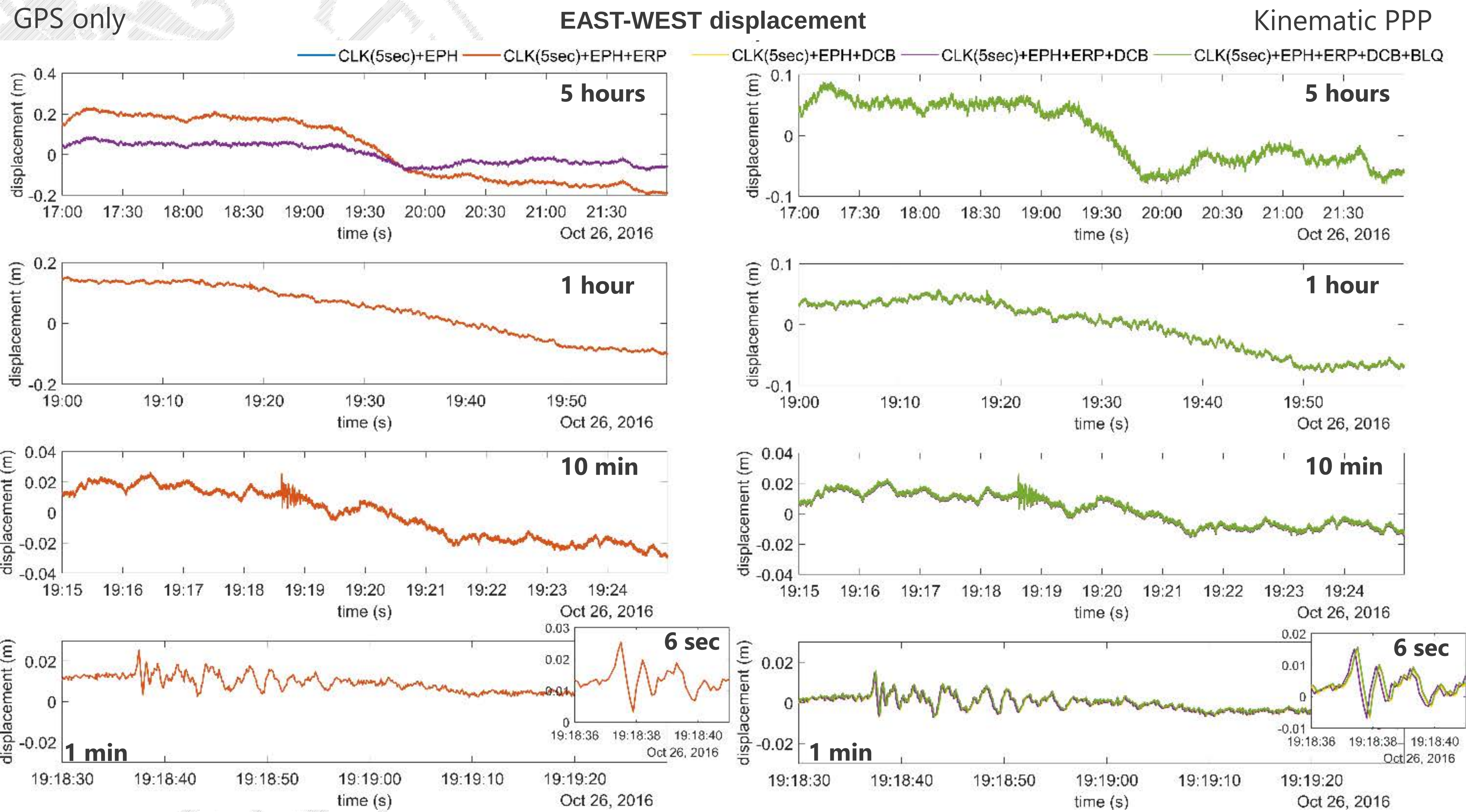


GPS: AMAT (10Hz);
EQ Norcia 2016-10-26 19:18:08 UTC, Mw 6.6

HR-GNSS – the influence of CODE products on time series

GPS only

RTKlib 2.4.3
Kinematic PPP



RMS & corelation coefficients → ERP, BLQ – no influence in HR-PPP within short periods of time

GPS: AMAT (10Hz);
EQ Norcia 2016-10-26 19:18:08 UTC, Mw 6.6

Observation errors in HR-GNSS

HR-GNSS

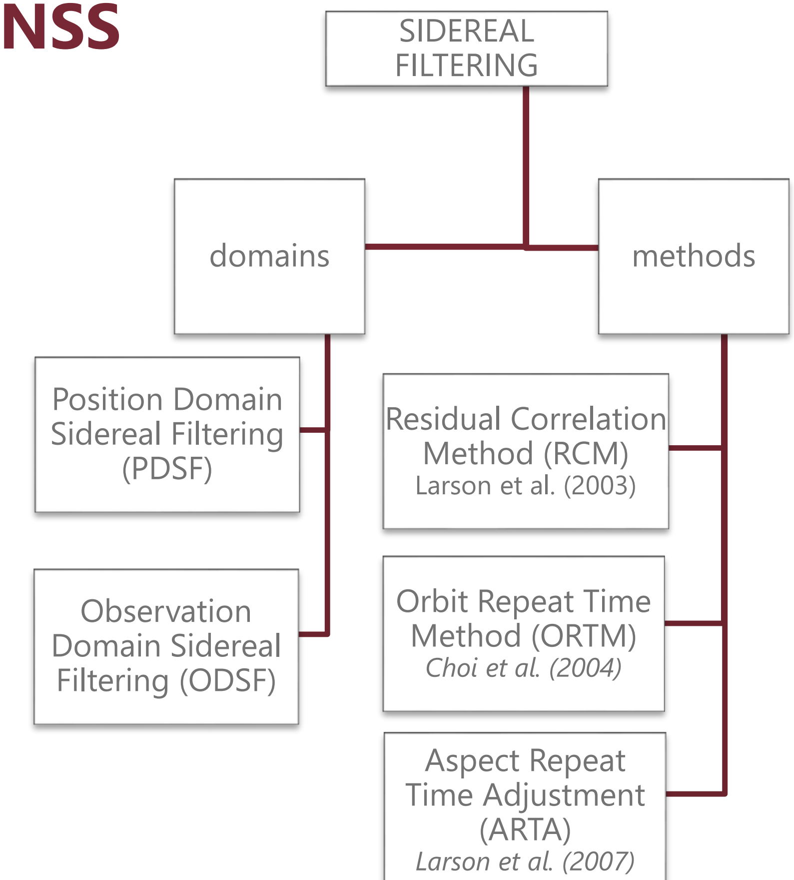
position analysis in subsequent epochs | short (several-minute) time series analysis

→ large influence of systematic errors

- errors resulting from satellite geometry → mostly eliminated by corrections and models
- errors resulting from geophysical effects → mostly eliminated by corrections and models
- errors resulting from clock-drift → should be taken into account → eg. *using interpolated clock*
- random errors → should be taken into account
- higher-order ionospheric errors → should be taken into account
  - *in case of*
    - *high ionospheric activity*
    - *large earthquakes*
- multipath error → should be taken into account → eg. *sidereal filtering* *multipath maps*

(Shu et al., 2017)

Multipath error reduction in HR-GNSS



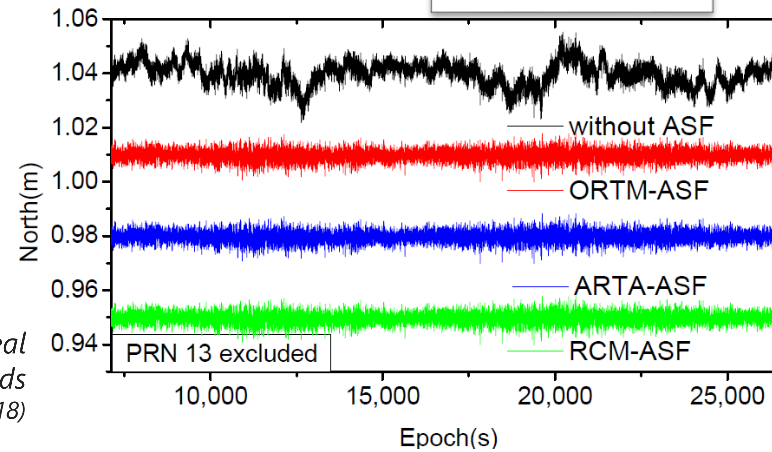
Methods:

- **Sidereal filtering**

  The model is built of coordinates or observation residuals from of the previous day(s). Then the correction of the data of the subsequent day(s) is applied by subtracting the corresponding correction value for each epoch considering the sidereal day shift.

  (eg. Bock et al., 2000; Choi et al., 2004; Emore et al., 2007)

- **Multipath hemispherical maps**
- **Digital filtering**



Displacement time series influenced by different sidereal filtering methods
(Wang et al., 2018)

Multipath error reduction in HR-GNSS

Methods:

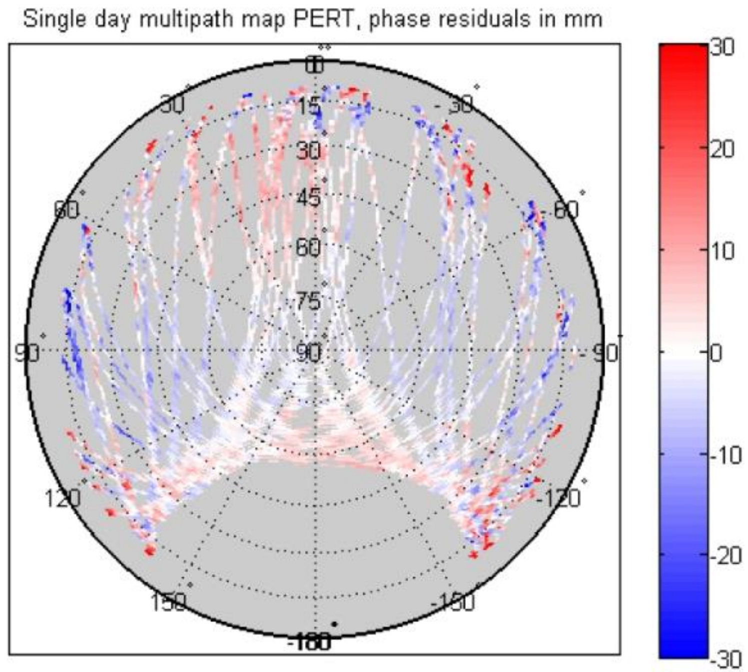
- **Sidereal filtering**
- **Multipath hemispherical maps**

  The model is built with carrier-phase residuals in a grid with fixed density for the GNSS receiver located in a specific location. Then the observations in each cell are corrected.

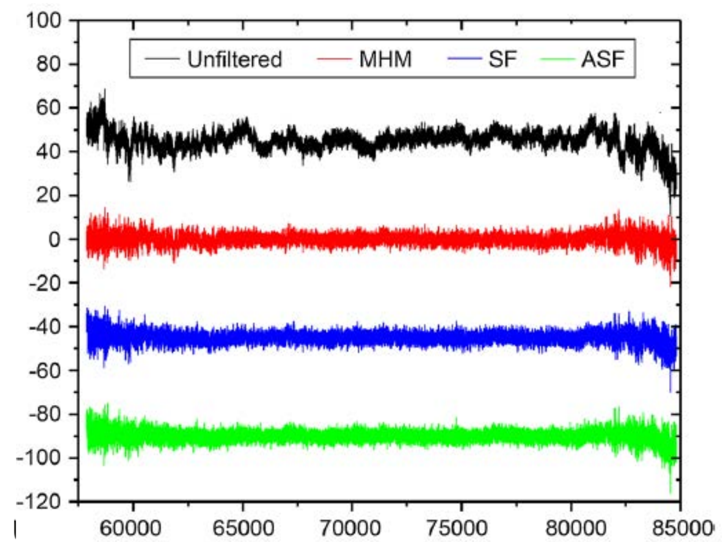
  (eg. Moore et al., 2013; Fuhrmann et al., 2014; Dong et al., 2015)

- **Digital filtering**

  (Kamatham et al., 2013)



Multipath map for PERT station
(Huisman et al., 2009)



PRN 09 L1-residuals
(Dong et al., 2015)

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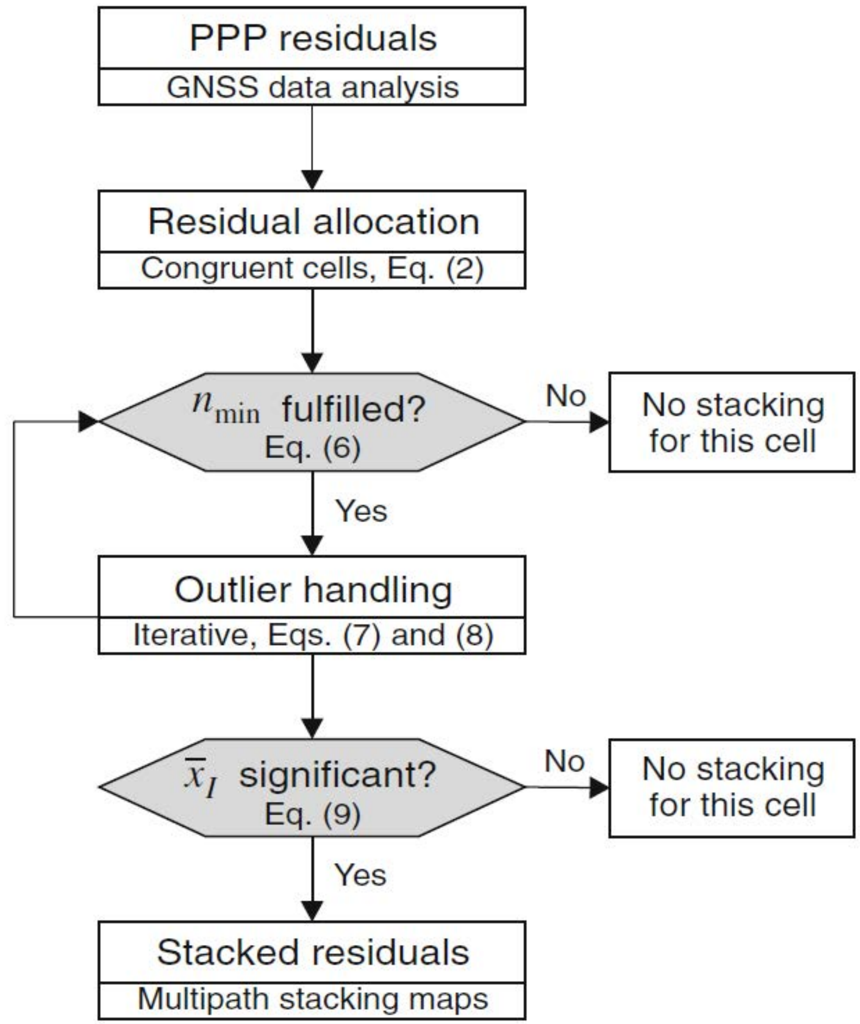
Seismic phenomena in the light of high-rate GPS Precise Point Positioning results

MULTIPATH MAPS

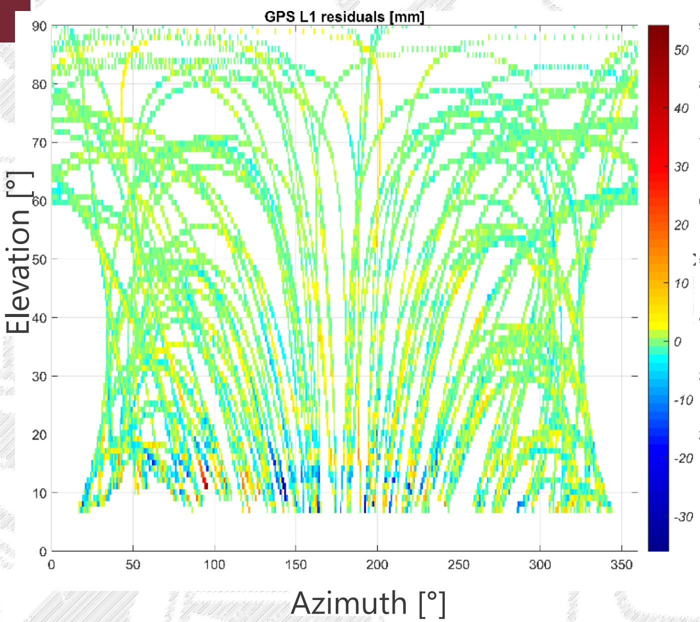
Multipath map generation scheme

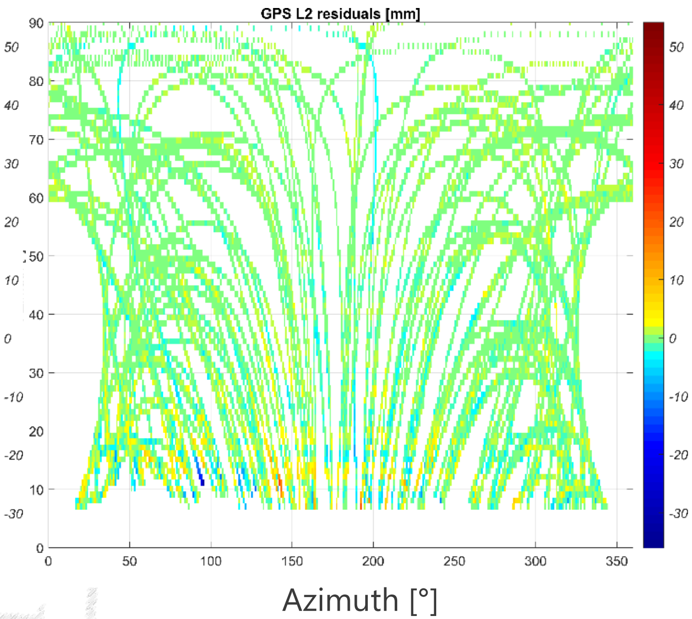
- ✓ 30-days 30-sec observations
- ✓ processed with CSRS-PPP v2.21.0
  - static mode
  - GPS (+GLONASS)
  - IGS Final
  - elevation: 7.5°
- ✓ carrier-phase observations
- ✓ **maps obtained separately for L1-L2 frequencies**

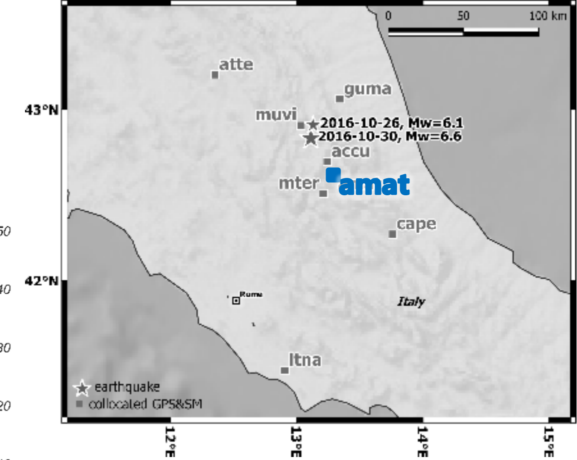


Flowchart of the proposed stacking approach using congruent cells
(Fuhrmann et al., 2014)

Multipath 1x1° map for AMAT station

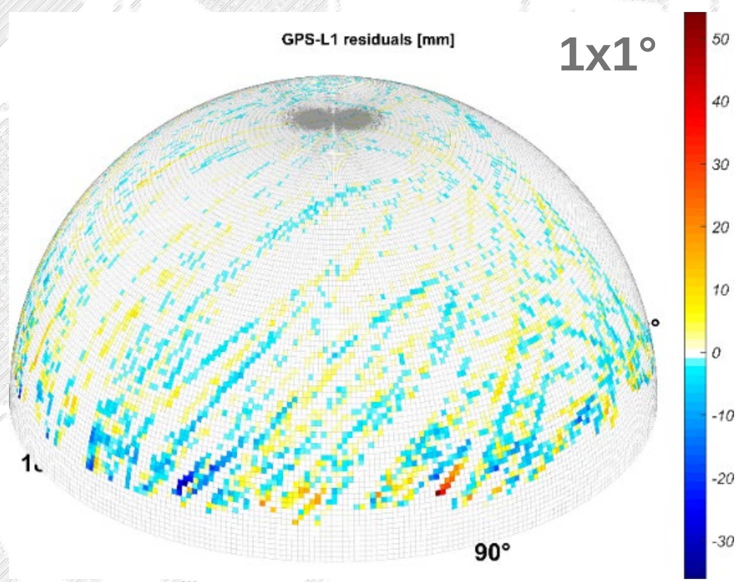


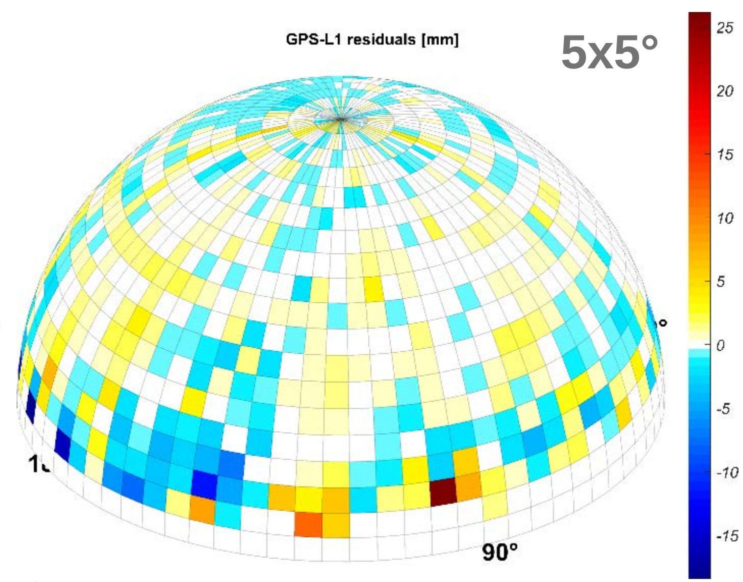




GPS: AMAT (10Hz);
EQ Norcia 2016-10-26
19:18:08 UTC, Mw 6.6

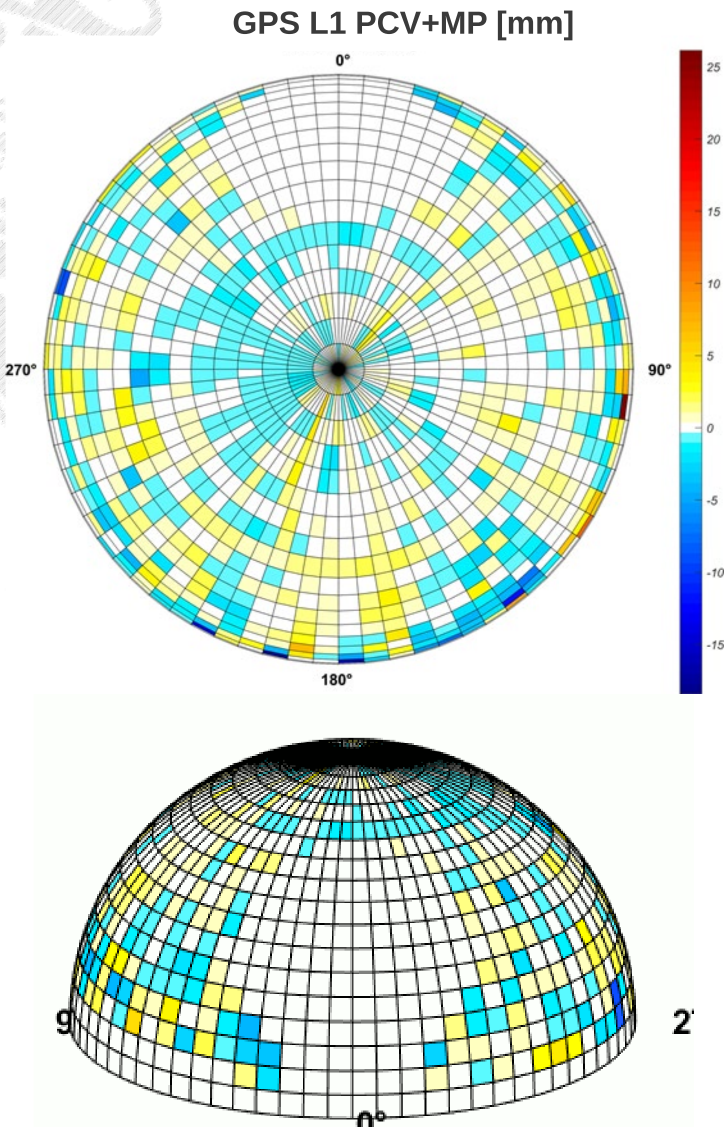
antenna: LEIAR25.R4 LEIT
system: GPS

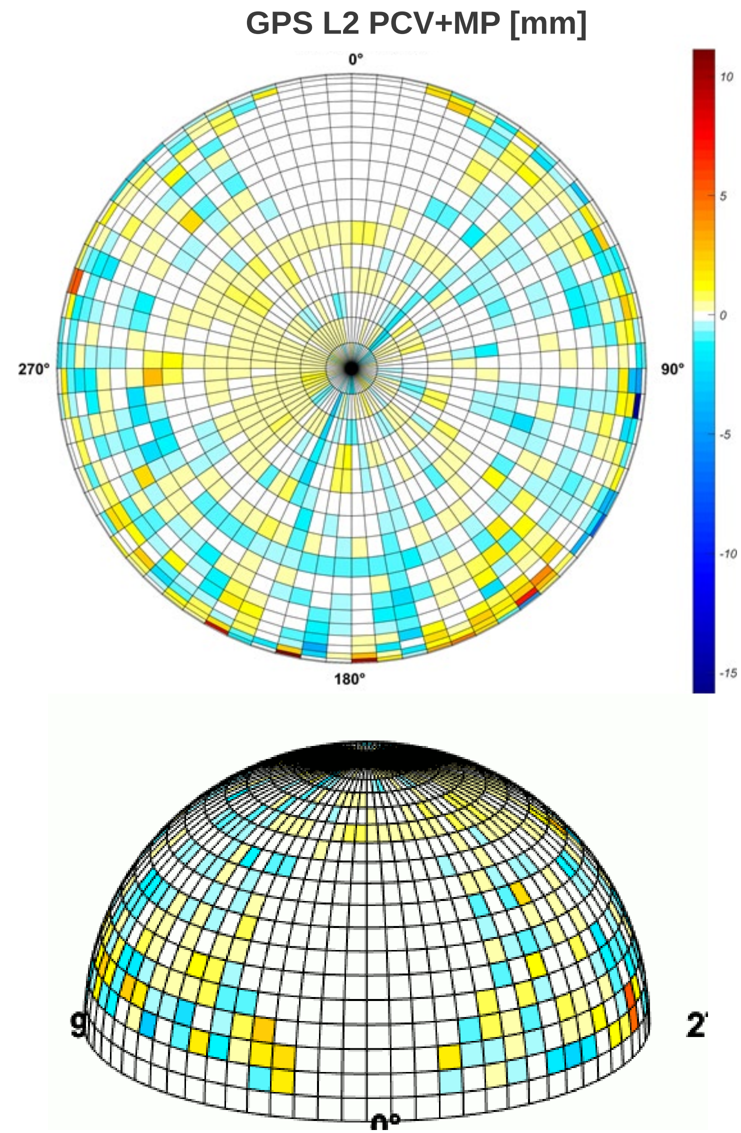




PCV antenna model corrected with multipath map

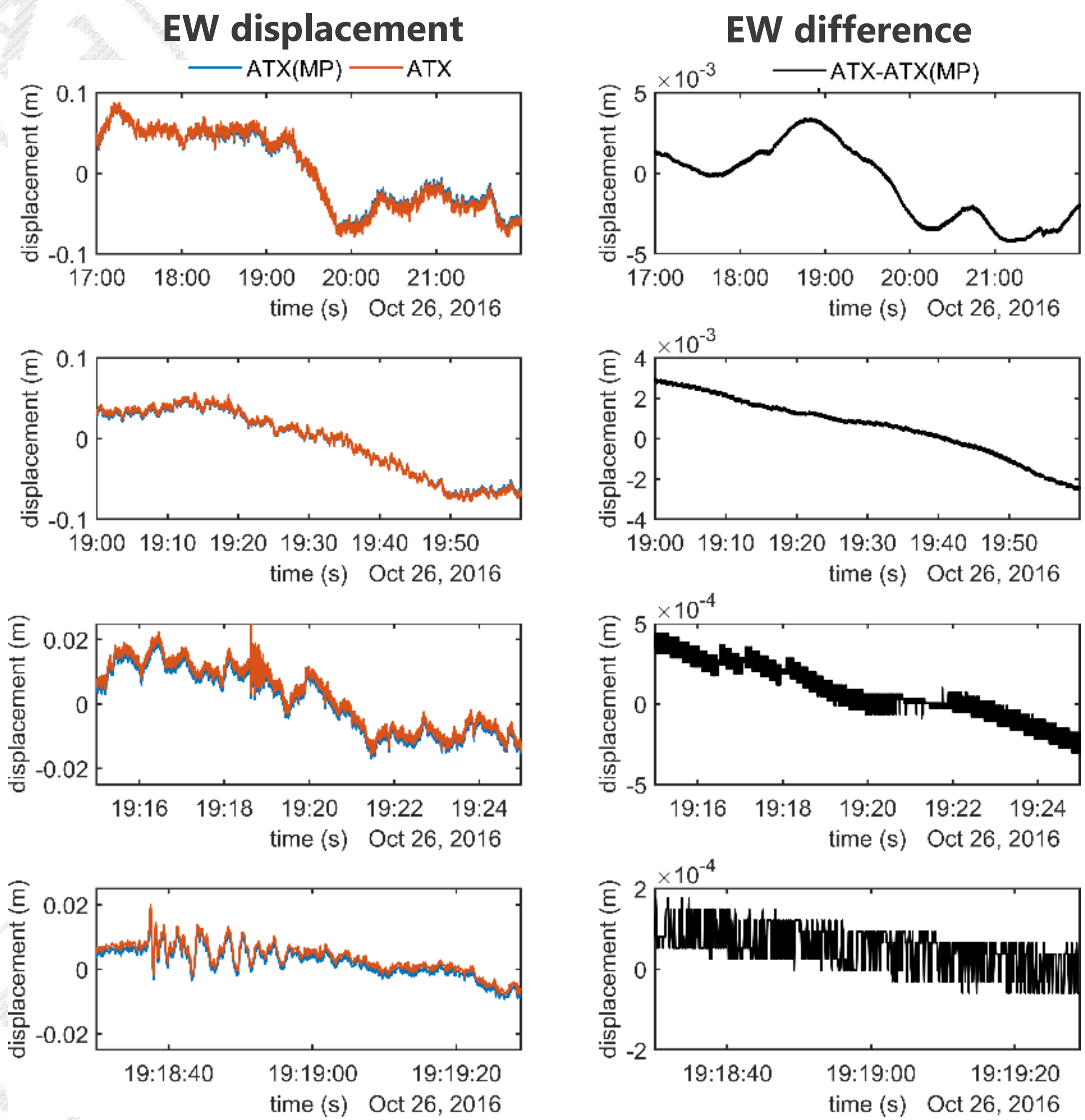
AMAT station





Result

GPS: AMAT (10Hz);
EQ Norcia 2016-10-26
19:18:08 UTC, Mw 6.6



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Seismic phenomena in the light of high-rate GPS Precise Point Positioning results

POSITION DOMAIN SIDEREAL FILTERING

Position Domain Sidereal Filter generation scheme

$$\begin{bmatrix} X_{k_1}^{est} \\ Y_{k_1}^{est} \\ Z_{k_1}^{est} \end{bmatrix} - \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \delta X_{k_1} \\ \delta Y_{k_1} \\ \delta Z_{k_1} \end{bmatrix} \xrightarrow{low-pass\ filter} \begin{bmatrix} \delta X_{k_1} \\ \delta Y_{k_1} \\ \delta Z_{k_1} \end{bmatrix}_F$$

$$\begin{bmatrix} X_{k_2} \\ Y_{k_2} \\ Z_{k_2} \end{bmatrix}_{corr} = \begin{bmatrix} X_{k_2}^{est} \\ Y_{k_2}^{est} \\ Z_{k_2}^{est} \end{bmatrix} - \begin{bmatrix} \delta X_{k_1} \\ \delta Y_{k_1} \\ \delta Z_{k_1} \end{bmatrix}_F$$

shifted by the satellite repeat period

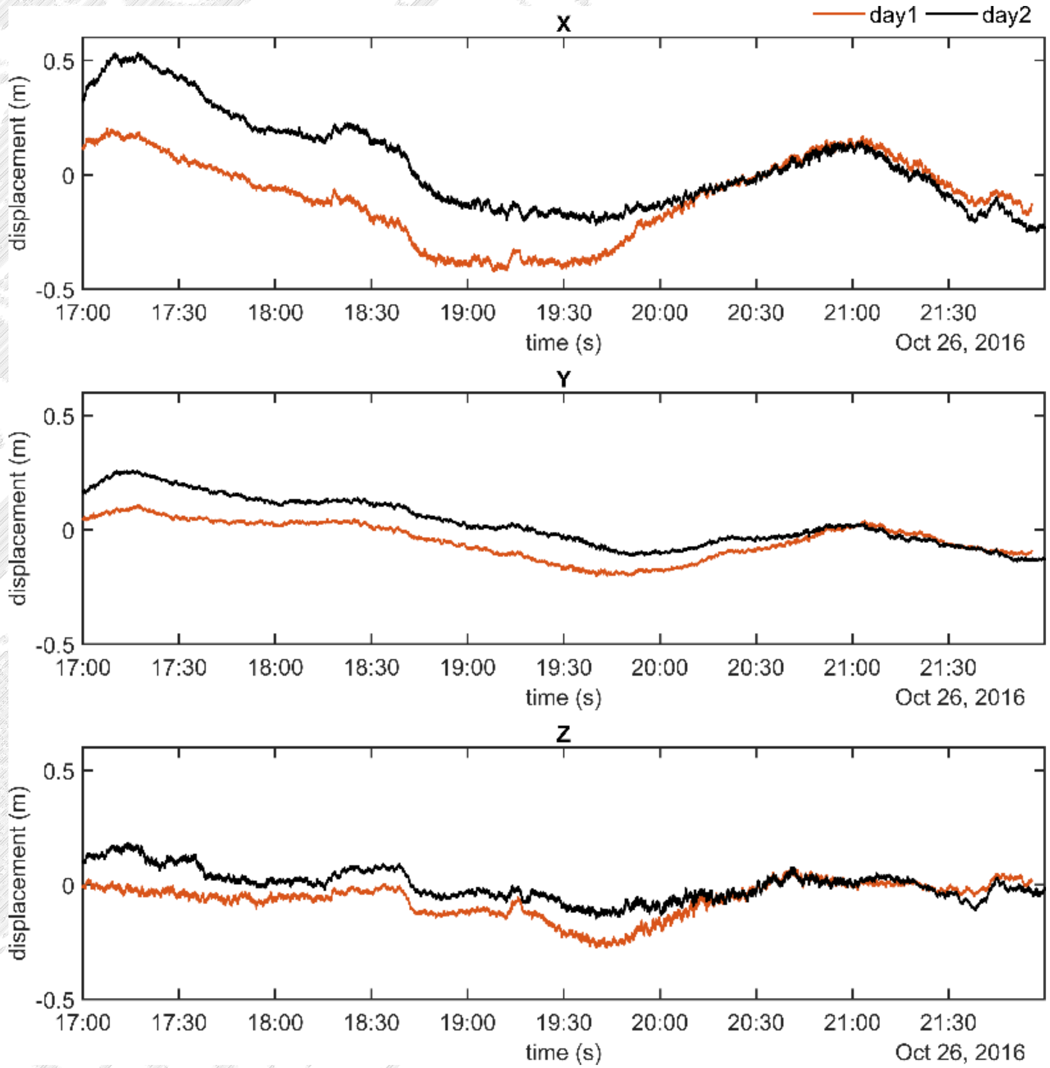
$$t_{k_2} = t_{k_1} + t_{repeat}$$

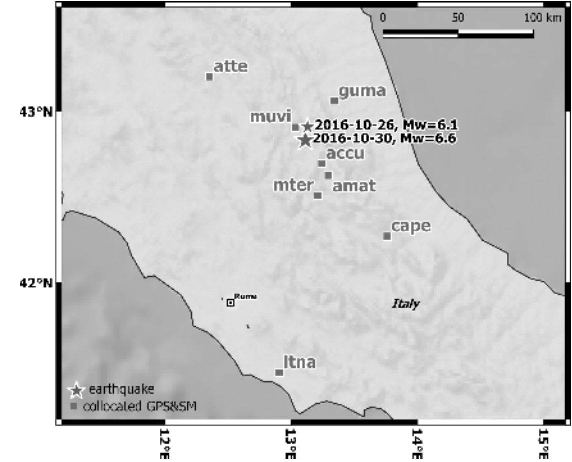
$$t_{repeat} = 86\,155\ s = 23\ h\ 55\ \min 4\ s$$

(Atkins, 2016)

Example

Nonfiltered displacements





GPS: AMAT (10Hz);
EQ Norcia 2016-10-26 19:18:08 UTC, Mw 6.6

RTKlib 2.4.3
CLK(5sec)+EPH+ERP+DCB

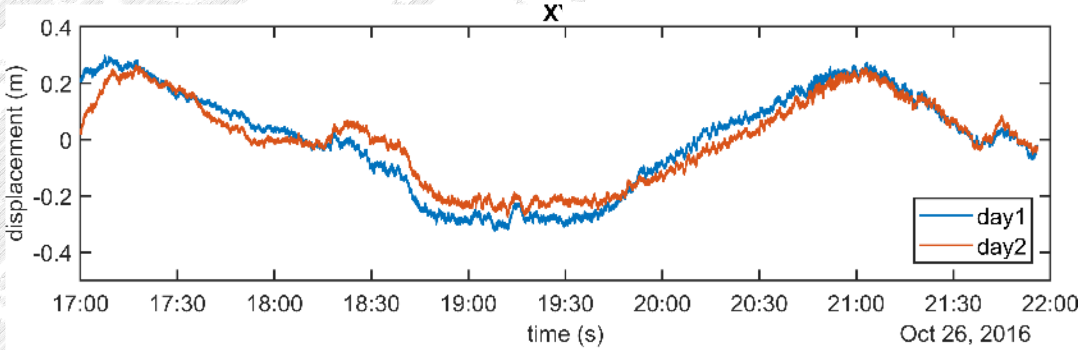
The data from DAY 1 is shifted by the sidereal day, for clarity

Example

GPS: AMAT (10Hz);
EQ Norcia 2016-10-26
19:18:08 UTC, Mw 6.6

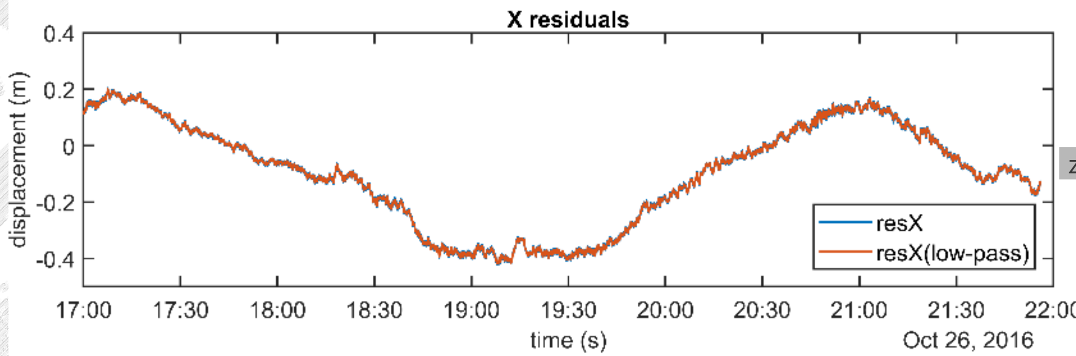
RTKlib 2.4.3
CLK(5sec)+EPH+ERP+DCB

Mechanism of PDSF

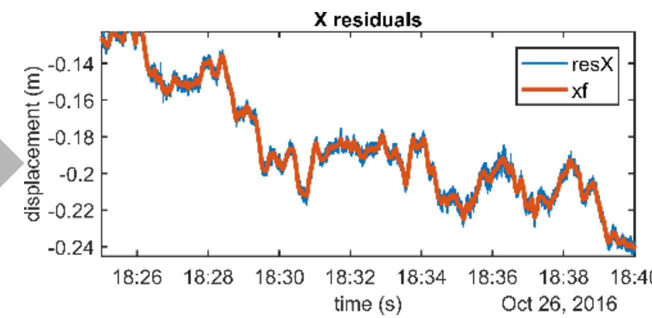


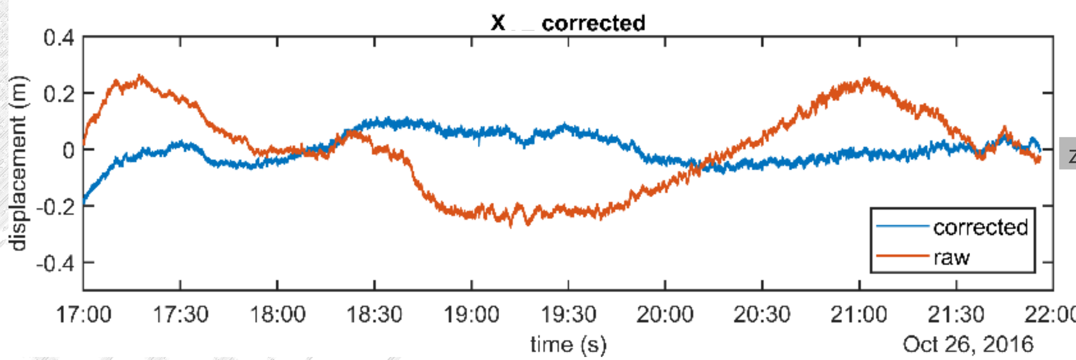
RMS GPS

	5 hours		15 min	
	raw	corrected	raw	corrected
'X'	0.148	0.051	0.011	0.008
'Y'	0.051	0.024	0.006	0.003
'Z'	0.058	0.034	0.008	0.006

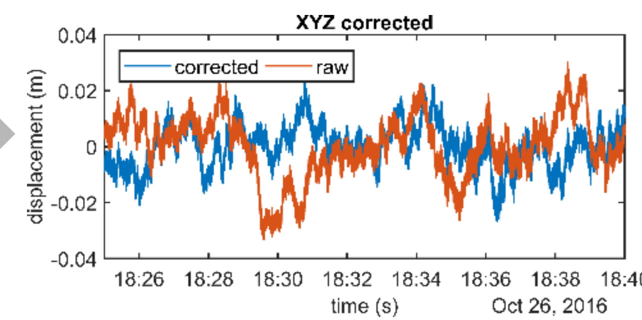


zoom





zoom



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DIGITAL FILTERING

HR-GNSS processing schema

RTKlib 2.4.3 PPP high-rate positioning (≥ 5Hz) → GPS positions time-series band-pass filtering → Alignment of GPS and SM displacement time-series → Correlation

Observations

- 10 Hz GPS-only
- 5-hour observation processing window

Calculation method

kinematic Precise Point Positioning

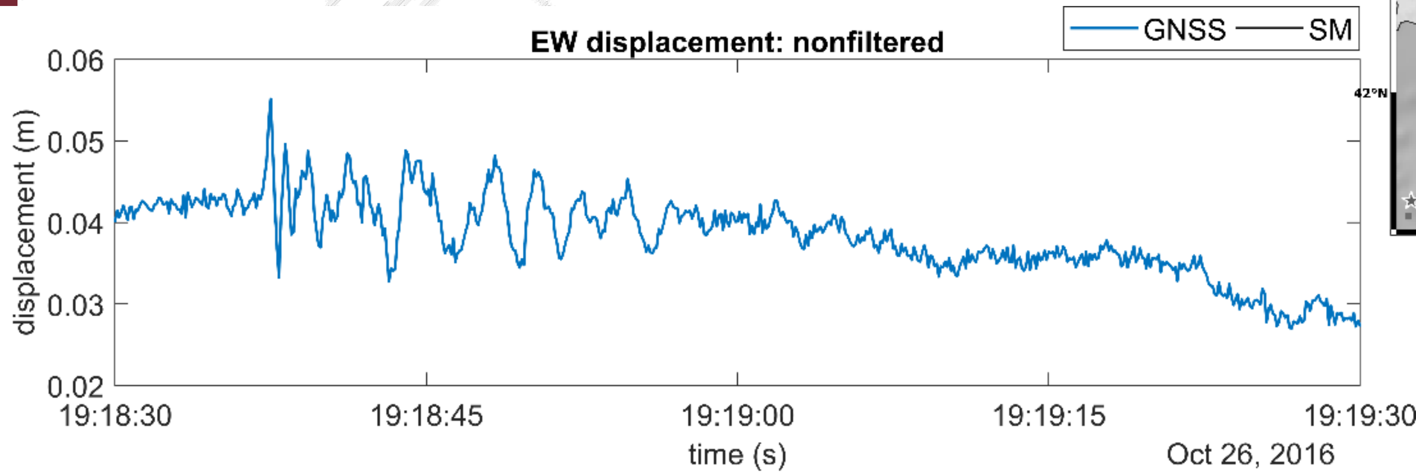
Processing parameters

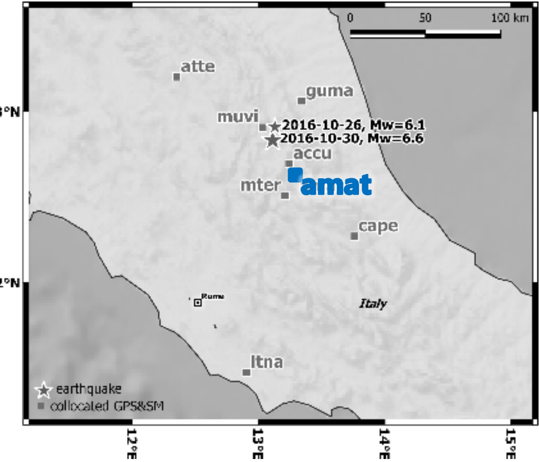
- final CODE (Center for Orbit Determination in Europe) orbits,
- 5-second GPS satellite clock,
- 10° satellite elevation mask,
- Earth rotation parameters
- differential code biases

Converting to displacements

- XYZ to local topocentric Cartesian coordinates transformation
- time series clipped to 20-100 seconds

HR-GNSS vs SM -example



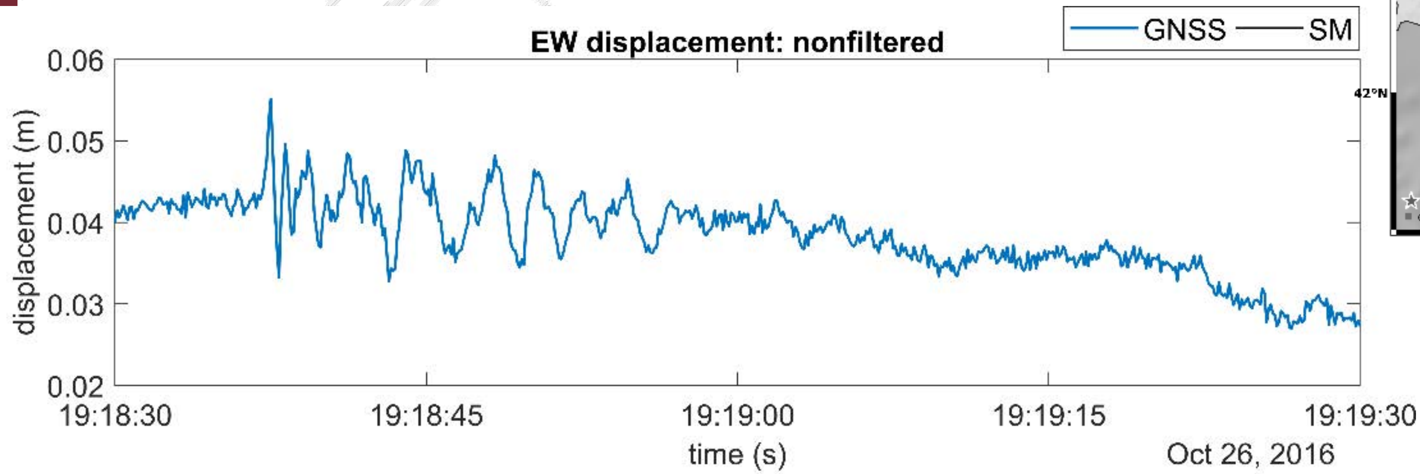


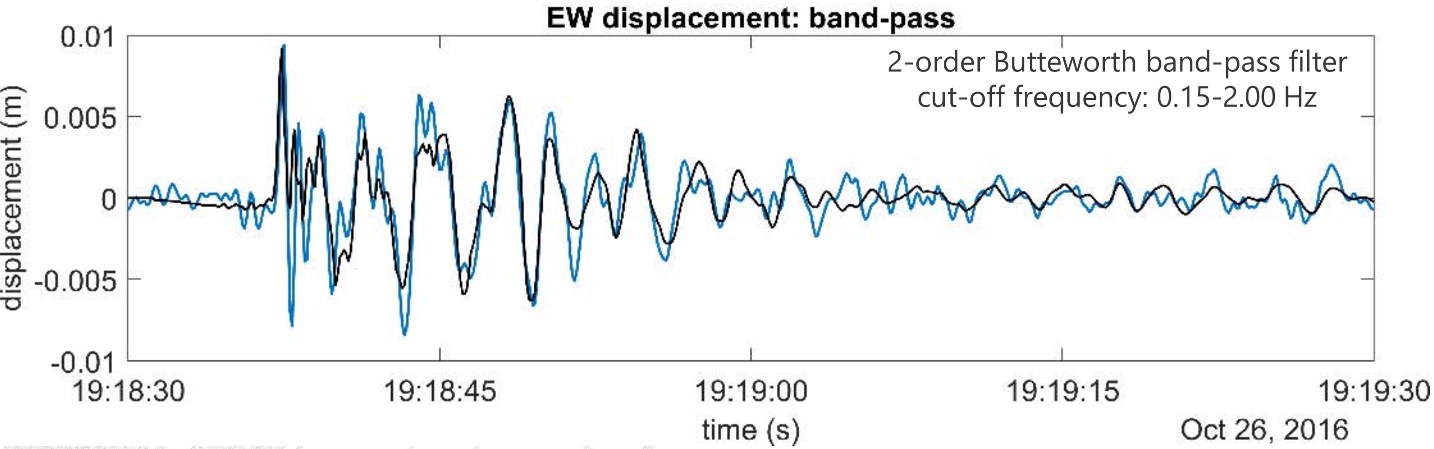
GPS: AMAT (10Hz);
Accelerometer: AMT (200Hz)
EQ Norcia 2016-10-26
19:18:08 UTC, Mw 6.6

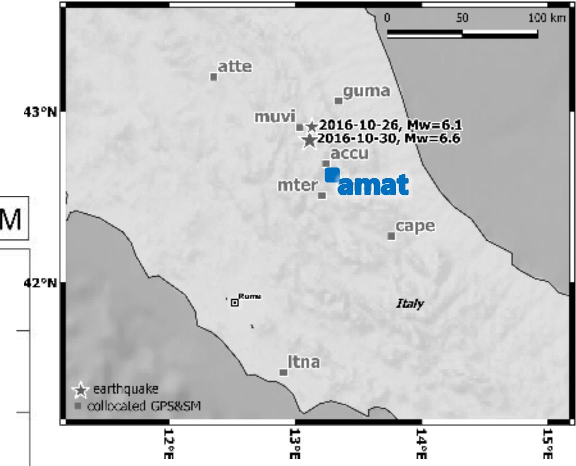
RTKlib 2.4.3
CLK(5sec)+EPH+ERP+DCB

(Kudłacik et al., 2019)

HR-GNSS vs SM -example







GPS: AMAT (10Hz);
Accelerometer: AMT (200Hz)
EQ Norcia 2016-10-26
19:18:08 UTC, Mw 6.6

RTKlib 2.4.3
CLK(5sec)+EPH+ERP+DCB

Correlation coefficient GPS-SM

	-	HPass	BPass
'E'	0.36	0.74	0.80
'N'	0.30	0.65	0.73
'U'	0.30	0.72	0.82

RMS GPS

	-	HPass	BPass
'E'	0.037	0.002	0.002
'N'	0.127	0.002	0.002
'U'	0.207	0.003	0.003

Peak to peak amplitude

	-	HPass	BPass	SM
'E'	0.028	0.022	0.018	0.015
'N'	0.024	0.020	0.017	0.014
'U'	0.041	0.023	0.024	0.018

(Kudłacik et al., 2019)

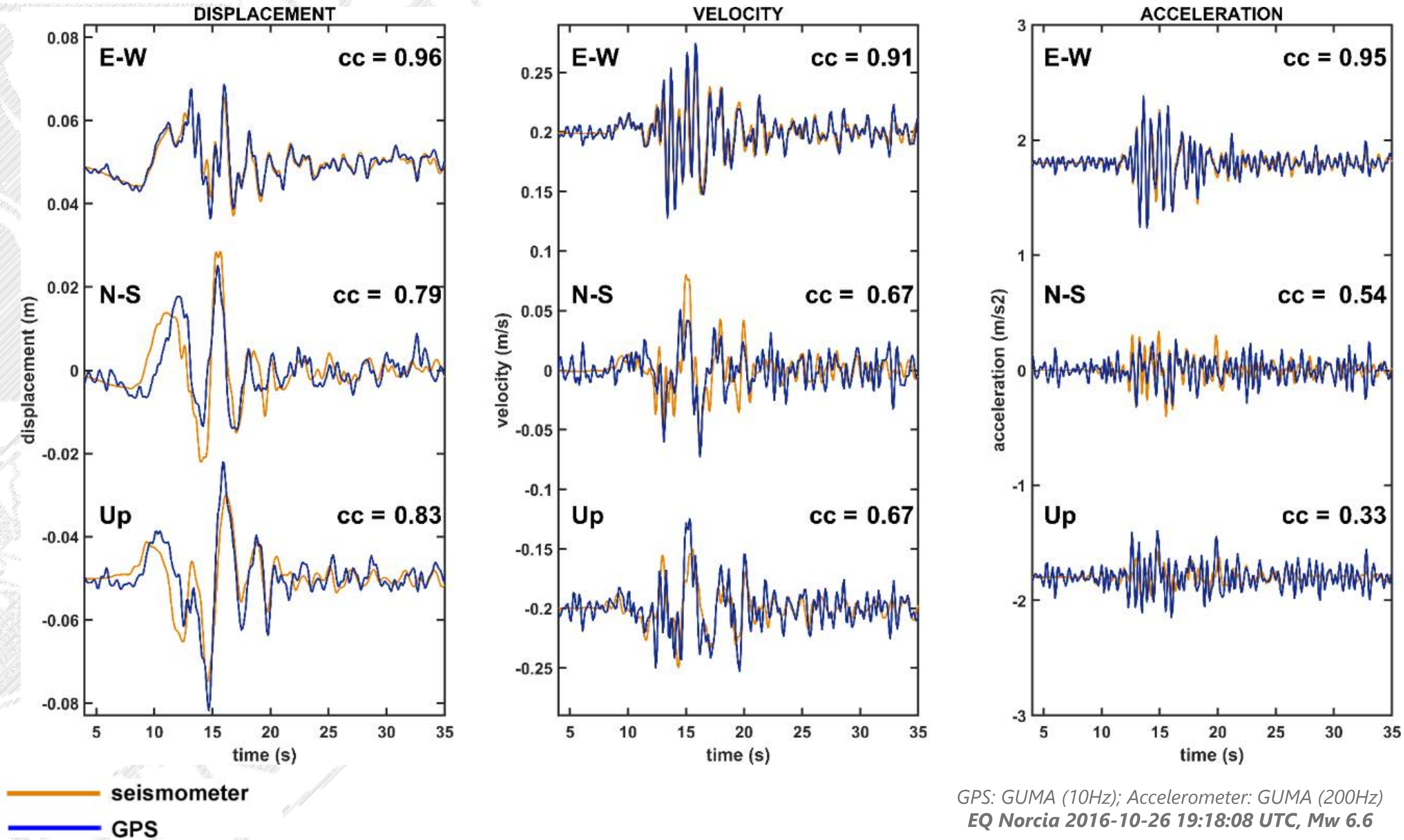
Korelacja szeregów czasowych pozycji HR-GPS i SM

EQ	sensors	distance [km]		cut-off [Hz]		CORRELATION COEFFICIENTS nonfiltered GPS time series			band-pass filtered GPS time series			precentage change		
	GPS/SM	epicentral	GPS/SM	low	high	E	N	U	E	N	U	E	N	U
Gorkha	KKN4/KATN	68.0	10.5	0.03	0.40	0.44	0.34	0.43	**0.70**	**0.87**	**0.96**	38%	**61%**	**55%**
	NAST/KATN	81.7	6.3	0.03	0.40	**0.63**	0.40	0.51	**0.79**	**0.90**	**0.92**	20%	**55%**	45%
Visso	ACCU/ACC	25.4	0.08	0.05	2.00	**0.61**	0.27	0.22	**0.95**	0.39	**0.77**	36%	31%	**72%**
	AMAT/AMT	33.7	0.8	0.15	1.50	**0.73**	0.19	0.67	**0.80**	0.52	**0.78**	8%	**63%**	14%
	GUMA/GUMA	24.0	0.5	0.15	2.00	**0.87**	**0.71**	**0.81**	**0.96**	**0.78**	**0.82**	9%	9%	2%
	MTER/RM33	44.9	0.4	0.15	1.00	0.37	0.20	0.33	**0.80**	0.57	0.49	**54%**	**65%**	32%
Norcia	ACCU/ACC	18.5	0.08	0.05	2.00	**0.82**	0.26	0.57	**0.96**	**0.78**	**0.75**	14%	**67%**	24%
	AMAT/AMT	26.8	0.9	0.10	1.50	**0.72**	0.57	**0.66**	**0.77**	**0.67**	**0.67**	7%	15%	1%
	ATTE/ATTE	74.0	0.4	0.05	1.50	**0.89**	0.23	**0.66**	**0.93**	0.34	**0.67**	4%	33%	1%
	CAPE/CPS	81.8	0.05	0.05	1.00	**0.84**	0.59	0.58	**0.94**	**0.72**	**0.72**	11%	18%	19%
	LTNA/LAT	152.4	0.6	0.05	1.00	**0.96**	**0.82**	0.37	**0.99**	**0.90**	0.40	3%	8%	8%
	MUVI/T1216	10.2	2.1	0.05	1.00	**0.62**	0.40	0.31	**0.84**	0.60	0.59	26%	33%	47%

Mean correlation coefficient: 0.55 → 0.75 +27%

HR-GPS/SM displacement, velocity, acceleration comparison

2-order Butterworth band-pass filter
cut-off frequency: 0.05-2.00 Hz



GPS: GUMA (10Hz); Accelerometer: GUMA (200Hz)
EQ Norcia 2016-10-26 19:18:08 UTC, Mw 6.6

(Kudłacik et al., 2019)

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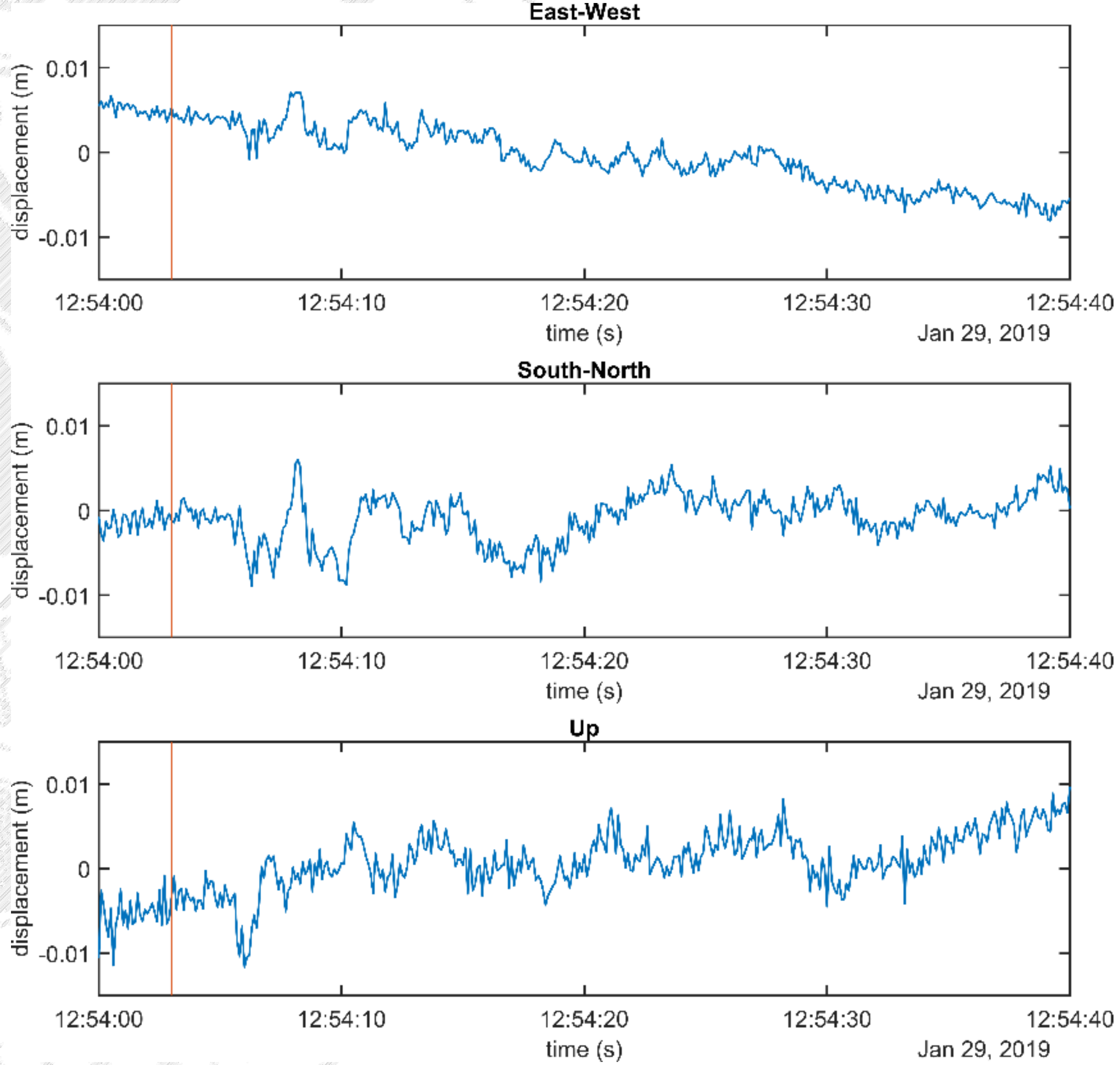
The application of HR-GNSS in mining tremor analysis

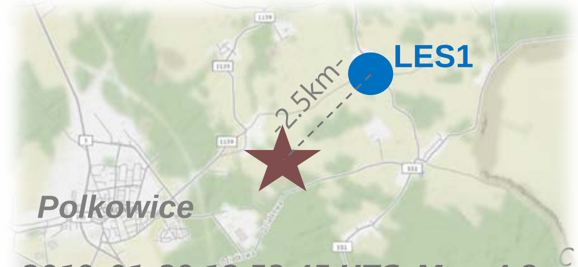
Mining tremor analysis with HR-GNSS

2019-01-29 12:53:45 UTC Mw=4.8
Legnica-Glogow Copper District

Nonfiltered displacements; GNSS station: LES1



Mining tremor analysis with HR-GNSS

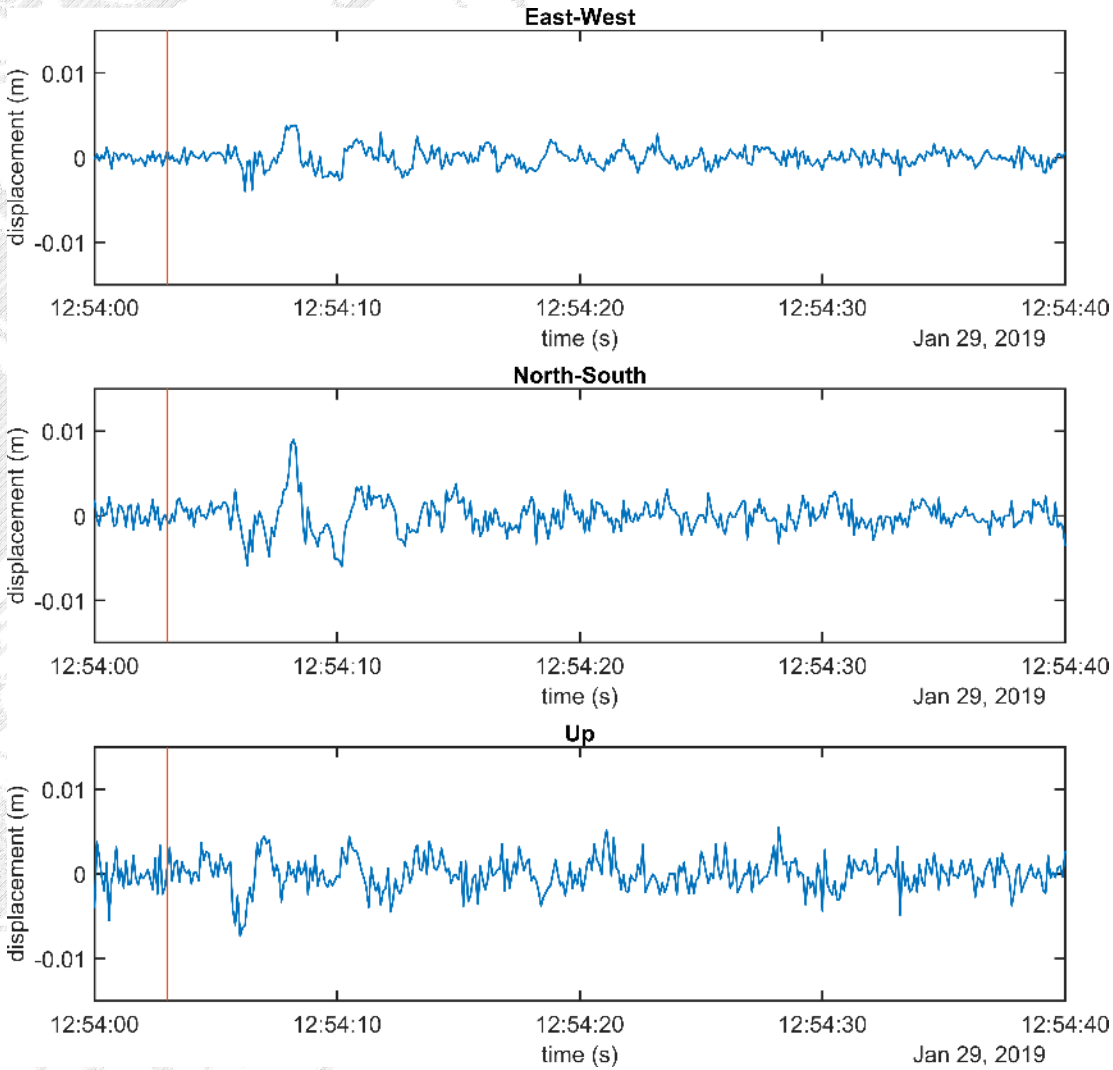


2019-01-29 12:53:45 UTC Mw=4.8

Legnica-Glogow Copper District

High-pass filtered displacements; GNSS station: LES1

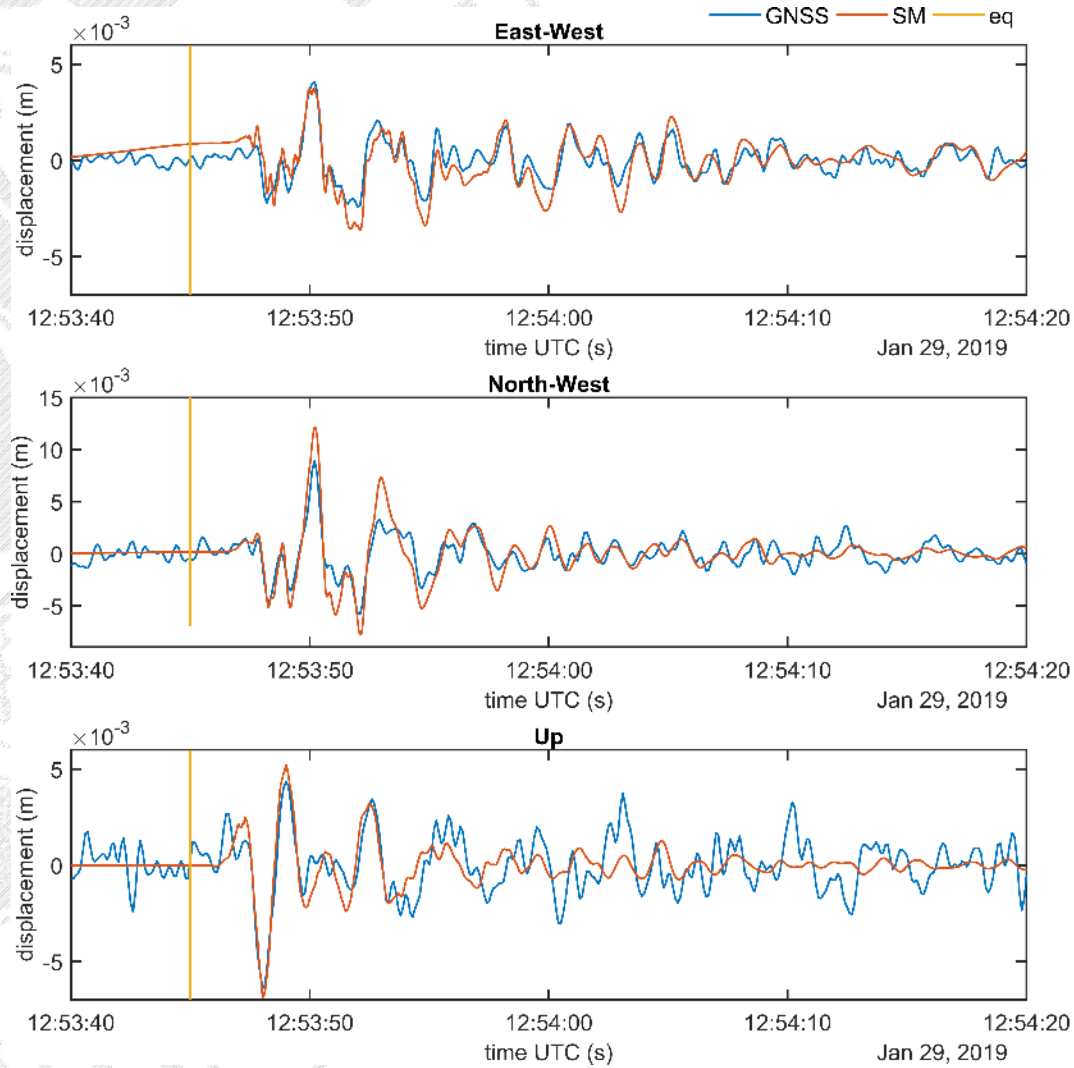
cut-off frequency: 0.17 Hz



Mining tremor analysis with HR-GNSS

Band-pass filtered displacements; GNSS station: LES1

cut-off frequency: 0.17-2.00 Hz



2019-01-29 12:53:45 UTC Mw=4.8

Legnica-Glogow Copper District

correlation coefficient	
'E'	0.82
'N'	0.86
'U'	0.65

	maxSM	minSM	maxGNSS	minGNSS
'E'	0.004	-0.004	0.004	-0.002
'N'	0.012	-0.008	0.009	-0.006
'U'	0.005	-0.007	0.004	-0.006

max-min difference	SM	GNSS
'E'	0.007	0.007
'N'	0.020	0.015
'U'	0.012	0.011

Future plans

- To continue the work on eliminating HR-GNSS errors to increase the precision of displacement time series

- To continue frequency analysis of time series of positions obtained from HR-GNSS

- To optimize of HR-GNSS data processing and determine the integration capabilities of HR-GNSS and seismological data to study small and medium natural and anthropogenic seismic events.