Synchronization of Long-Term OBS Seismic Recordings: the NEAREST Experiment

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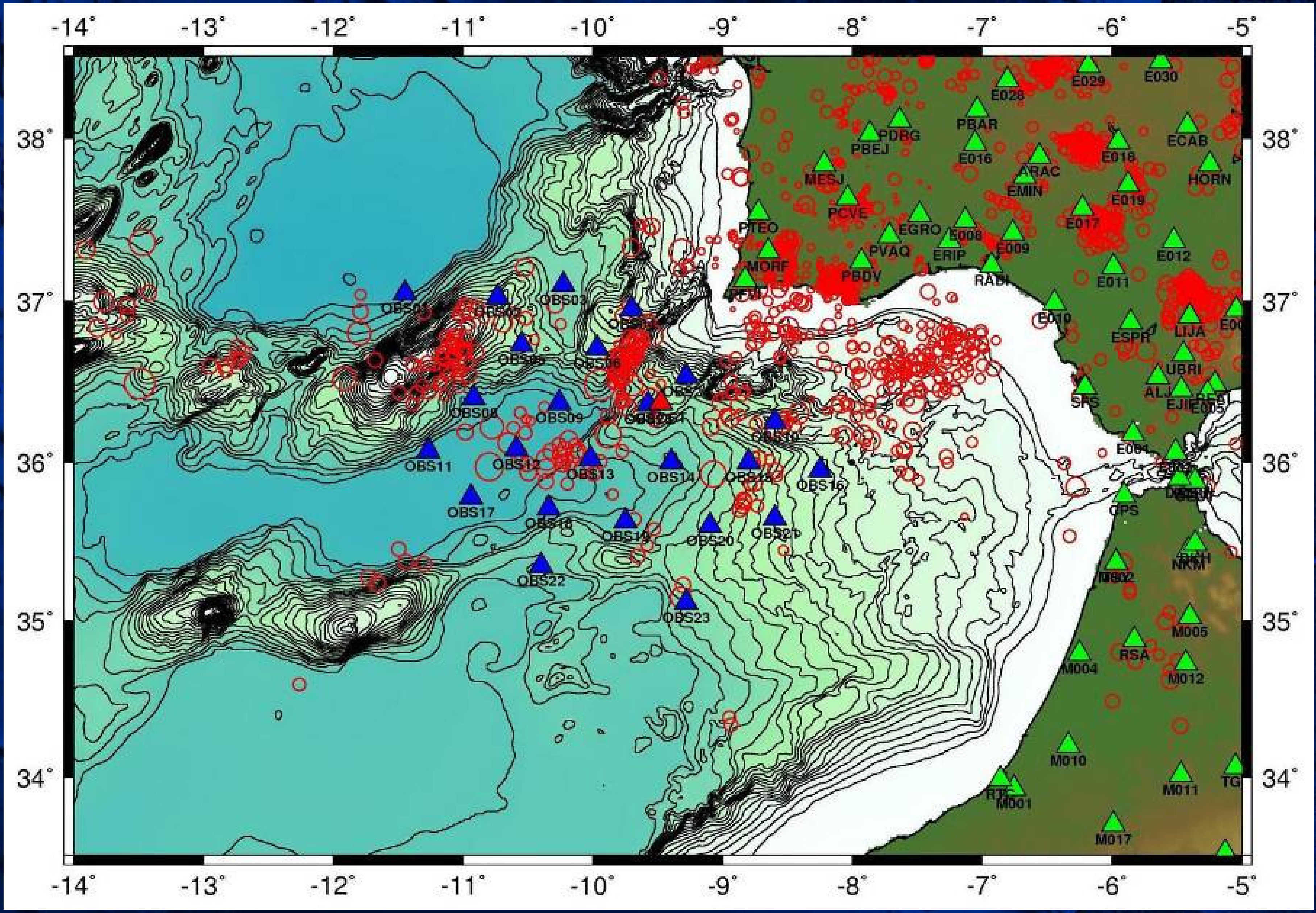
The NEAREST Passive Seismic Experiment

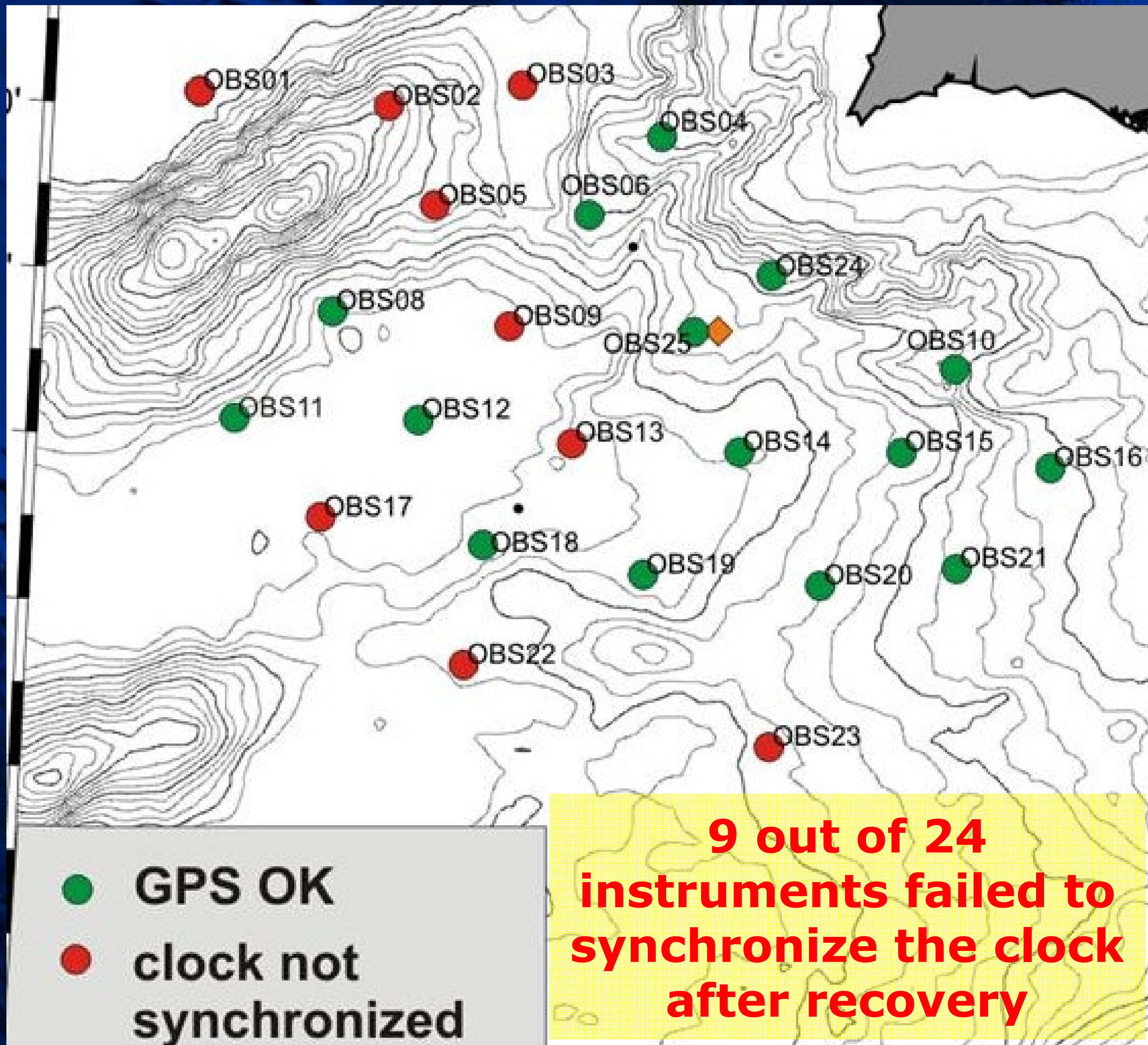


Levelling of seismometers

		2007									2008														
		02/aug	01/sep	02/sep	01/oct	02/oct	01/nov	02/nov	01/dec	02/dec	01/jan	02/jan	01/feb	02/feb	01/mar	02/mar	01/apr	02/apr	01/may	02/may	01/jun	02/jun	01/jul	02/jul	01/aug
OBS 1	s	x																							
OBS 2	s	xz					z	xz	z				yz												
OBS 3	s	x																							
OBS 4		xyz																							
OBS 5	s	x																							
OBS 6		x																							
OBS 7																									
OBS 8		x																							
OBS 9	s	x																							
OBS 10																									
OBS 11		xz																							
OBS 12																									
OBS 13	s	x																							
OBS 14		x																							
OBS 15		y																							
OBS 16																									
OBS 17	s	x																							
OBS 18																									
OBS 19																									
OBS 20																									
OBS 21																									
OBS 22	s	x																							
OBS 23	s	x																							
OBS 24																									
OBS 25																									

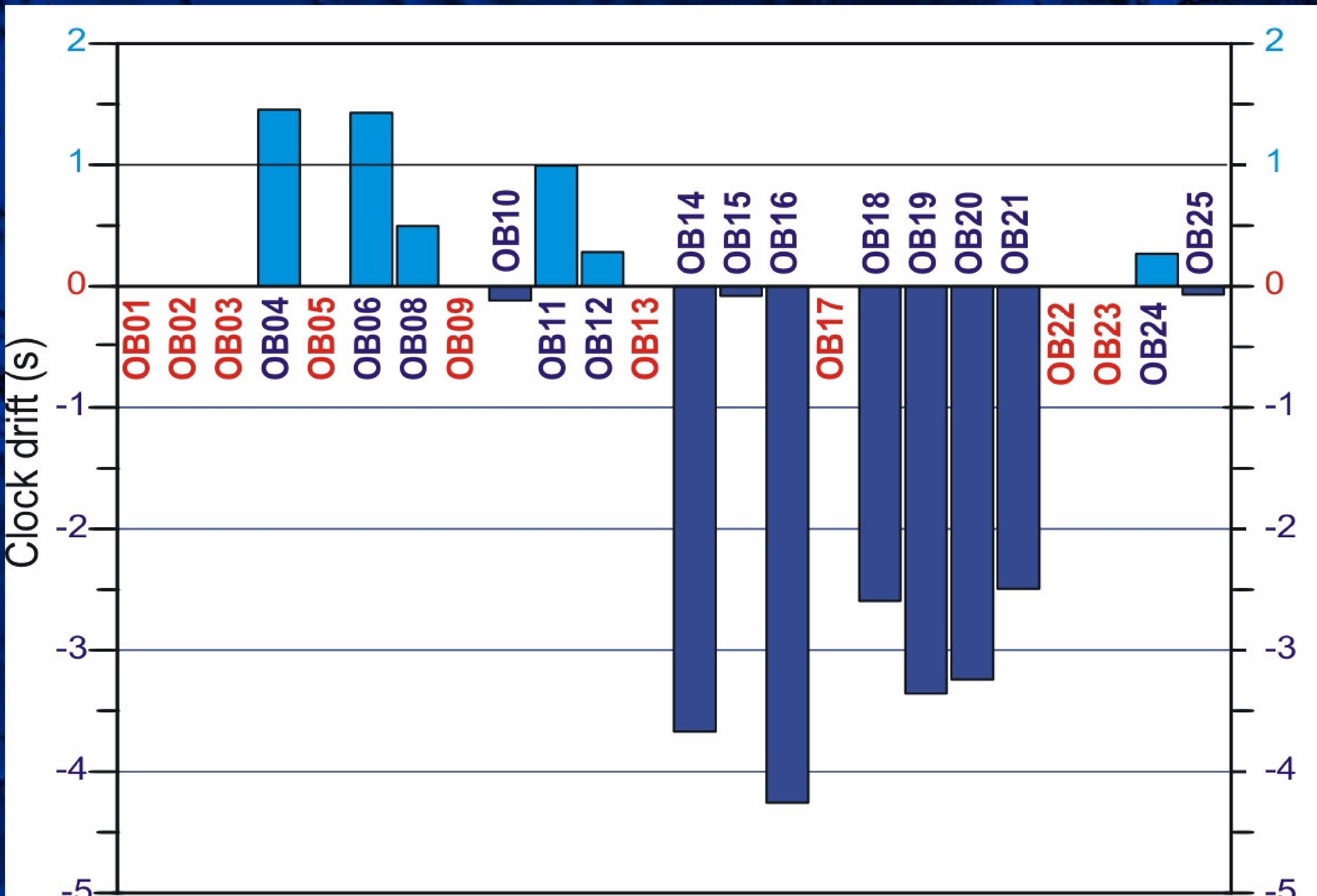
(green)	everything okay	OBS 1	battery low
(yellow)	1 comp. Dead	OBS 4	time okay,stop by END
(red)	2 comp. Dead	OBS 4	time okay, disk full
(dark red)	3 comp. Dead	s:	not synchronized

Clock synchronization



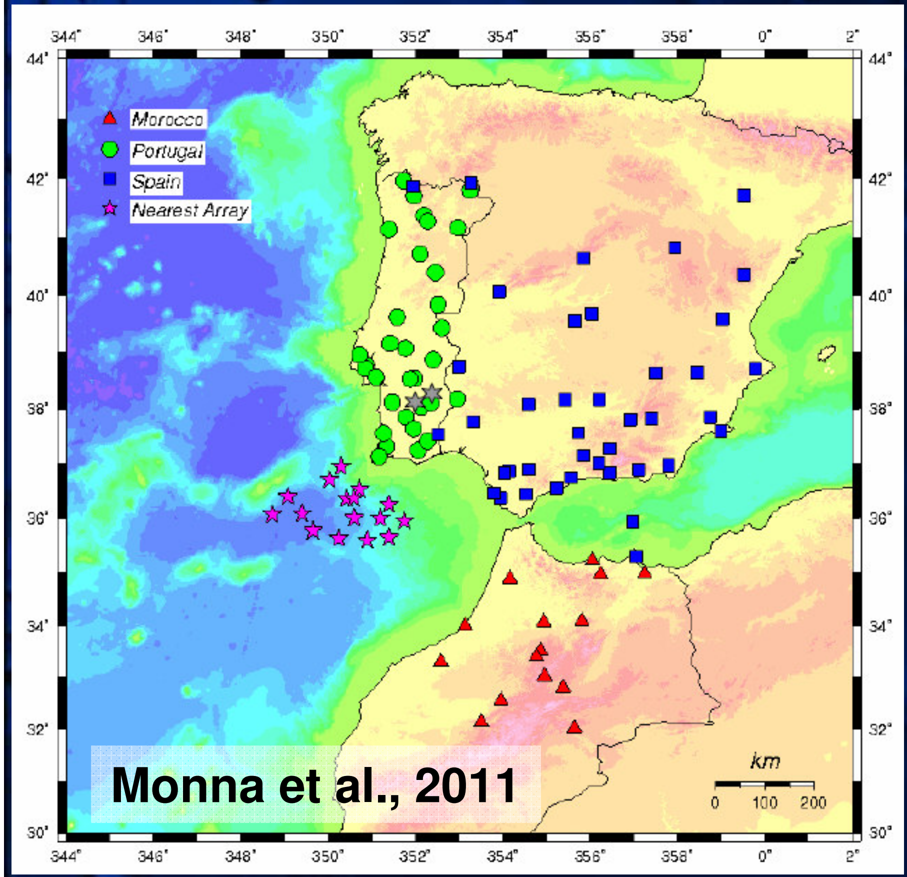
9 out of 24 instruments failed to synchronize the clock after recovery

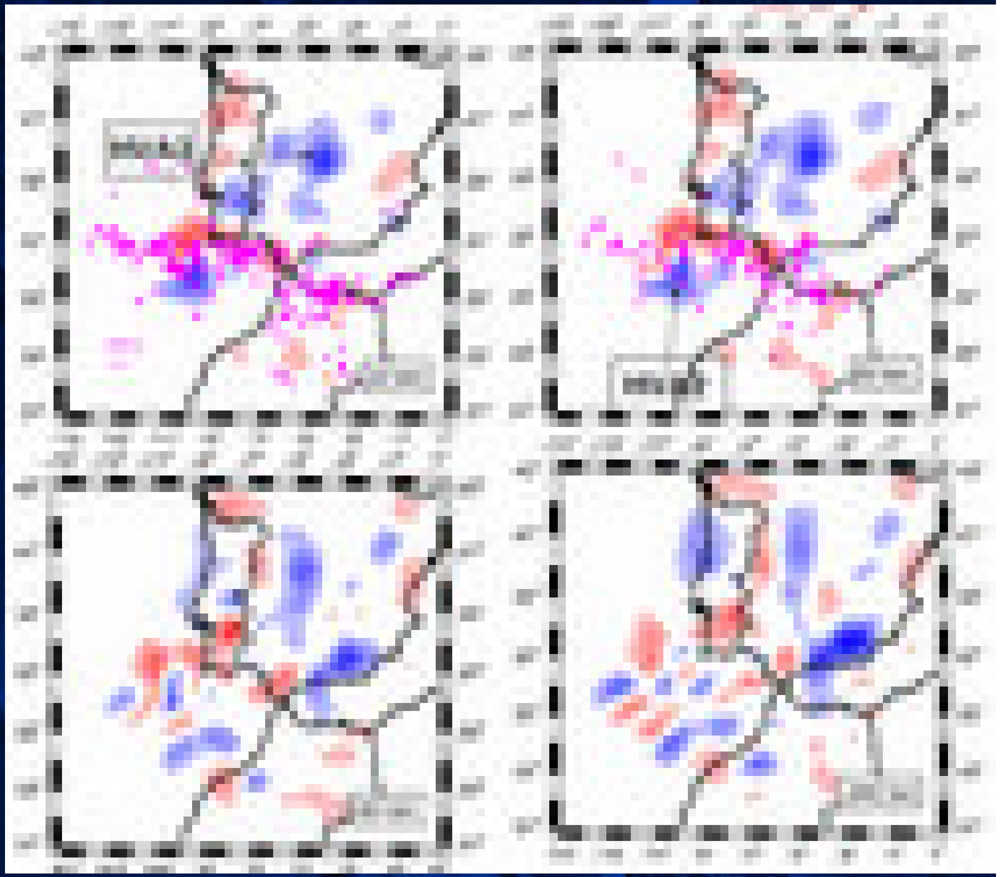
Clock synchronization

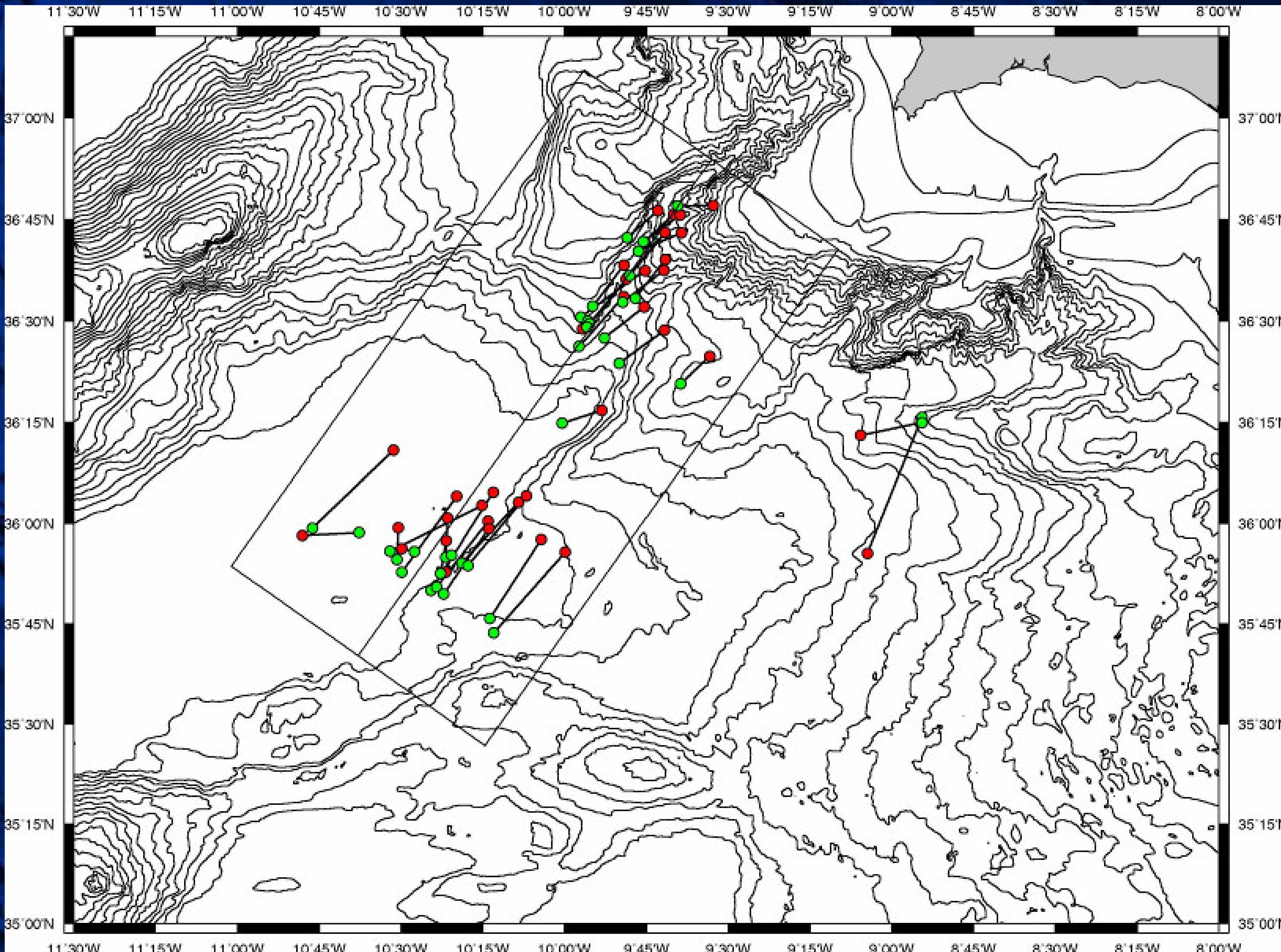


Task: Estimate Time Drift Corrections for the unsynchronized instruments

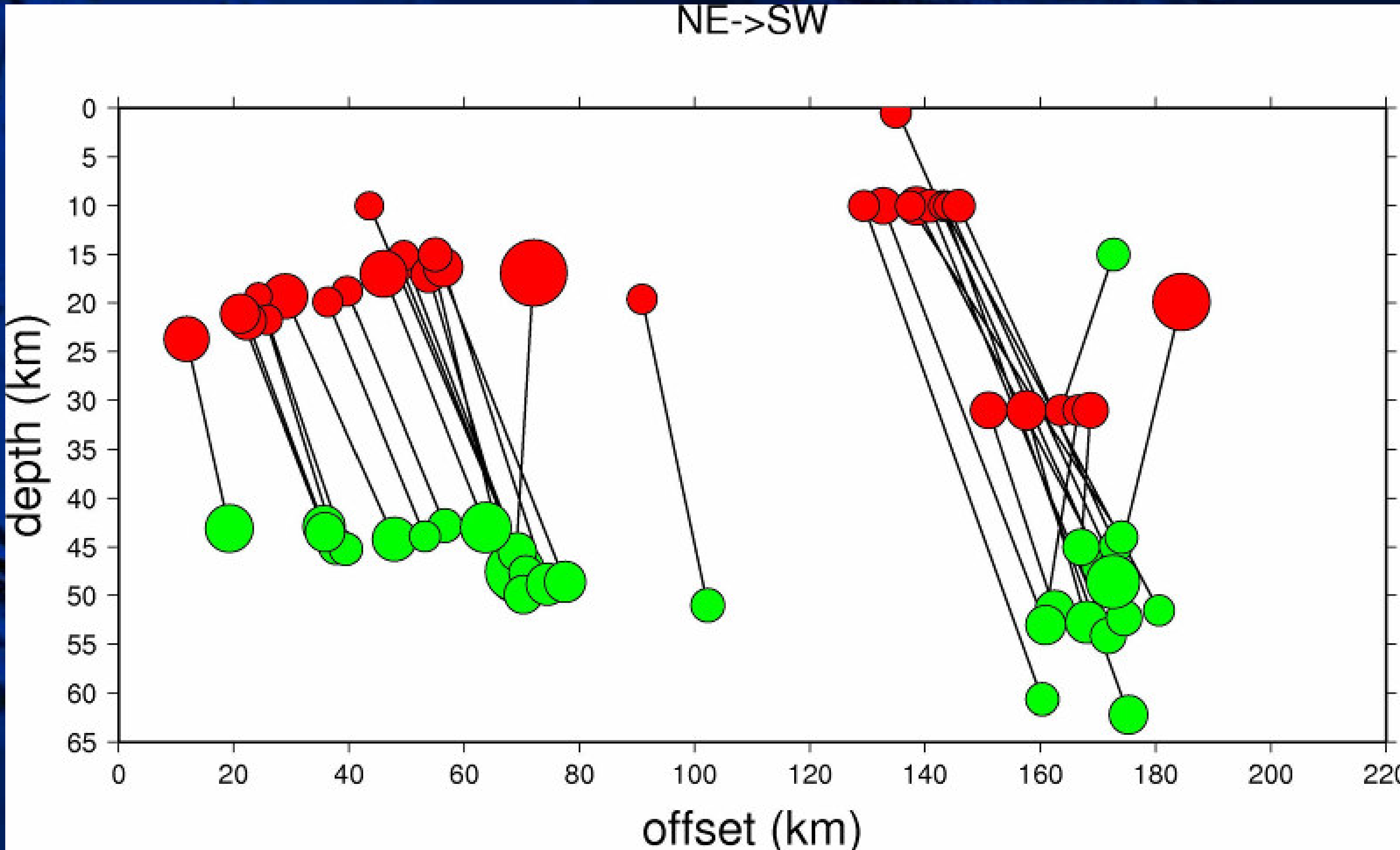
Target: at least 0.1s precision for local, regional and tele-seismic earthquake studies, integrating also land recordings







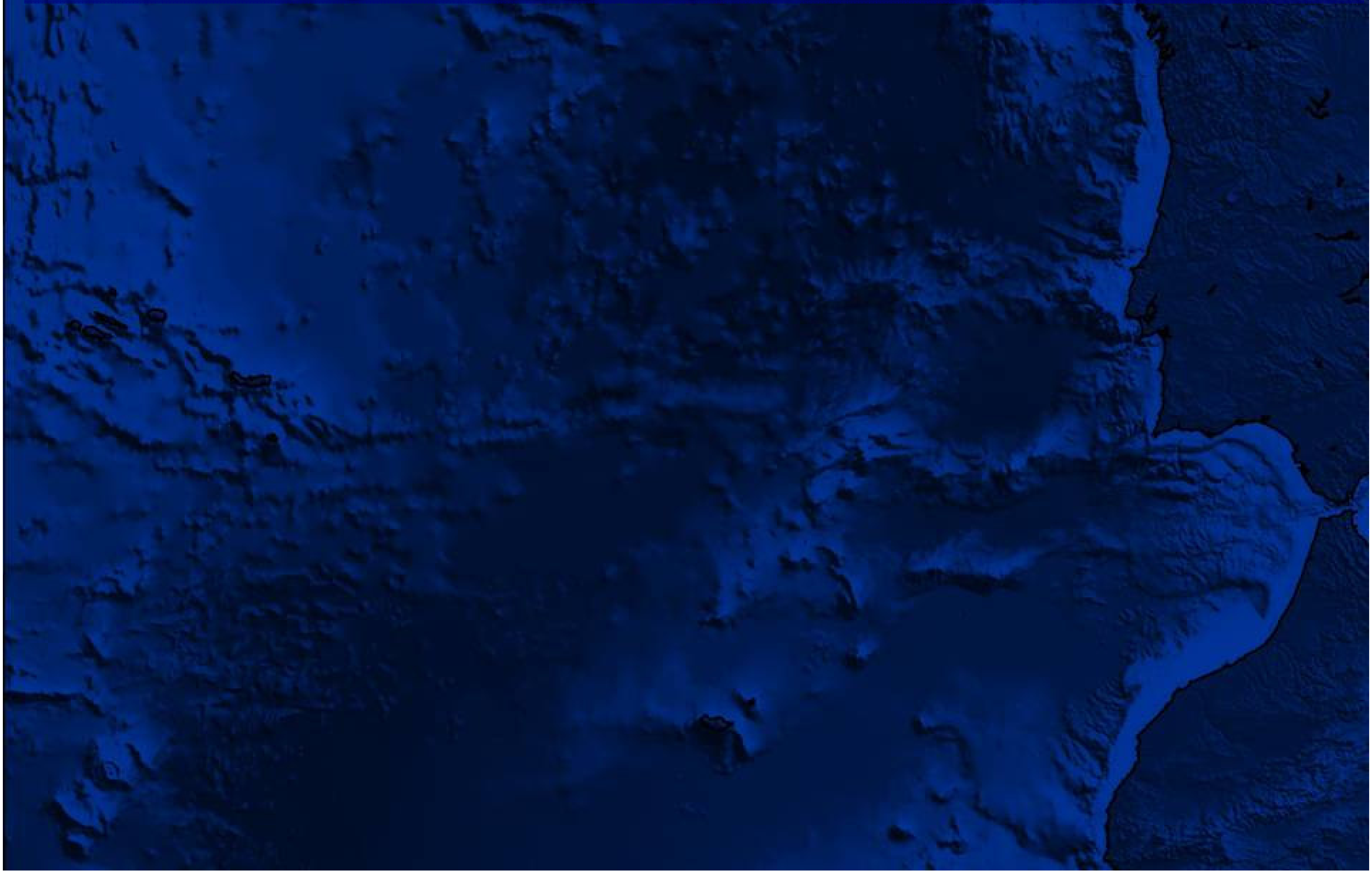
Comparison of land locations (in red) with OBS locations (in green)

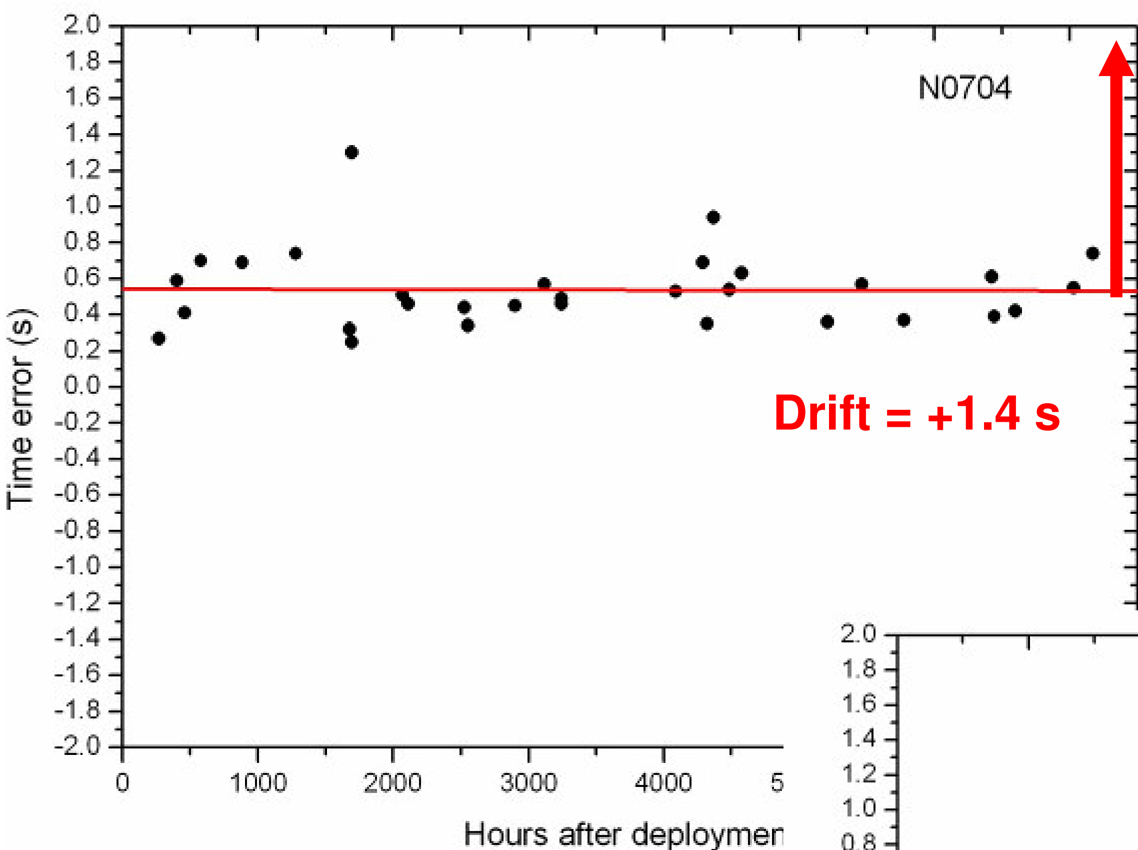


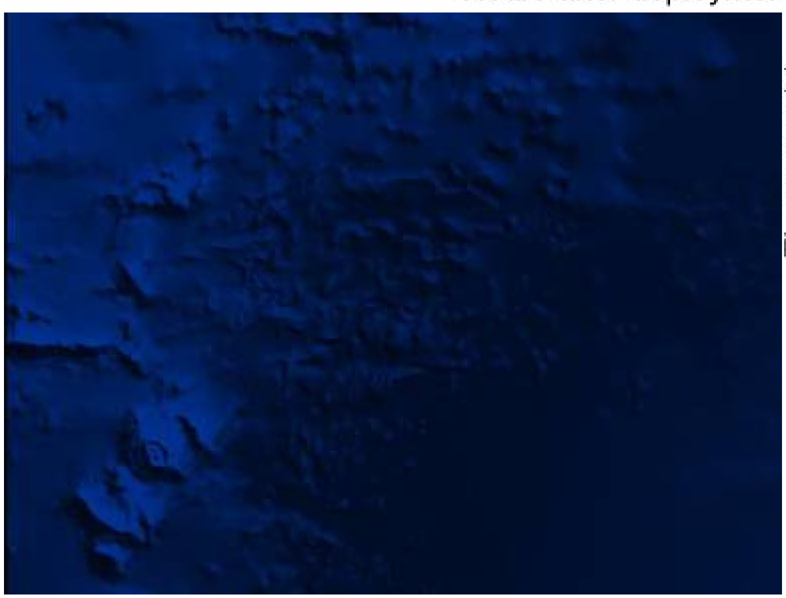
Comparison of land locations (in red) with OBS locations (in green)

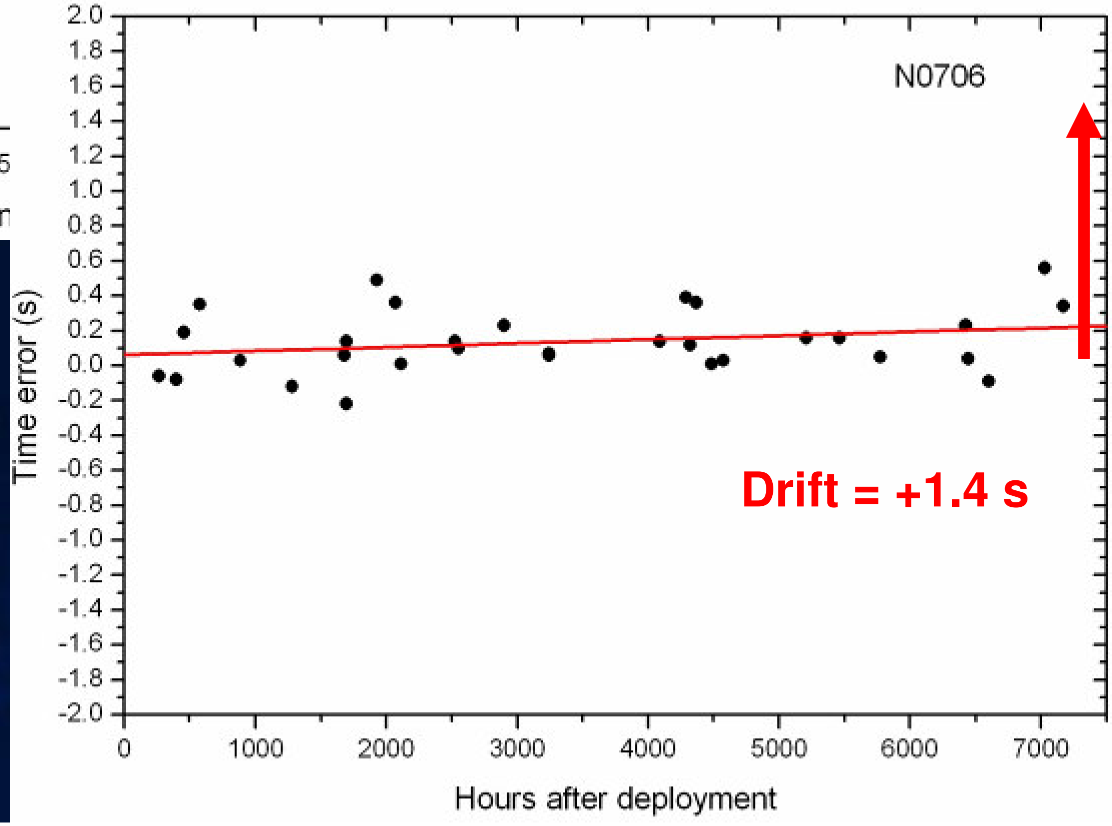
Purpose: train the land network to locate the Gulf of Cadiz earthquakes, epicenter and focal depth

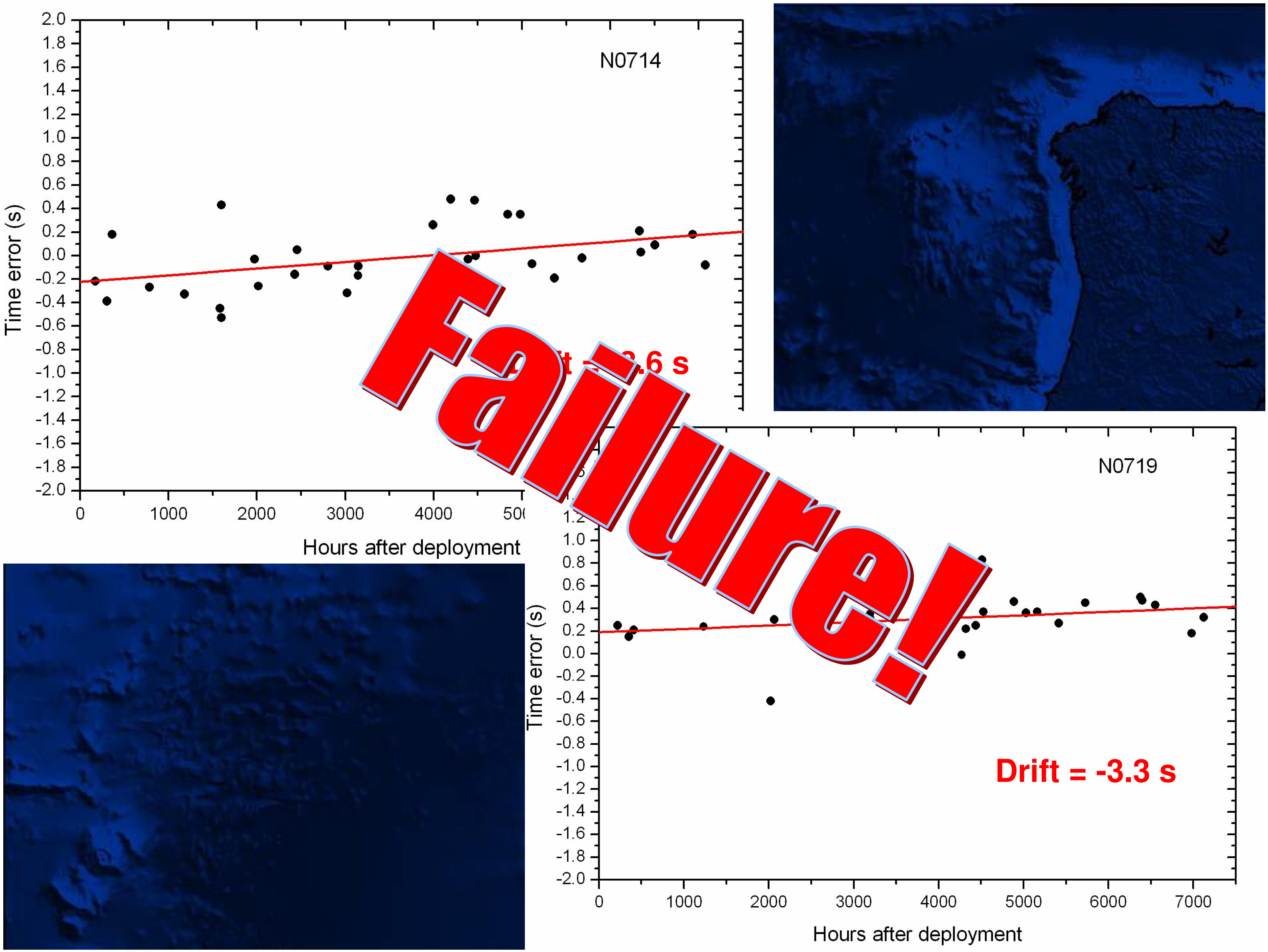
Trial 1: Use a small set of the largest events and check the variation in P-phase station errors



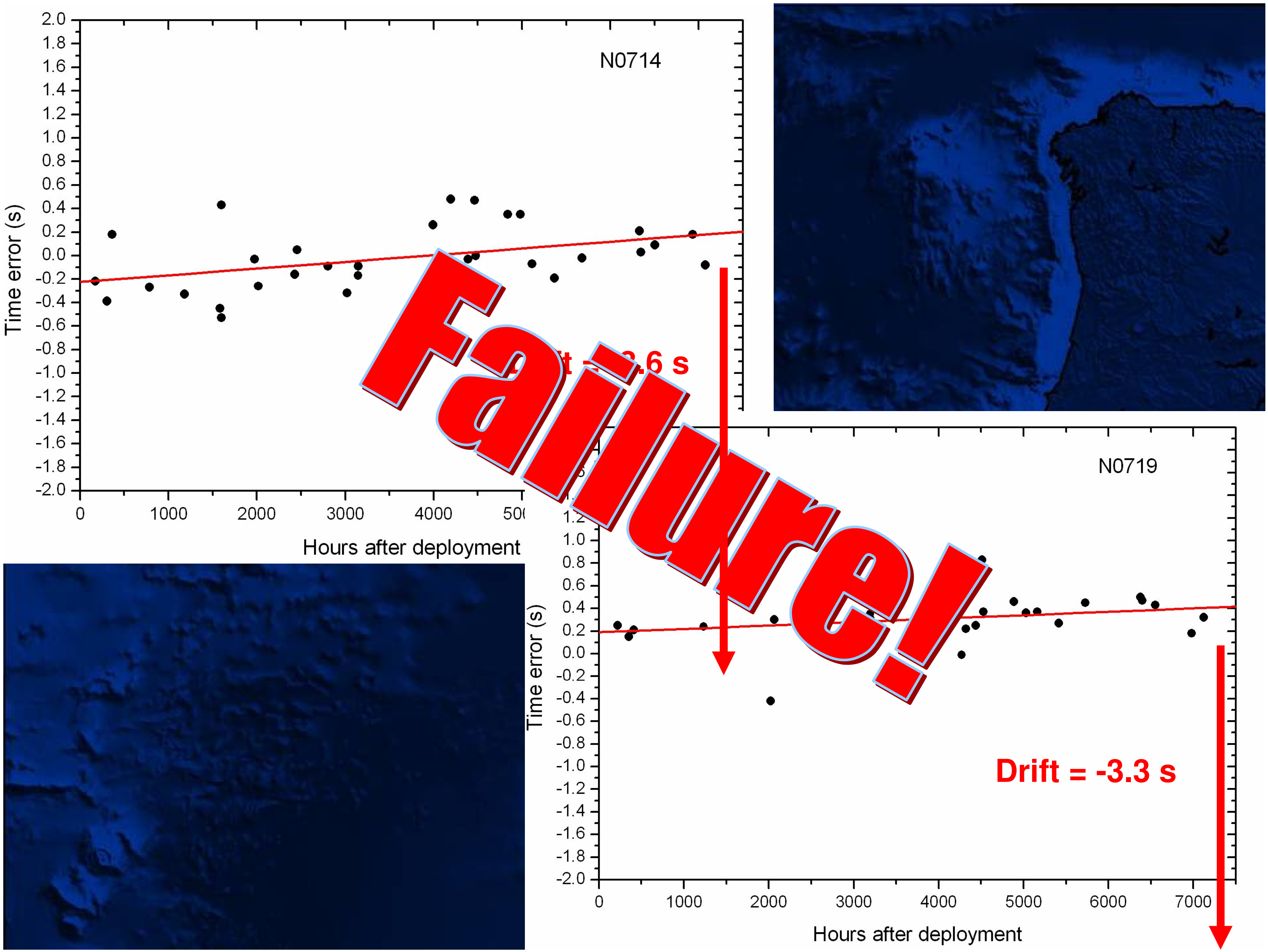

N0704
Time error (s)
Hours after deploymen
Drift = +1.4 s




N0706
Time error (s)
Hours after deployment
Drift = +1.4 s



N0714
Time error (s)
Hours after deployment
N0719
Time error (s)
Hours after deployment
Drift = -3.3 s
Failure!


N0714
Time error (s)
Hours after deployment
N0719
Time error (s)
Hours after deployment
Drift = -3.3 s
Failure!

Trial 2: Use Noise Correlation functions to estimate relative drifts between all clocks

Building the Noise Correlation Functions NCF

Decimation to 10 Hz

↓

Band-Pass Filter 4s to 12s

↓

1 bit Normalization

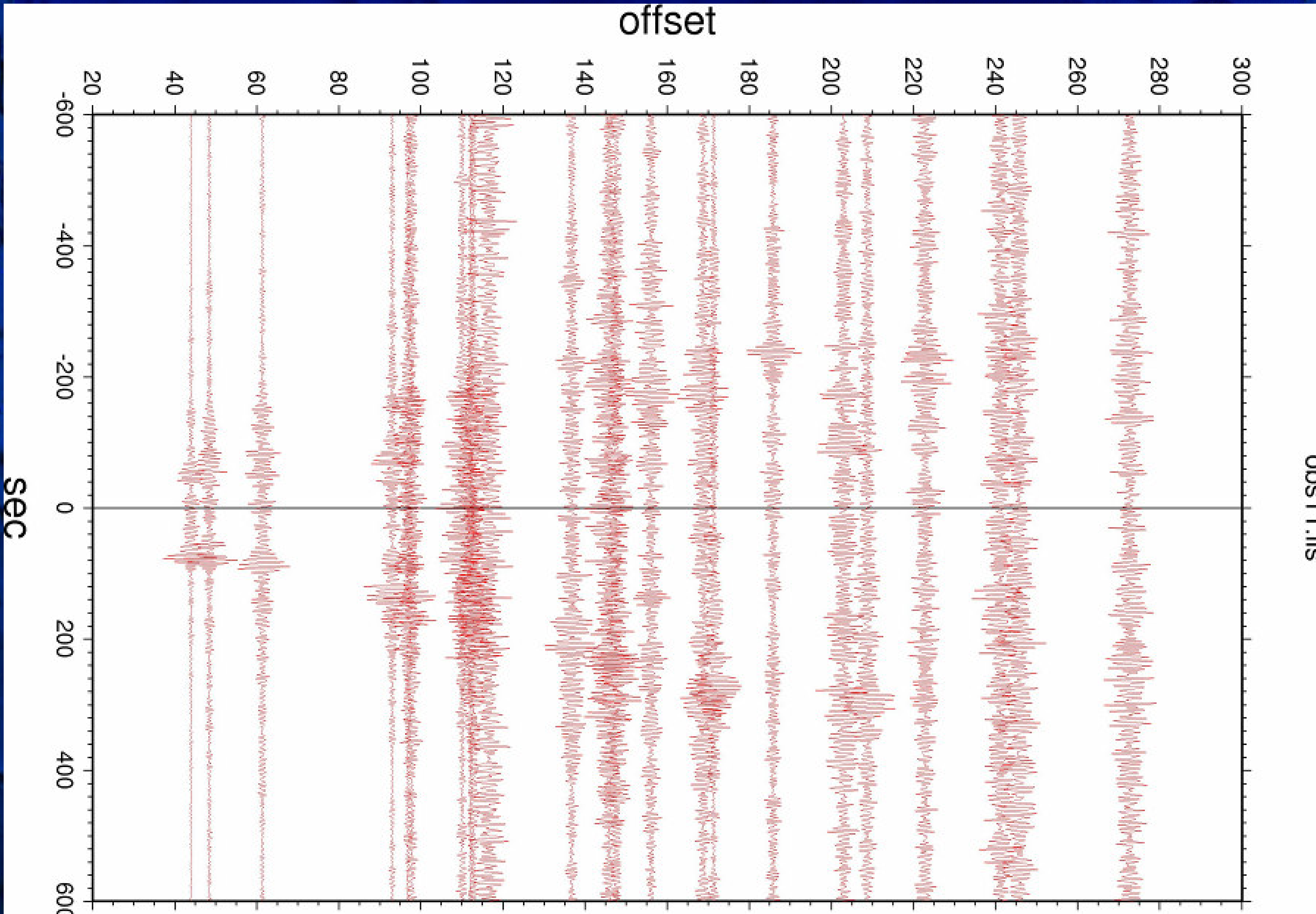
↓

Cross-Correlation

↓

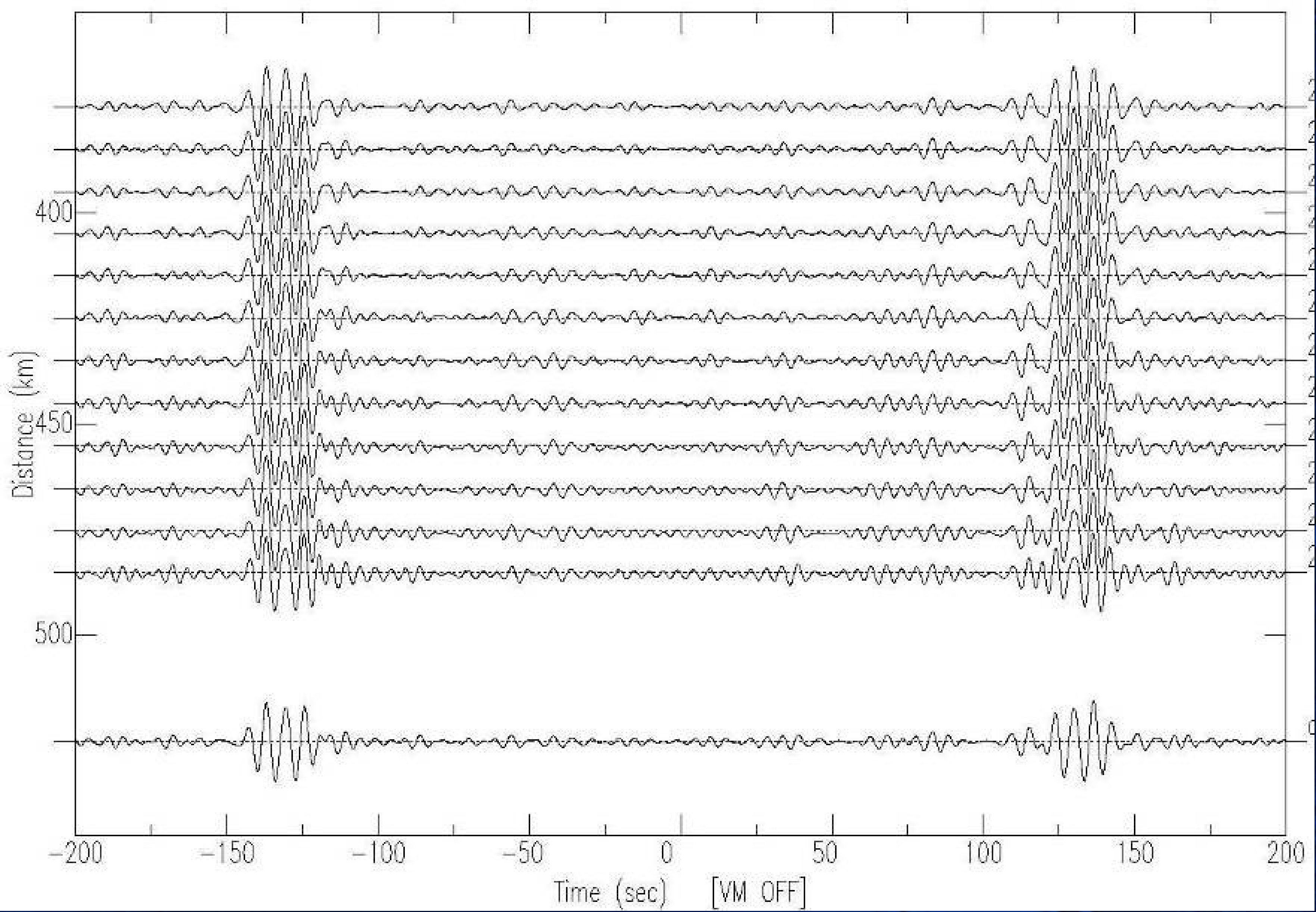
Stack

All NCF for OBS11

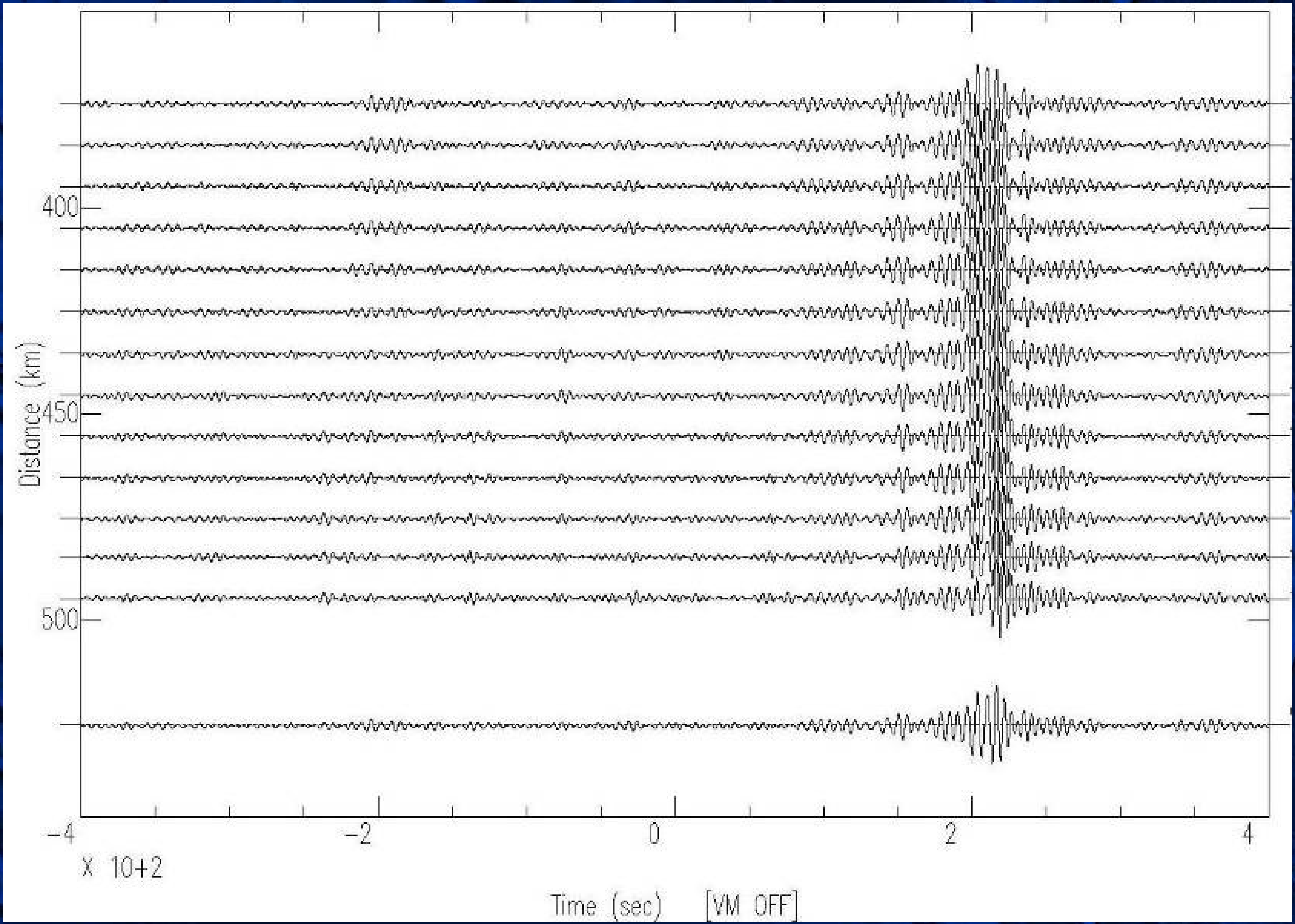


Time evolution of NCF OBS04-OBS05

90 day stack, every 10 days

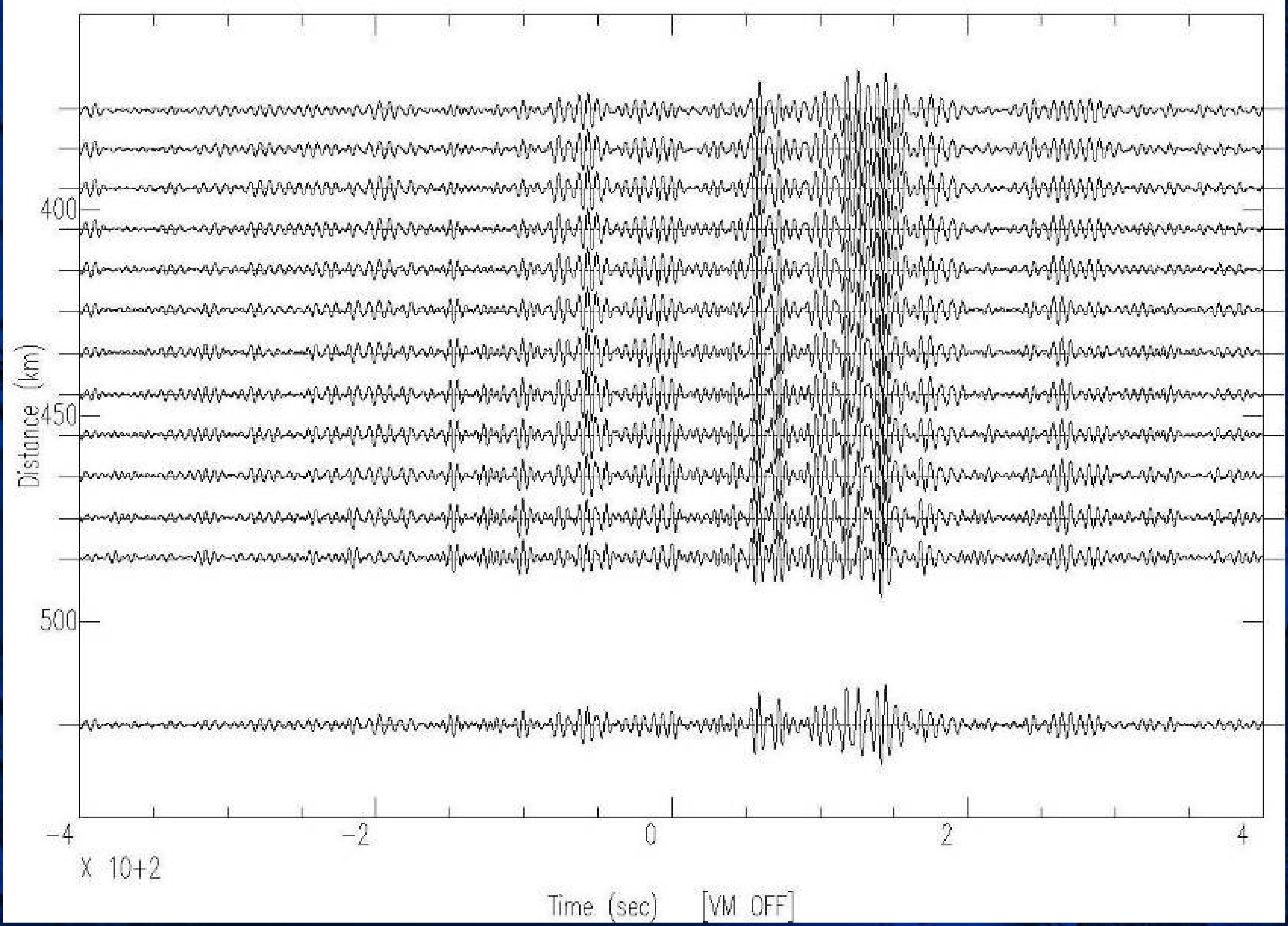


Time evolution of NCF OBS04-OBS12
90 day stack, every 10 days



Time evolution of NCF OBS05-OBS12

90 day stack, every 10 days



Estimating Clock Drift from NCF

$$\delta\tau_{ij}(t) = D_{ij}(t) + \varphi(t) + \varepsilon_{ij}(t)$$

$\delta\tau_{ij}$ — **Variation of surface wave travel time measured on the NCF**

$D_{ij}(t)$ — **Time delay caused by a relative drift of the two station clocks**

$\varepsilon_{ij}(t)$ — **time-shift due to a change in the spatial distribution of the source**

$\varphi(t)$ — **time-shift due to a change in the medium**

Stehly et al., 2007

Estimating Clock Drift from NCF

$$\frac{\delta\tau_{ij}(t)+\delta\tau_{ij}(-t)}{2}=D_{ij}(t)+\frac{\varepsilon_{ij}(t)+\varepsilon_{ij}(-t)}{2}$$

$$\frac{\delta\tau_{ij}(t)-\delta\tau_{ij}(-t)}{2}=\varphi(t)+\frac{\varepsilon_{ij}(t)-\varepsilon_{ij}(-t)}{2}$$

Clock Drift is anti-symmetric

Material properties are symmetric

Change in source distribution is unknown, estimated to decrease with longer time series

Stehly et al., 2007

Estimating Clock Drift from NCF

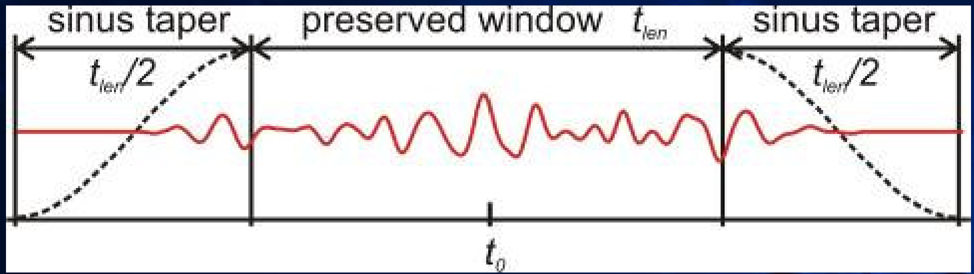
Clock Drift is linear with time

$$D_{ij}(t) = \alpha_{ij}\, t$$

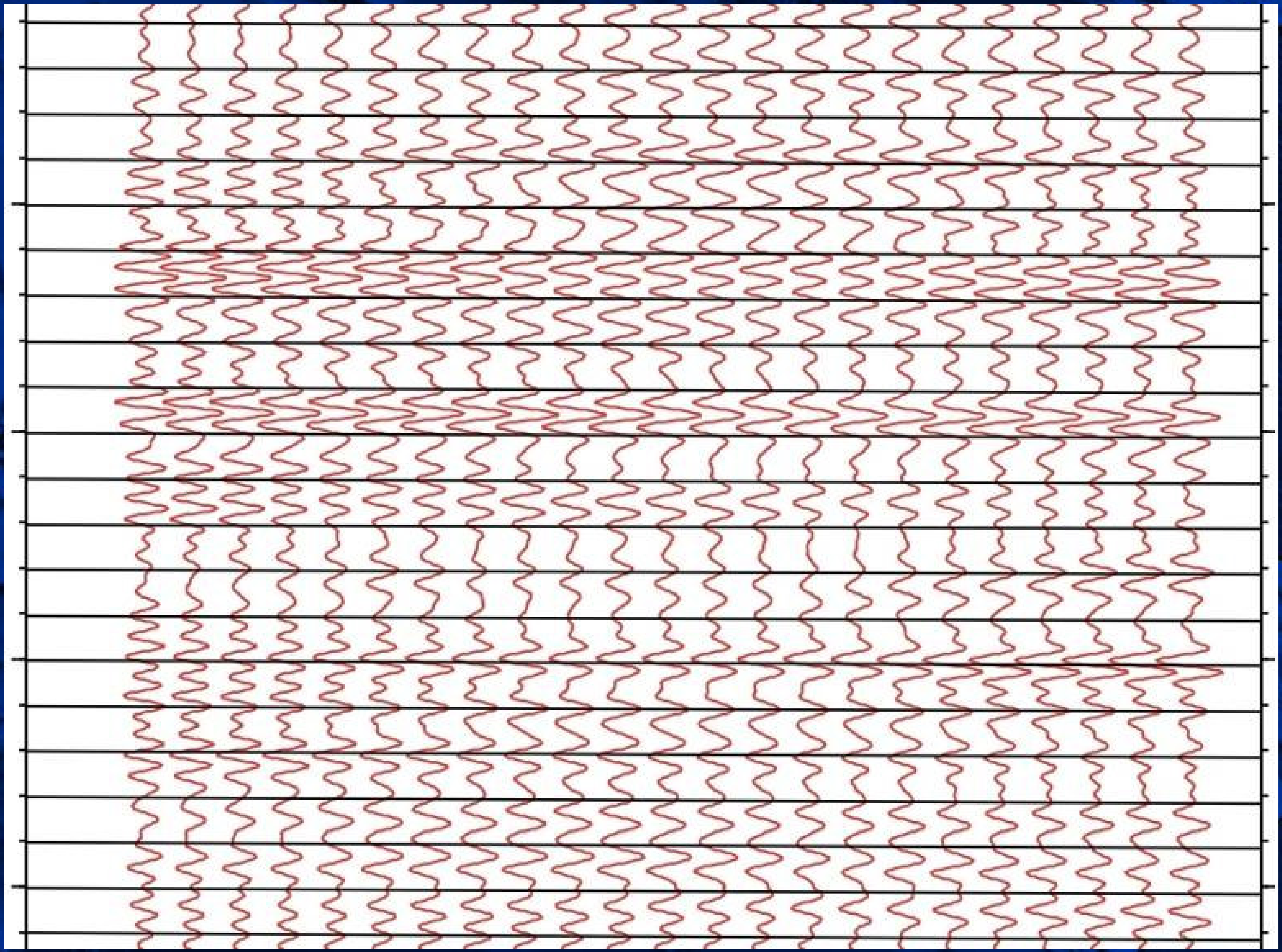
Material properties and source distribution changes are NOT linear with time

$$\delta\tau_{ij}(t) = D_{ij}(t) = \alpha_{ij}\, t$$

Linear trends computed by cross-correlation



Linear trends computed for the pair OBS11-OBS22



49 useful slopes -> drift = 1.91 ± 0.26 s/year

Estimating Clock Drift from NCF

α_{j0} Is the drift of clock j in relation to reference

$$\alpha_{j0} - \alpha_{i0} = \alpha_{ij} \pm s_{ij} \qquad i = 1,23 \quad j = i + 1,24$$

Gives a maximum of 276 equations for 24 unknowns

Solution of over-determined system by SVD

Absolute drift is estimated imposing one set of reference clocks

$$\alpha_{i0} = 0 \pm 0.05\ s / year \qquad i = 10\ ,15\ ,25$$

Results

Table 3 – Observed and computed clock drift values in seconds per year (s/year). All possible equations were used. $\chi_N^{\ 2} = 3.90$

OBS	Drift	α_{i0}	$\pm s$	OBS	Drift	α_{i0}	$\pm s$
obs01	--.—	0.70	0.16	obs14	-3.89	0.55	0.13
obs02	--.—	--.—	--.—	obs15	-0.09	0.02	0.05
obs03	--.—	0.78	0.14	obs16	-4.56	-0.73	0.12
obs04	1.53	0.41	0.10	obs17	--.—	-0.62	0.12
obs05	--.—	-0.08	0.13	obs18	-2.77	-0.25	0.12
obs06	1.50	0.54	0.13	obs19	-3.58	0.55	0.12
obs08	0.52	0.59	0.14	obs20	-3.46	0.57	0.11
obs09	--.—	-0.33	0.13	obs21	-2.67	1.48	0.11
obs10	-0.12	-0.01	0.05	obs22	--.—	0.91	0.11
obs11	1.05	0.96	0.14	obs23	--.—	-0.72	0.15
obs12	0.30	-0.75	0.13	obs24	0.37	0.42	0.15
obs13	--.—	0.76	0.12	obs25	-0.10	-0.01	0.05

Results

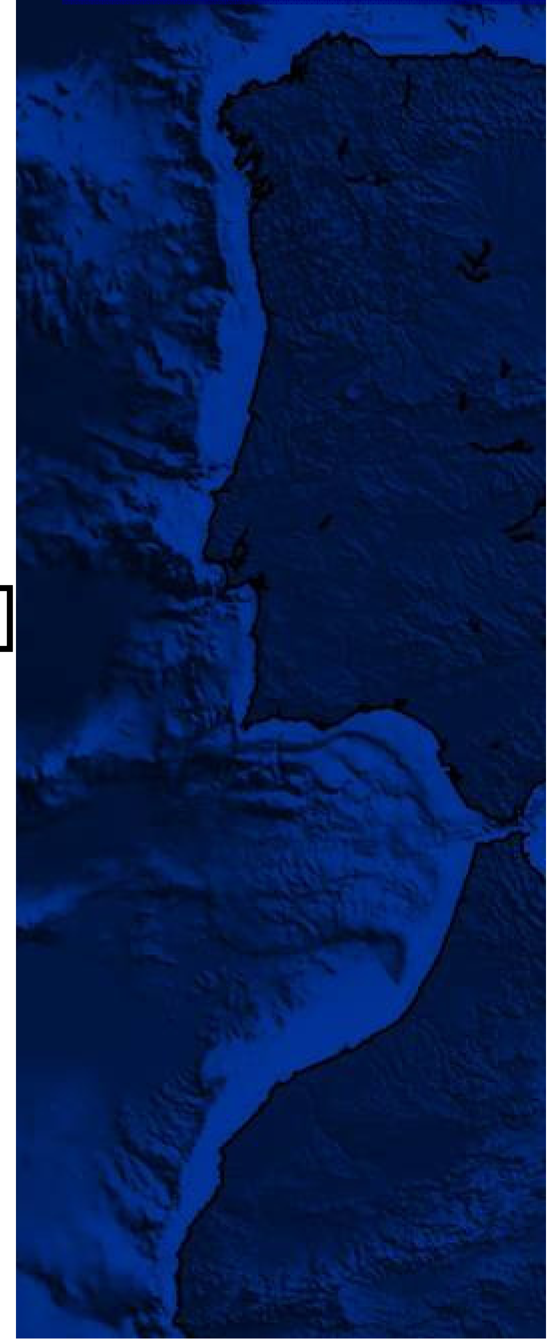


Table 5 – Computed clock drift values in seconds per year (s/year) for two different data sets and 3 selection choices.

	All instruments						**Good instruments only**					
	Selection (i)		Selection (ii)		Selection (iii)		Selection (i)		Selection (ii)		Selection (iii)	
χ_N^2	**1.84**		**0.34**		**0.52**		**1.23**		**0.21**		**0.31**	
OBS	α_{i0}	$\pm s$	α_{i0}	$\pm s$	α_{i0}	$\pm s$	α_{i0}	$\pm s$	α_{i0}	$\pm s$	α_{i0}	$\pm s$
obs01	0.66	0.27	0.78	1.07	0.78	0.43	*	*	*	*	*	*
obs03	0.67	0.16	0.72	0.23	0.75	0.19	*	*	*	*	*	*
obs04	0.29	0.12	0.34	0.19	0.41	0.17	0.13	0.14	0.37	0.25	0.41	0.23
obs05	-0.16	0.15	-0.22	0.24	-0.11	0.18	*	*	*	*	*	*
obs06	0.44	0.15	0.45	0.20	0.49	0.18	0.51	0.18	0.49	0.26	0.52	0.24
obs08	0.45	0.16	0.50	0.19	0.53	0.18	0.53	0.24	0.58	0.28	0.62	0.27
obs09	-0.43	0.14	-0.38	0.20	-0.37	0.17	*	*	*	*	*	*
obs10	0.00	0.05	0.00	0.05	0.00	0.05	0.00	0.05	0.00	0.05	0.00	0.05
obs11	0.83	0.16	0.87	0.25	0.94	0.20	0.82	0.26	0.92	0.48	0.92	0.42
obs12	-0.89	0.15	-0.84	0.23	-0.83	0.18	-0.79	0.21	-0.79	0.29	-0.74	0.25
obs13	0.67	0.14	0.76	0.18	0.75	0.17	*	*	*	*	*	*
obs14	0.49	0.14	0.60	0.22	0.57	0.18	0.55	0.18	0.59	0.26	0.57	0.22
obs15	0.01	0.05	0.00	0.05	0.00	0.05	0.01	0.05	0.01	0.05	0.00	0.05
obs16	-0.76	0.15	-0.80	0.17	-0.79	0.16	-0.76	0.15	-0.80	0.17	-0.79	0.16
obs17	-0.69	0.14	-0.65	0.19	-0.61	0.17	*	*	*	*	*	*
obs18	-0.38	0.14	-0.34	0.19	-0.31	0.17	-0.30	0.19	-0.30	0.26	-0.27	0.24
obs19	0.49	0.13	0.47	0.16	0.50	0.14	0.54	0.15	0.48	0.18	0.50	0.16
obs20	0.60	0.12	0.68	0.16	0.65	0.14	0.60	0.15	0.66	0.17	0.64	0.16
obs21	1.40	0.12	1.14	0.20	1.07	0.13	1.31	0.13	1.14	0.20	1.06	0.16
obs22	0.75	0.13	1.01	0.20	0.99	0.17	*	*	*	*	*	*
obs23	-0.72	0.17	-0.60	0.26	-0.68	0.22	*	*	*	*	*	*
obs24	0.27	0.18	0.29	0.21	0.30	0.21	0.28	0.19	0.33	0.24	0.34	0.23
obs25	-0.01	0.05	-0.01	0.05	0.00	0.05	-0.01	0.05	-0.01	0.05	0.00	0.05

Testing the methodology

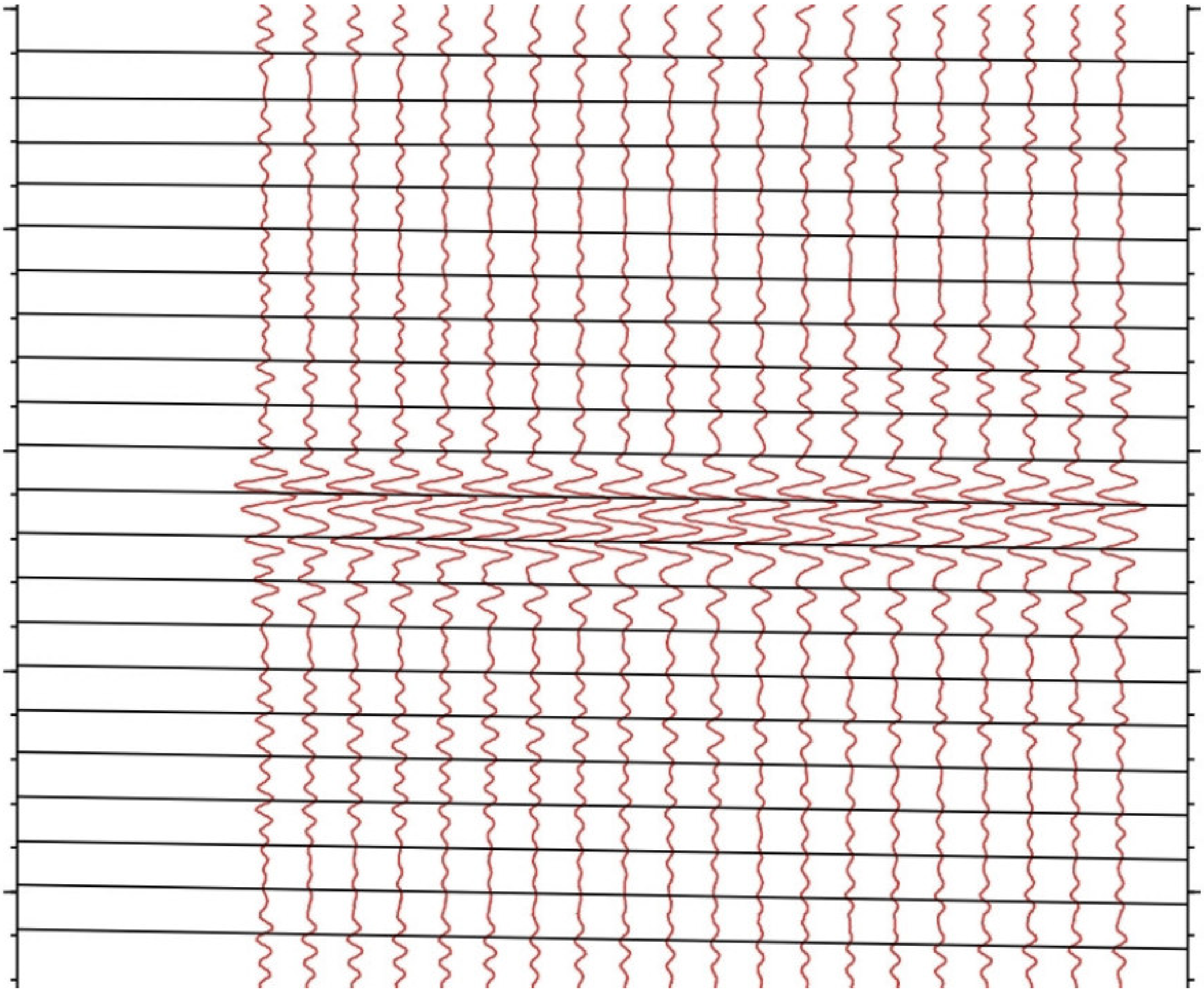


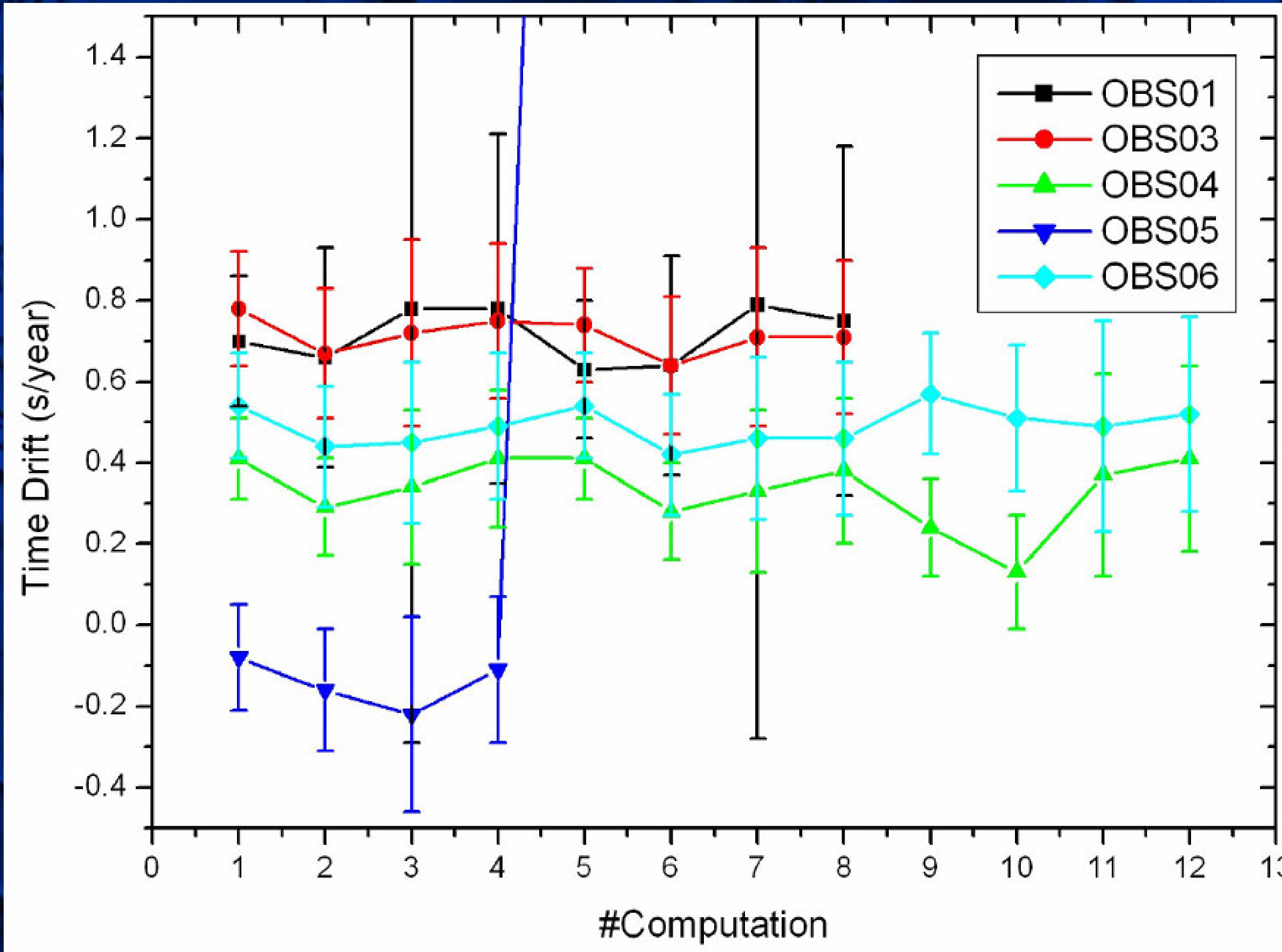
Figure 14 – Example of clock drift computation for the pair OBS04-OBS05. OBS05 recordings were artificially delayed by 4.80 s/year .

Testing the methodology

Table 6 – Computed clock drift values in seconds per year (s/year) with OBS05 artificially delayed. 4 cases are represented.

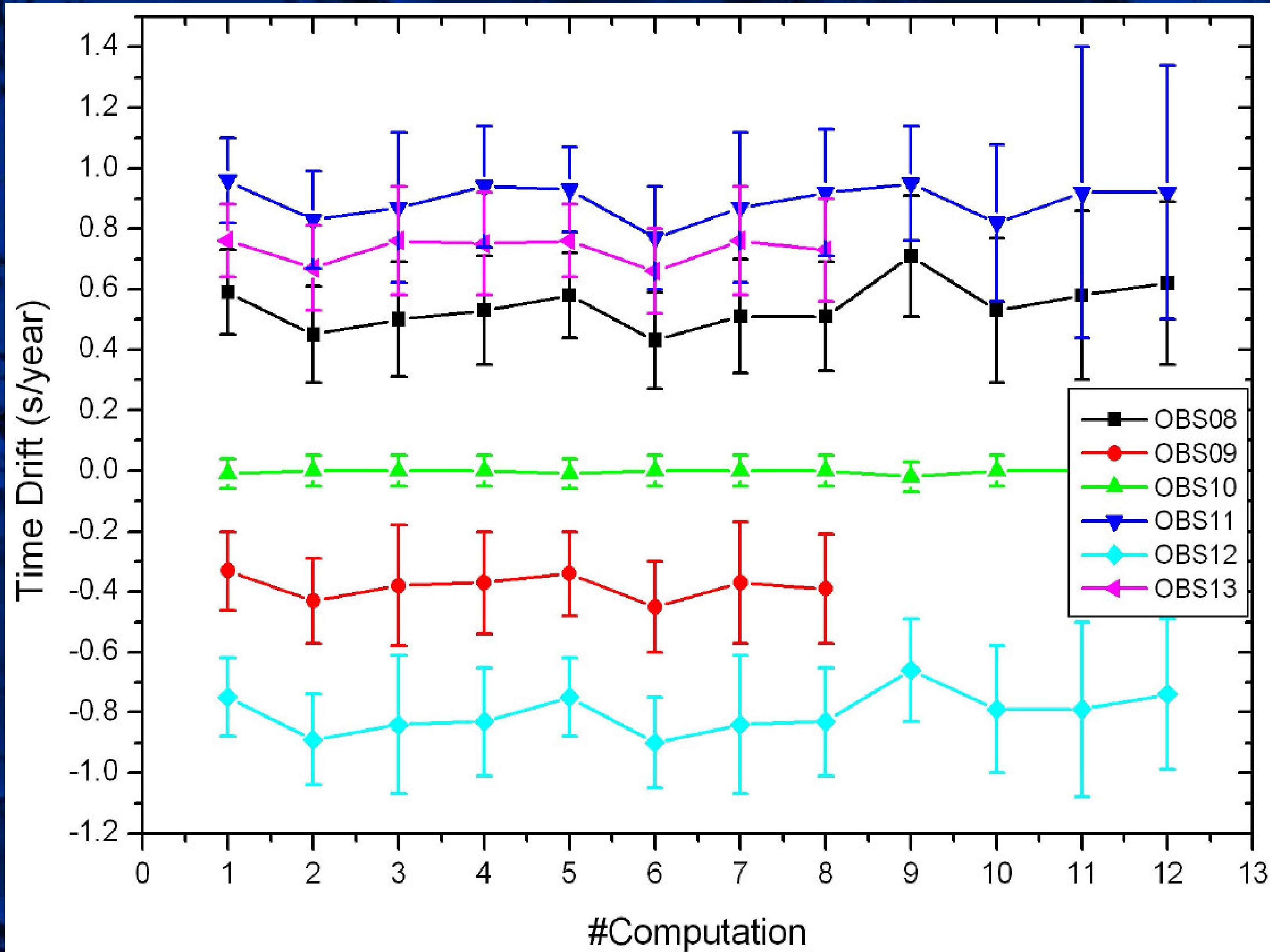
	All pairs		Selection (i)		Selection (ii)		Selection (iii)	
$\chi_N^{\ 2}$	**4.55**		**1.78**		**0.40**		**0.62**	
OBS	α_{i0}	$\pm s$	α_{i0}	$\pm s$	α_{i0}	$\pm s$	α_{i0}	$\pm s$
obs01	0.63	0.17	0.64	0.27	0.79	1.07	0.75	0.43
obs03	0.74	0.14	0.64	0.17	0.71	0.22	0.71	0.19
obs04	0.41	0.10	0.28	0.12	0.33	0.20	0.38	0.18
obs05	**5.20**	**0.20**	**5.27**	**0.27**	**5.38**	**0.35**	**5.38**	**0.30**
obs06	0.54	0.13	0.42	0.15	0.46	0.20	0.46	0.19
obs08	0.58	0.14	0.43	0.16	0.51	0.19	0.51	0.18
obs09	-0.34	0.14	-0.45	0.15	-0.37	0.20	-0.39	0.18
obs10	-0.01	0.05	0.00	0.05	0.00	0.05	0.00	0.05
obs11	0.93	0.14	0.77	0.17	0.87	0.25	0.92	0.21
obs12	-0.75	0.13	-0.90	0.15	-0.84	0.23	-0.83	0.18
obs13	0.76	0.12	0.66	0.14	0.76	0.18	0.73	0.17
obs14	0.56	0.14	0.49	0.14	0.60	0.22	0.59	0.20
obs15	0.02	0.05	0.01	0.05	0.00	0.05	0.00	0.05
obs16	-0.73	0.12	-0.76	0.15	-0.80	0.17	-0.79	0.17
obs17	-0.63	0.12	-0.72	0.14	-0.66	0.19	-0.64	0.18
obs18	-0.27	0.12	-0.41	0.15	-0.33	0.19	-0.34	0.18
obs19	0.54	0.12	0.48	0.13	0.47	0.16	0.49	0.14
obs20	0.57	0.11	0.59	0.13	0.68	0.16	0.64	0.14
obs21	1.50	0.11	1.41	0.12	1.14	0.20	1.07	0.13
obs22	0.90	0.11	0.73	0.13	1.01	0.20	0.98	0.17
obs23	-0.72	0.15	-0.73	0.16	-0.60	0.27	-0.69	0.22
obs24	0.50	0.15	0.26	0.18	0.29	0.21	0.29	0.21
obs25	-0.01	0.05	-0.01	0.0	-0.01	0.05	0.00	0.05

Results



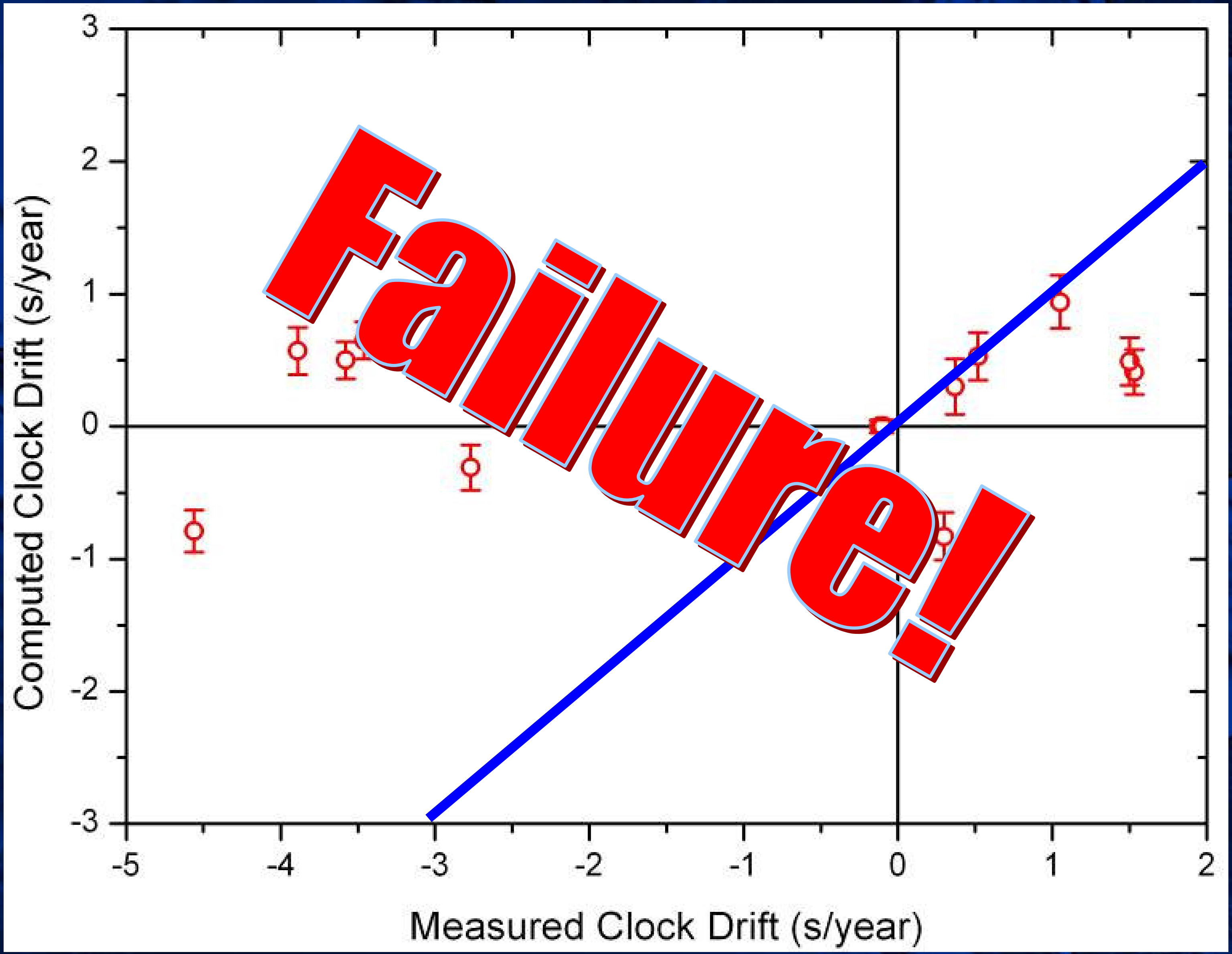
Time Drift (s/year)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
1
2
3
4
5
6
7
8
9
10
11
12
13
#Computation
OBS01
OBS03
OBS04
OBS05
OBS06

Results



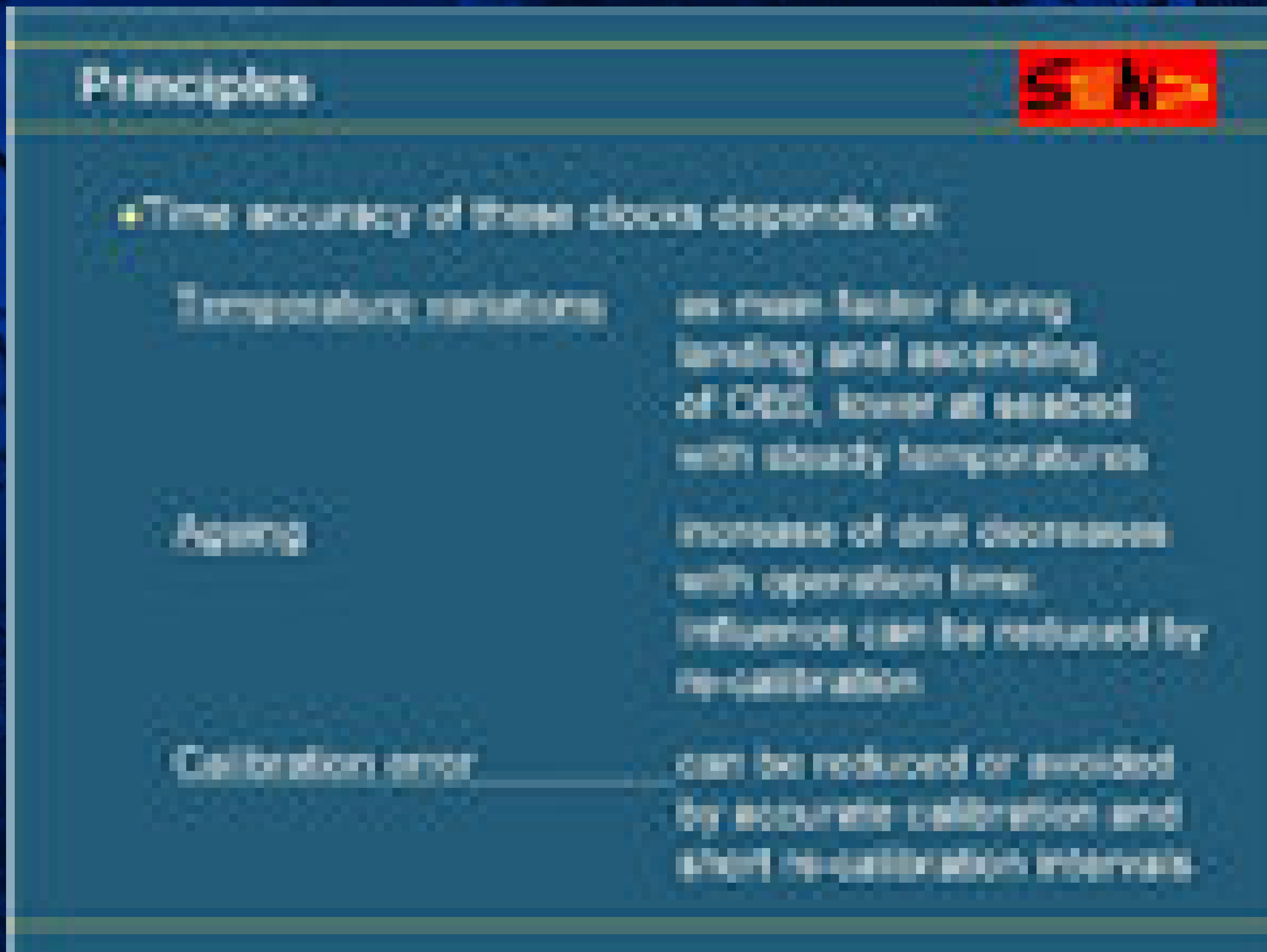
Time Drift (s/year)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13
#Computation
OBS08
OBS09
OBS10
OBS11
OBS12
OBS13

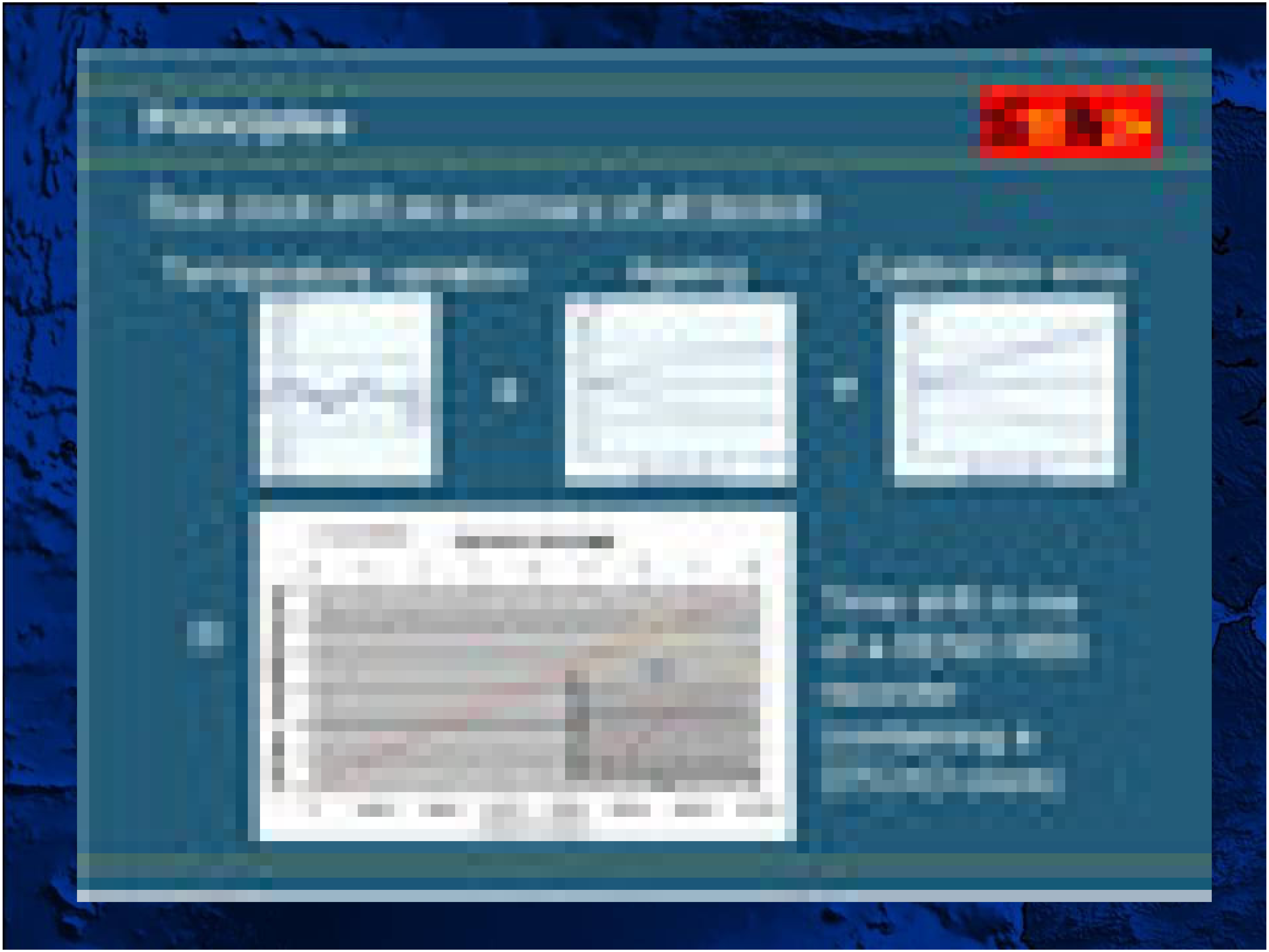
Results



Failure!
Computed Clock Drift (s/year)
Measured Clock Drift (s/year)
3
2
1
0
-1
-2
-3
-5
-4
-3
-2
-1
0
1
2

Breakthrough: The NERIES OBS meeting in Paris – meeting with Klaus Schleisiek, General Manager of SEND



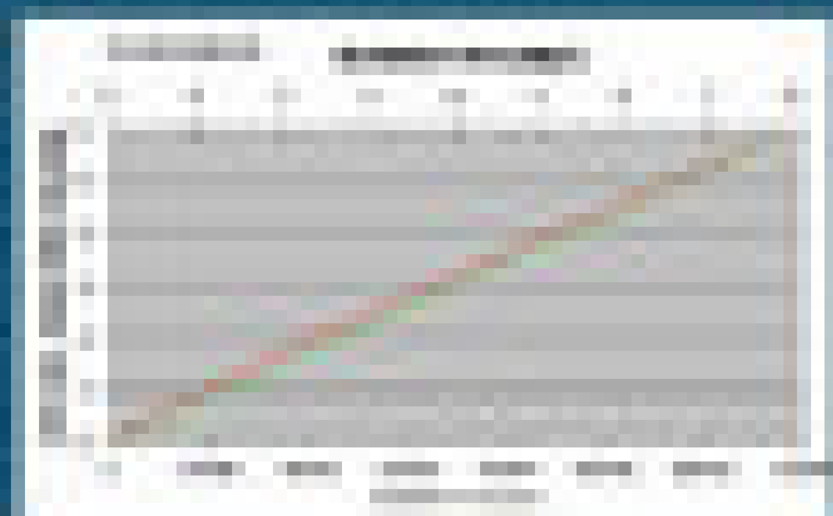


Details of Drift Correction

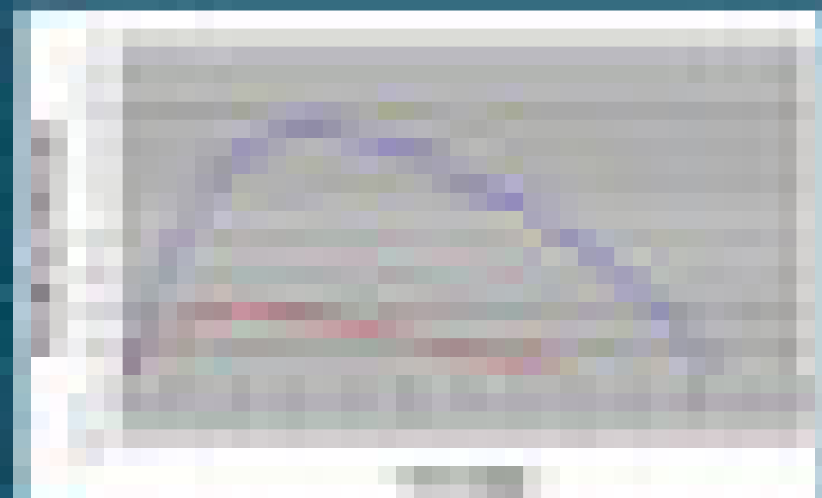
- Determination of correction value by using the linear trend of clock drift
- The remaining inaccuracy due to non-linear effects

Example:

Subtraction of linear drift trend (green line) from real drift (red line), measured with MBS recorder at constant temperature of 3°C over a period of 13 days



=> following graphs of remaining drift errors



Details of Drift Correction

- The remaining inaccuracy due to non-linear effects

  Red line:
  remaining drift below 0.42 ms in 7.4 days
  => 0.42 ms/6.39E05 s = 0.66 E-09

  Blue line:
  remaining drift below 1.5 ms in 19.5 days
  => 1.50 ms/1.68E06 s = 0.89 E-09

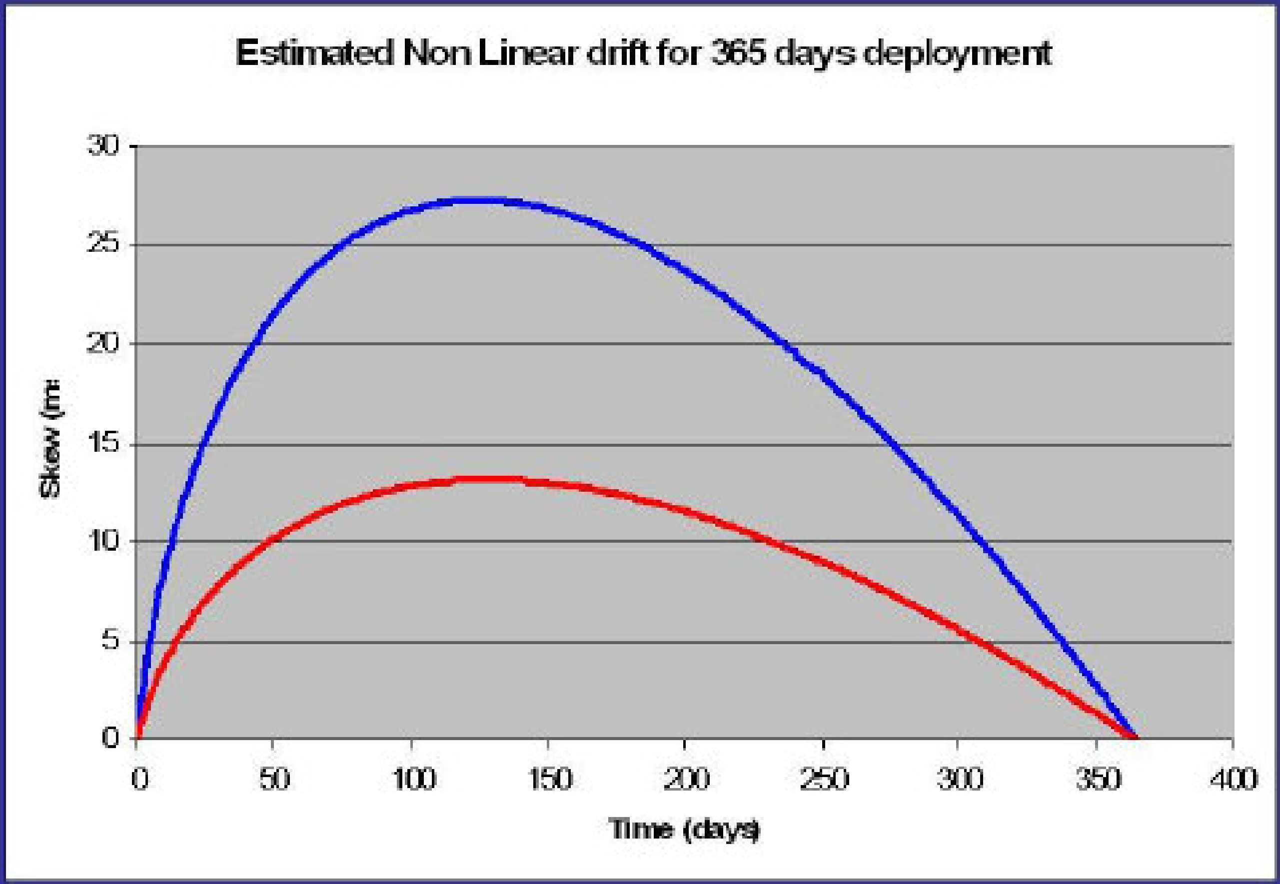
  => error after linear correction: ~ 0.5 - 1 E-09

=> Resulting accuracy comparable to oven controlled crystal oscillators

- **Extrapolated inaccuracy for a 365 day operation:**

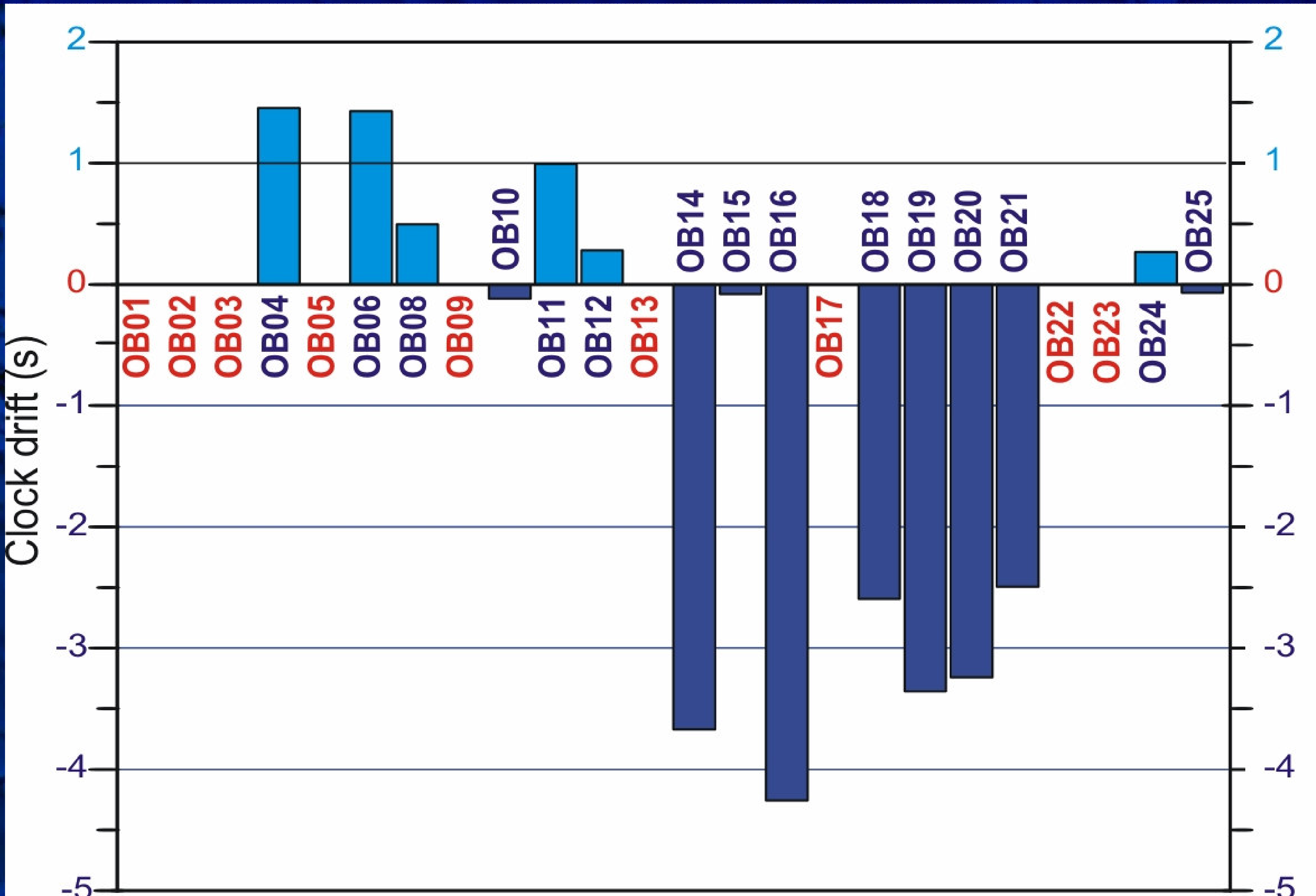
red line belongs to an MBS with several month operation time in total

blue line belongs to an MBS with approx. one month operation time.



- **What if you cannot synchronize the clock after recovery?**
- **What would be the expected time drift?**

- **What happened?**



I suspect an anomaly, namely, either the synchronization time (GPS-command) or the skew time (SKEW or DRIFT command) was off by 3 or 4 seconds. We have seen this in the past. There is even an (unpublished) command in the MCS to correct that: SECONDJUMPS. But now, it is too late to apply it. You have to look at events at the beginning, in the middle, and at the end of the recording and compare it with "good" OBS data to decide what happened.

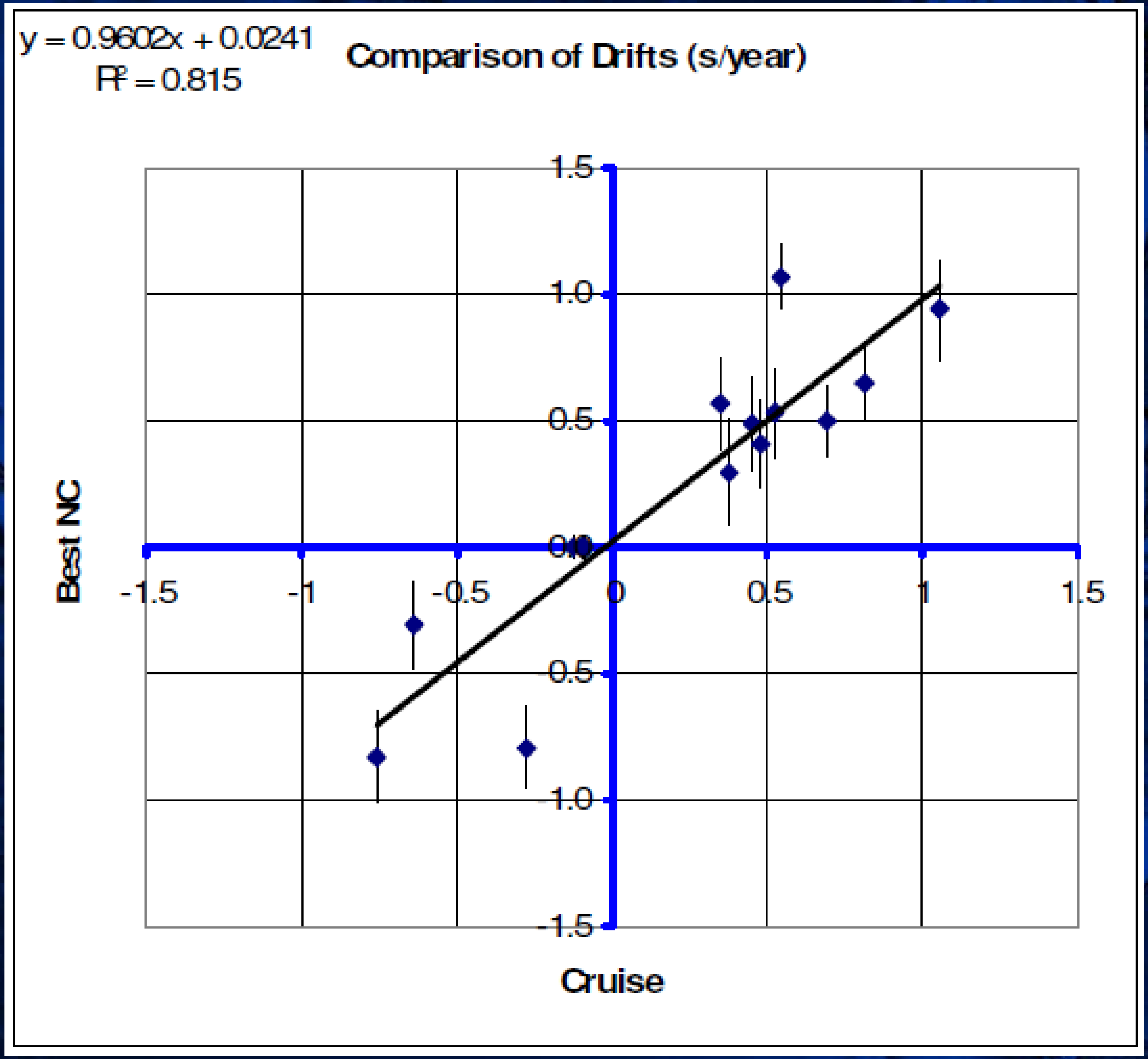
Klaus Schleisiek

Trial 3: Back to square one. Revise earthquake phase data, integrate with NCF, propose a time correction for **all** instruments

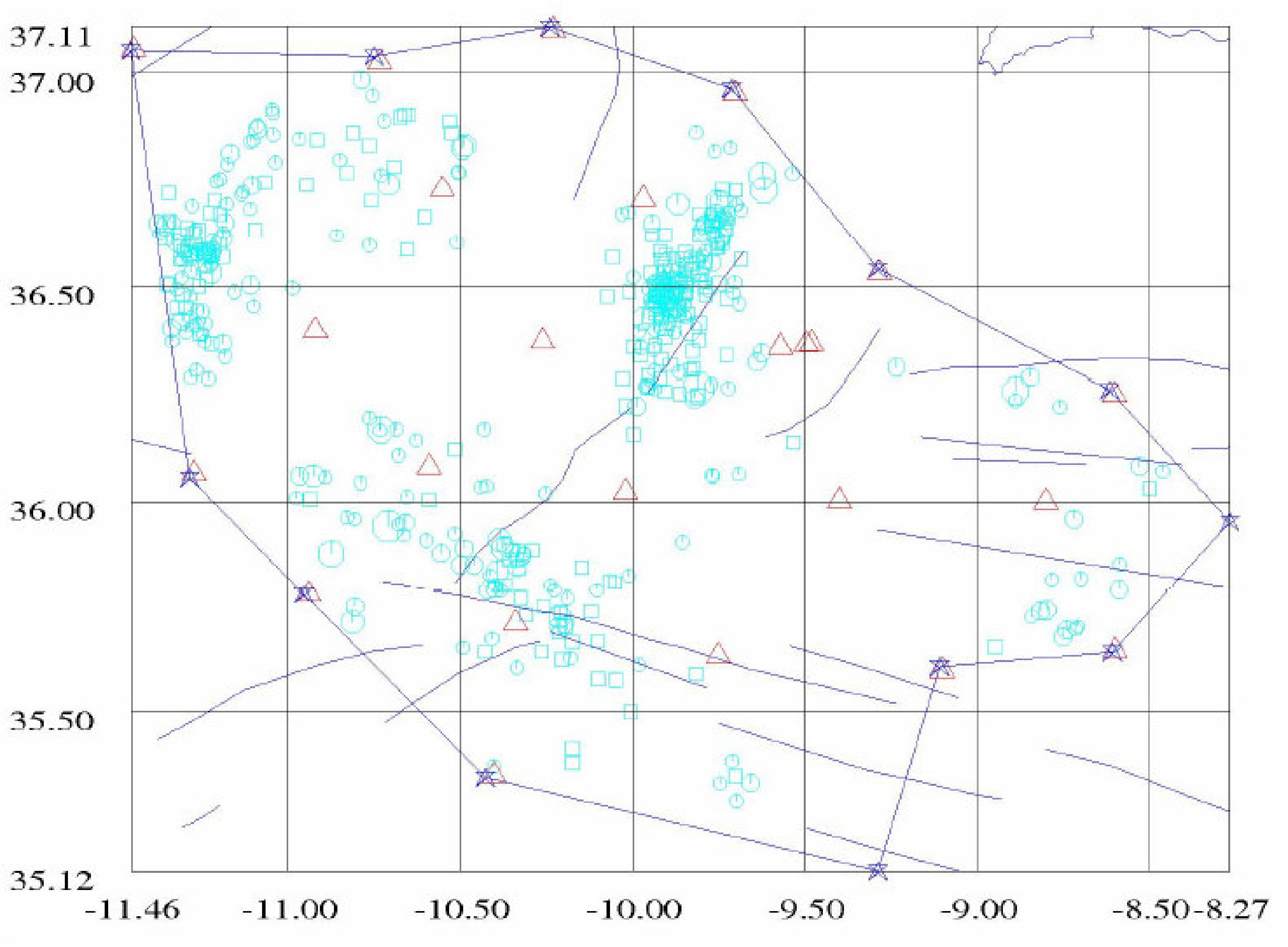
Table 3 – Clock drifts in seconds per year after an integer second correction is applied to the skew time measured onboard.

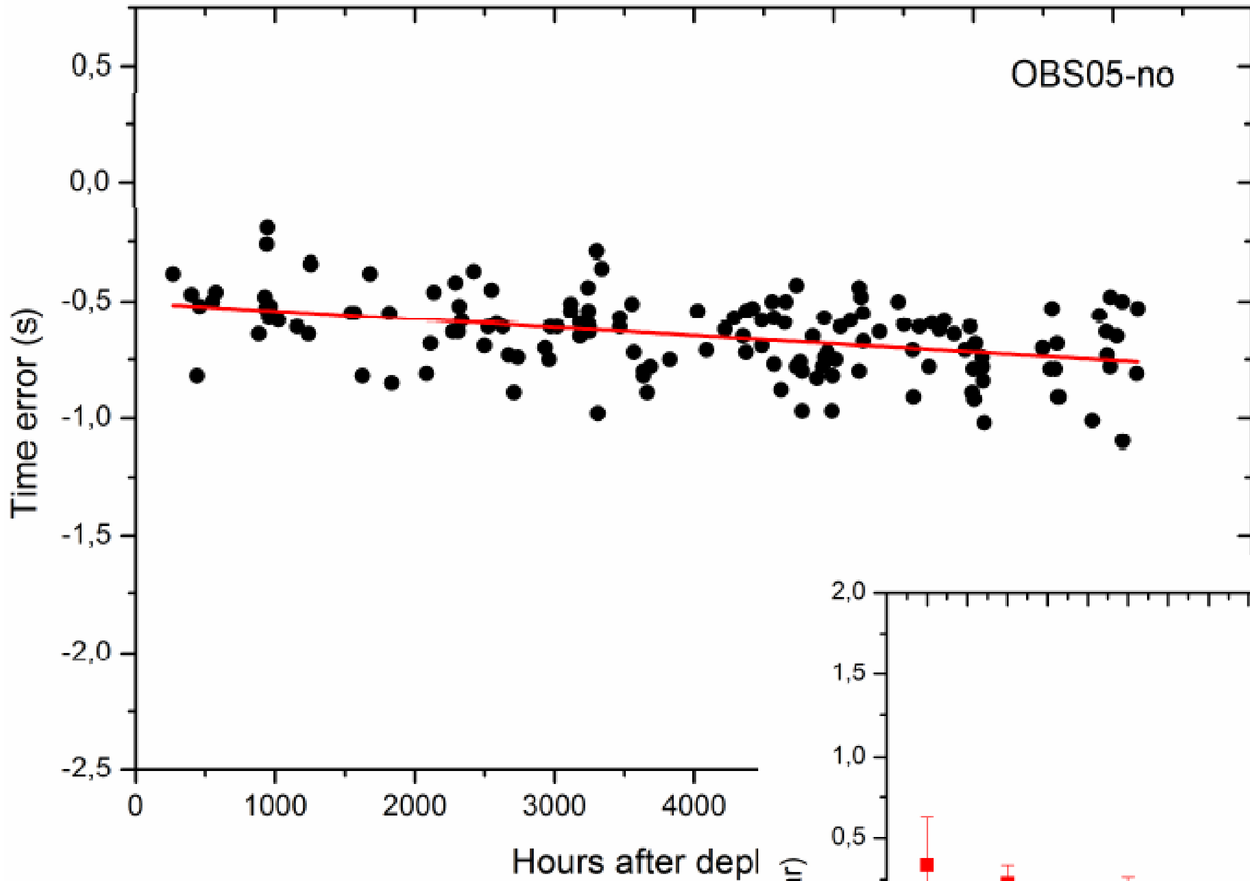
OBS	Drift s/year	Correction s	OBS	Drift s/year	Correction s
OBS01	--.—	--.—	OBS14	0.348	-4
OBS02	--.—	--.—	OBS15	-0.086	0
OBS03	--.—	--.—	OBS16	-0.277	-4
OBS04	0.482	1	OBS17	--.—	--.—
OBS05	--.—	--.—	OBS18	-0.633	-2
OBS06	0.451	1	OBS19	0.688	-4
OBS08	0.522	0	OBS20	0.816	-4
OBS09	--.—	--.—	OBS21	0.542	-3
OBS10	-0.123	0	OBS22	--.—	--.—
OBS11	1.053	0	OBS23	--.—	--.—
OBS12	-0.761	1	OBS24	0.377	0
OBS13	--.—	--.—	OBS25	-0.099	0

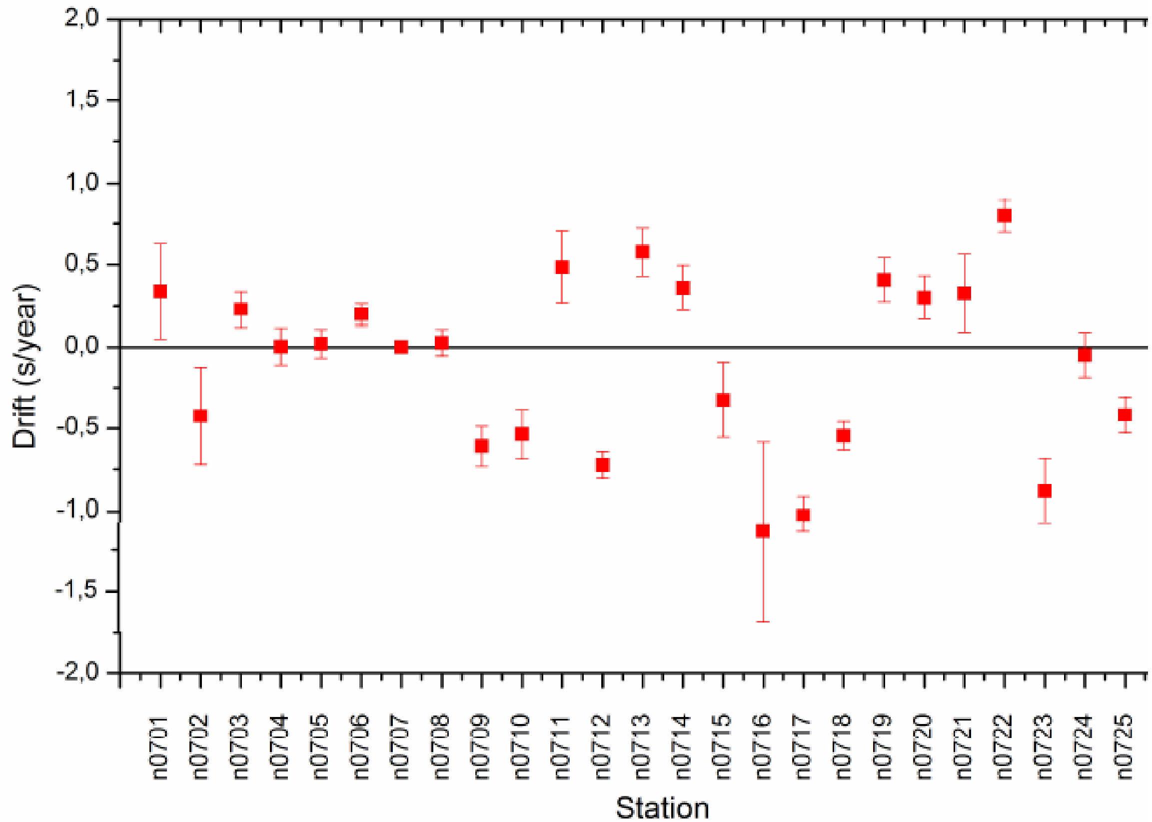
Argument: an improved correlation with clock drift estimated by NCF

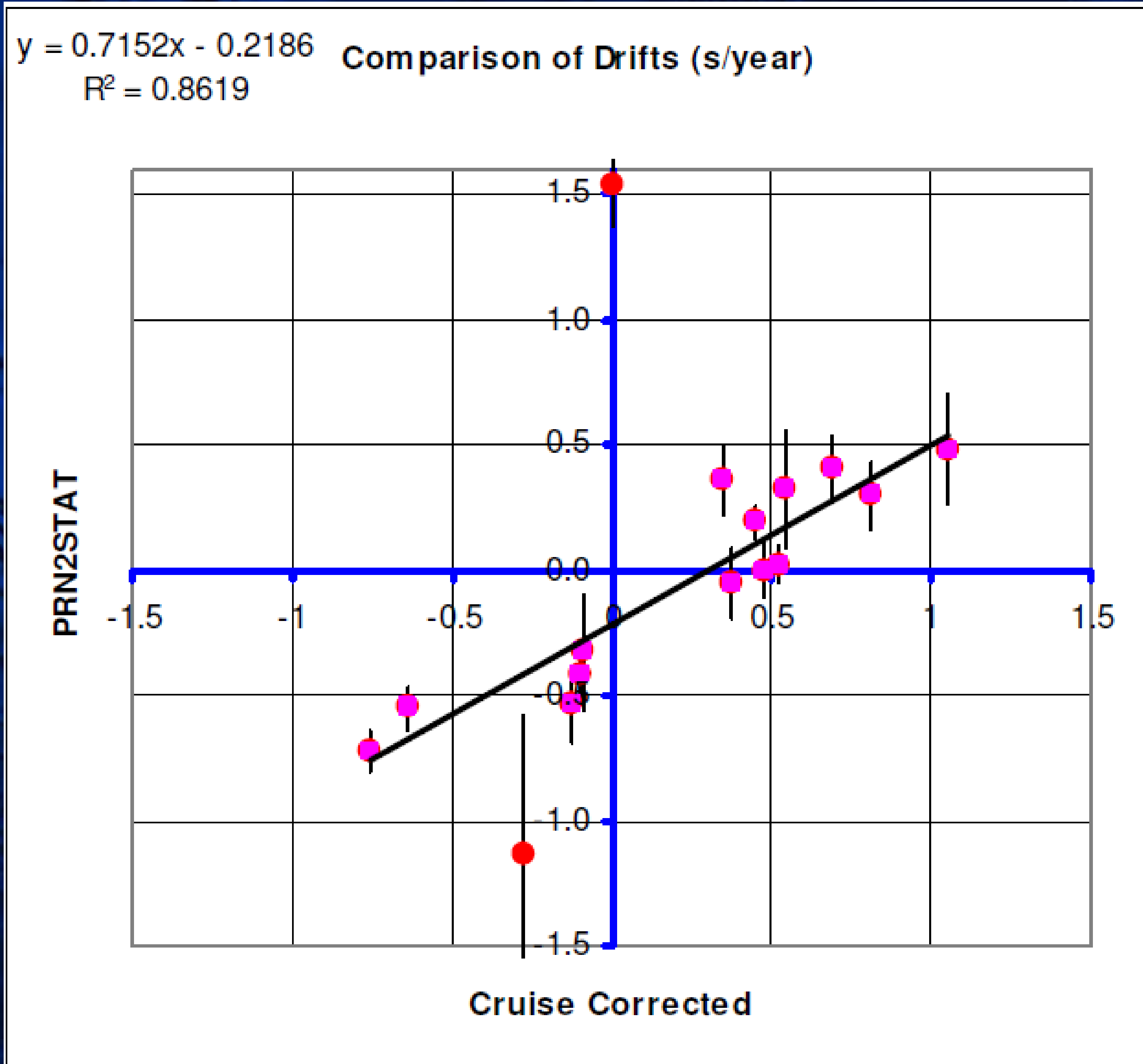


Selection of 296 best located events in the area defined by the OBS network

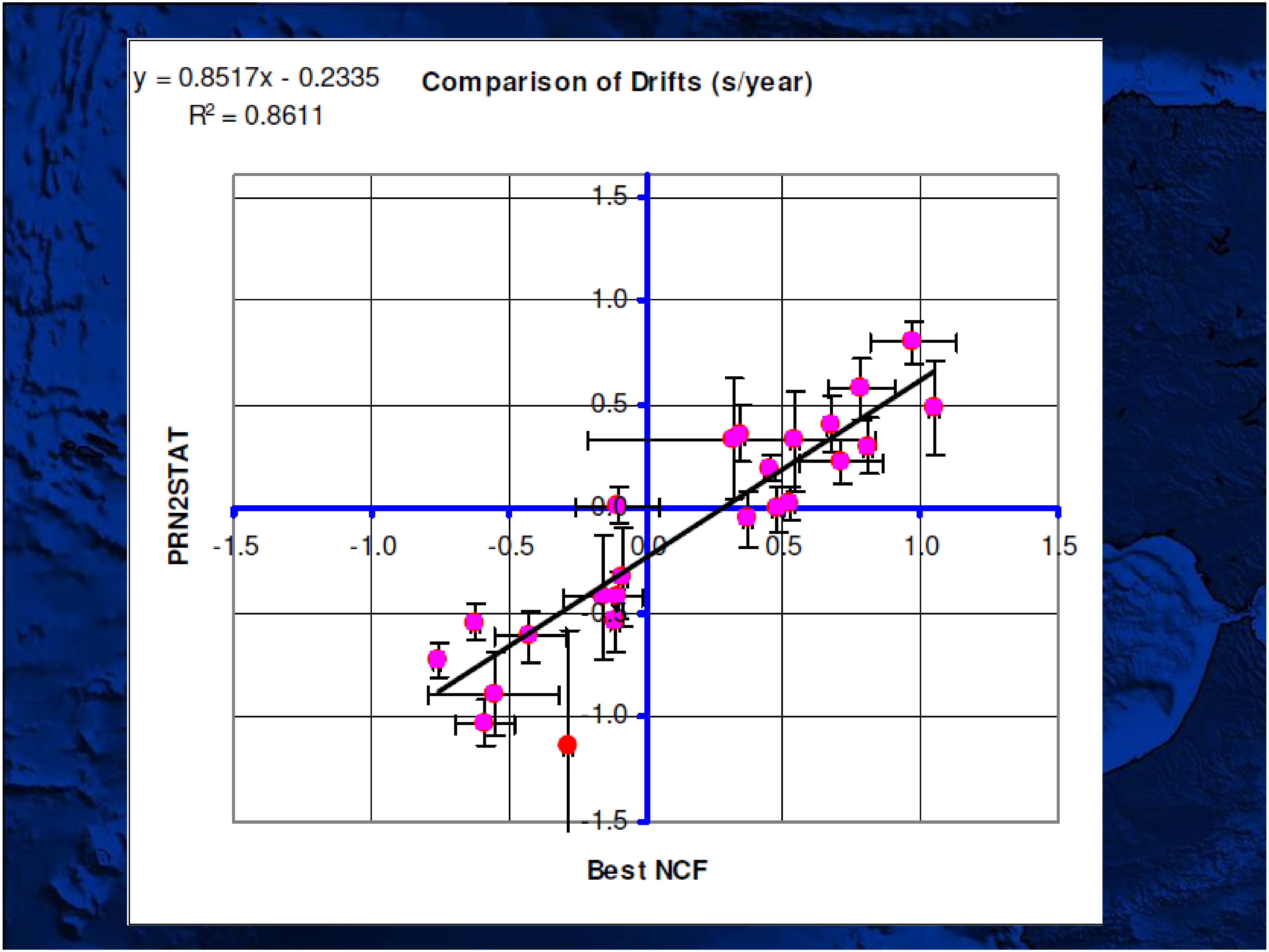



OBS05-no
Time error (s)
0,5
0,0
-0,5
-1,0
-1,5
-2,0
-2,5
0
1000
2000
3000
4000
Hours after depl


Drift (s/year)
2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
n0701
n0702
n0703
n0704
n0705
n0706
n0707
n0708
n0709
n0710
n0711
n0712
n0713
n0714
n0715
n0716
n0717
n0718
n0719
n0720
n0721
n0722
n0723
n0724
n0725
Station

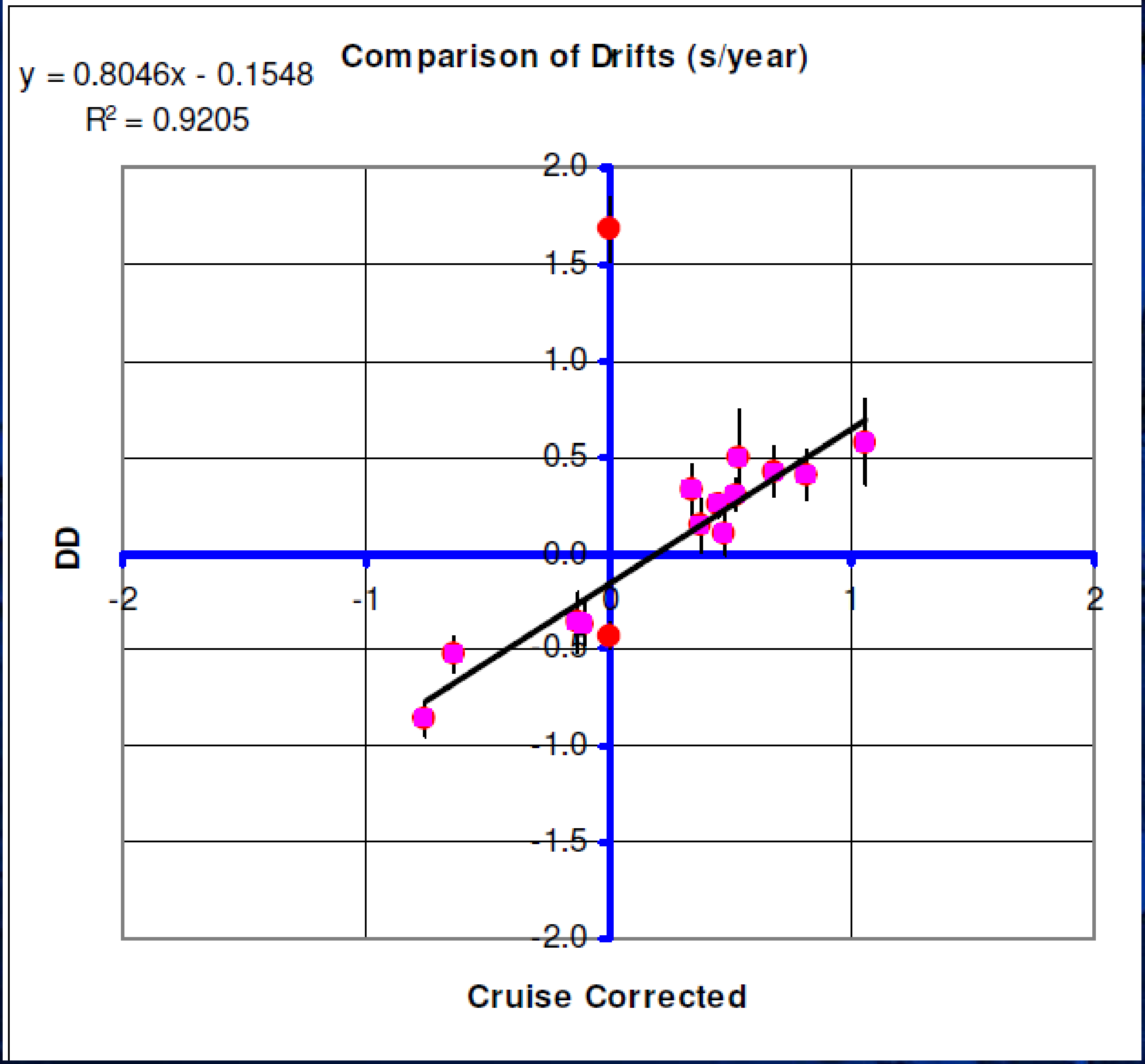


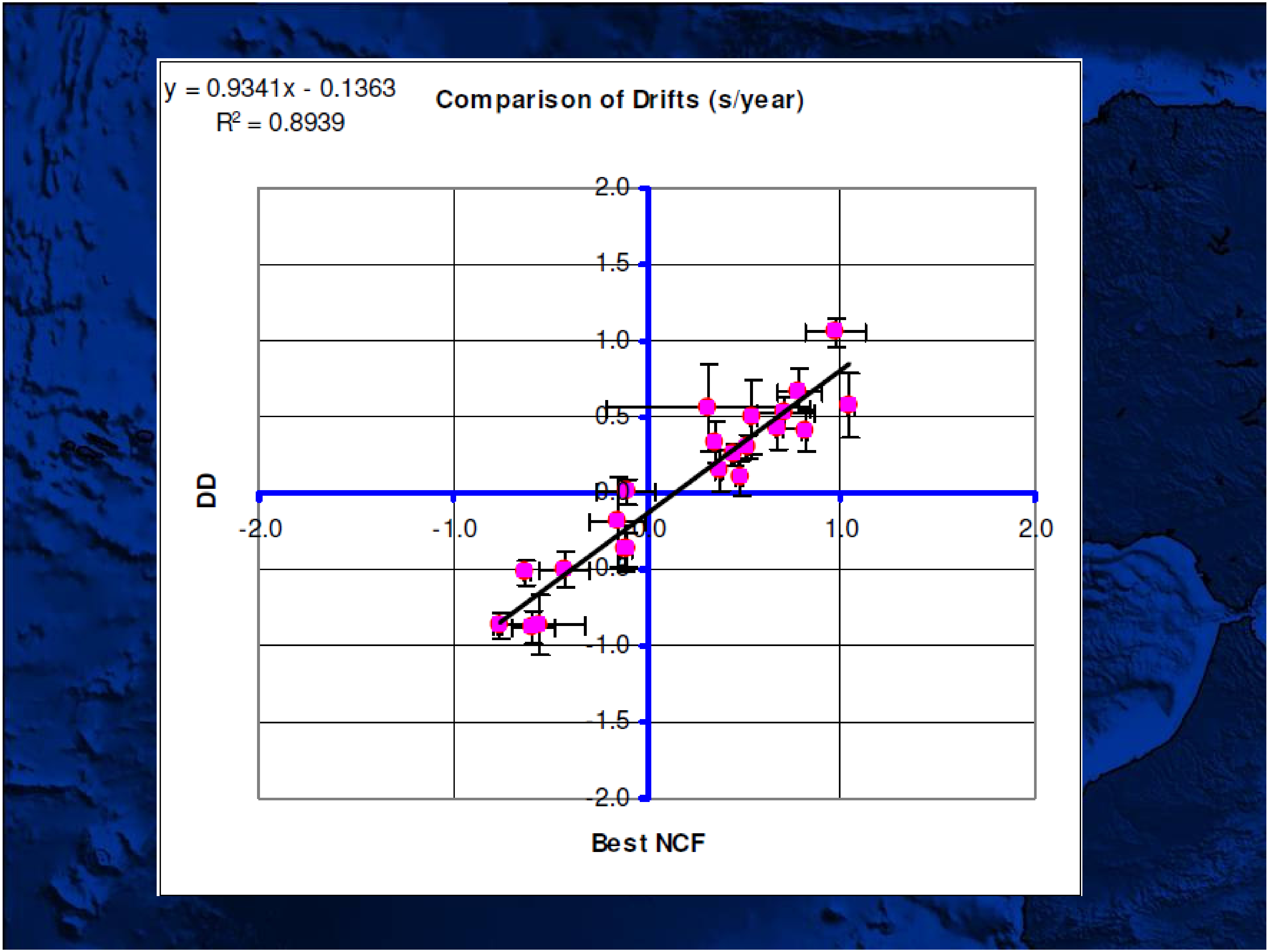
y = 0.7152x - 0.2186
R2 = 0.8619
Comparison of Drifts (s/year)
PRN2STAT
Cruise Corrected
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.5
-1
-0.5
0
0.5
1
1.5



y = 0.8517x - 0.2335
R² = 0.8611
Comparison of Drifts (s/year)
PRN2STAT
Best NCF
1.5
1.0
0.5
0.0
-1.0
-1.5
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

Using double differences instead of residuals

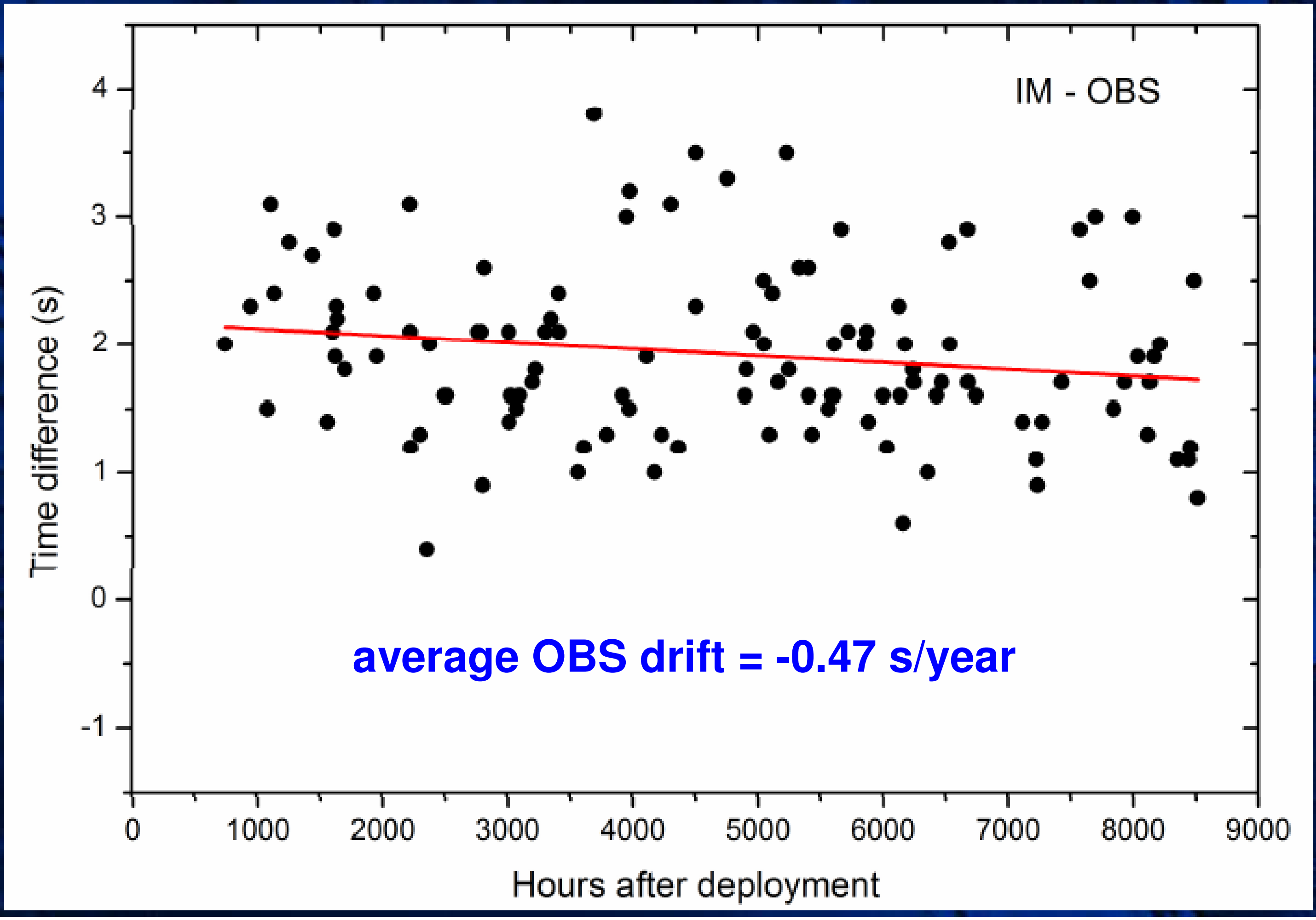


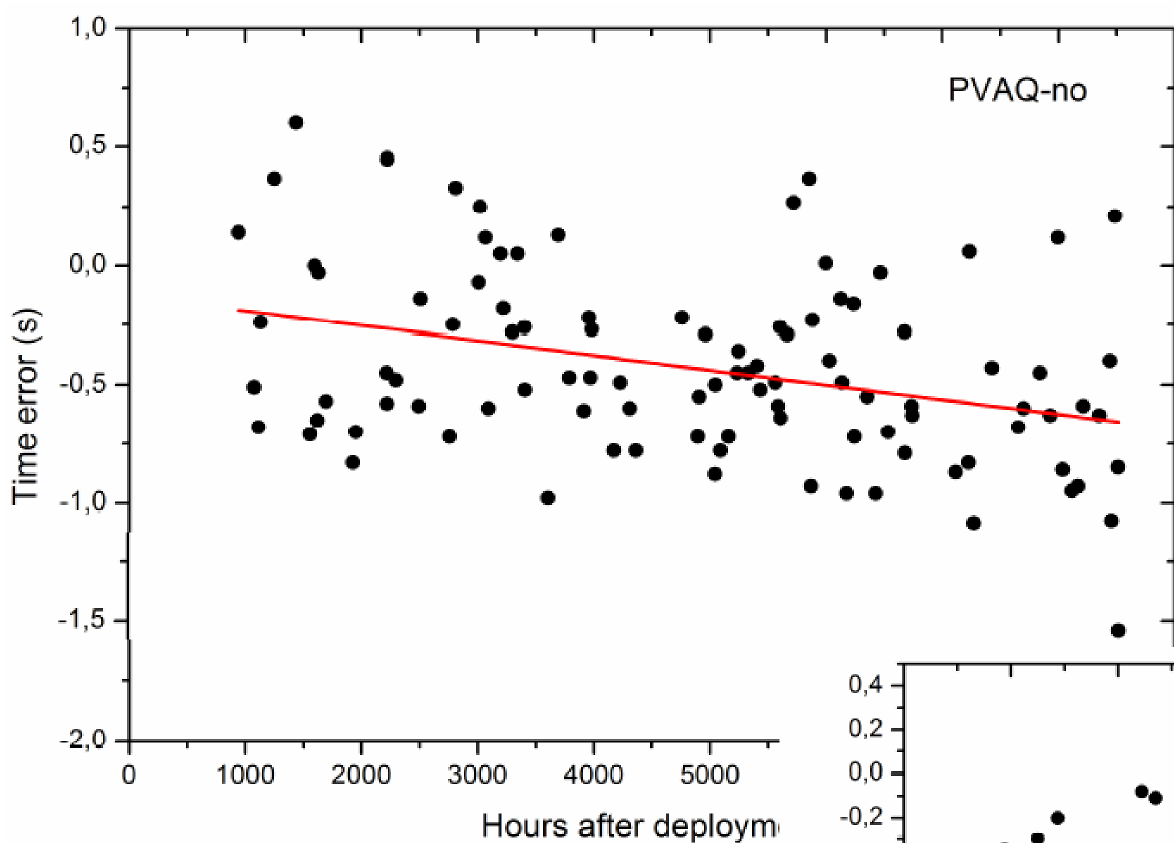


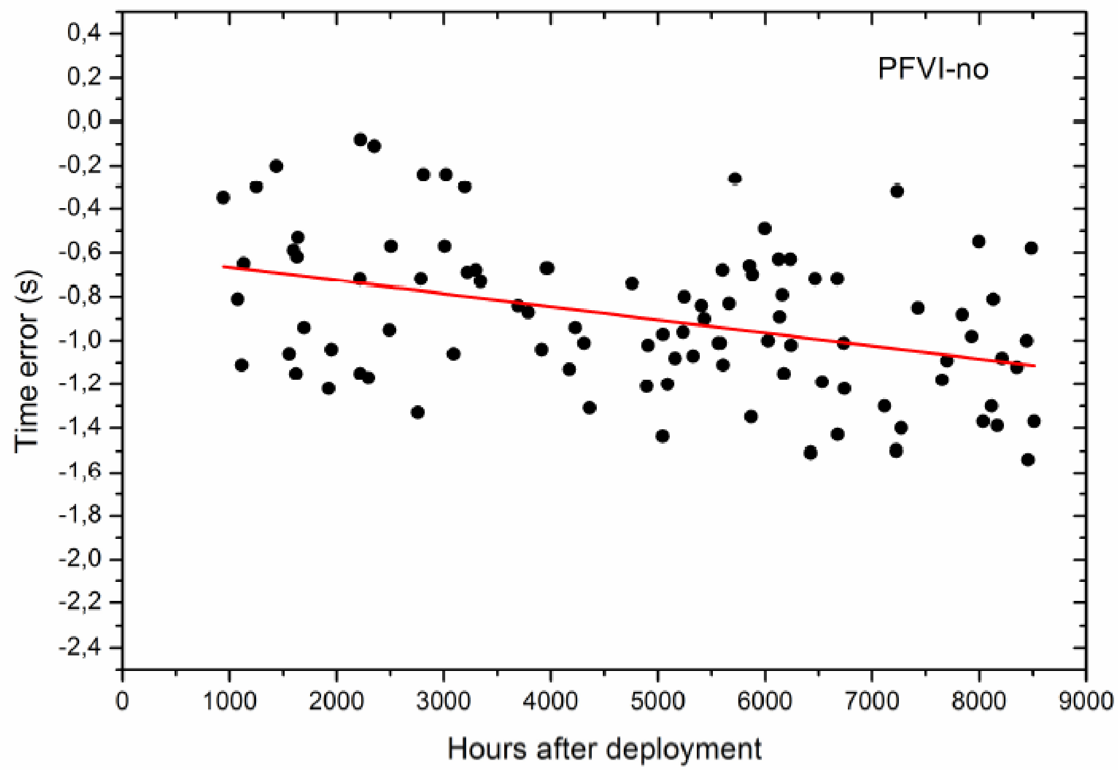
y = 0.9341x - 0.1363
R² = 0.8939
Comparison of Drifts (s/year)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.0
-1.0
0.0
1.0
2.0
DD
Best NCF

Searching for an absolute time reference:
integration of land recordings

We used 118 events also recorded by the land network




PVAQ-no
Time error (s)
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
0
1000
2000
3000
4000
5000
Hours after deploym


PFVI-no
Time error (s)
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
-1,2
-1,4
-1,6
-1,8
-2,0
-2,2
-2,4
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Hours after deployment

Systematic drift of the land stations when compared to the OBS data

Table 6 – Clock drifts in seconds per year computed from the evolution of P-wave arrival residuals for the land stations.

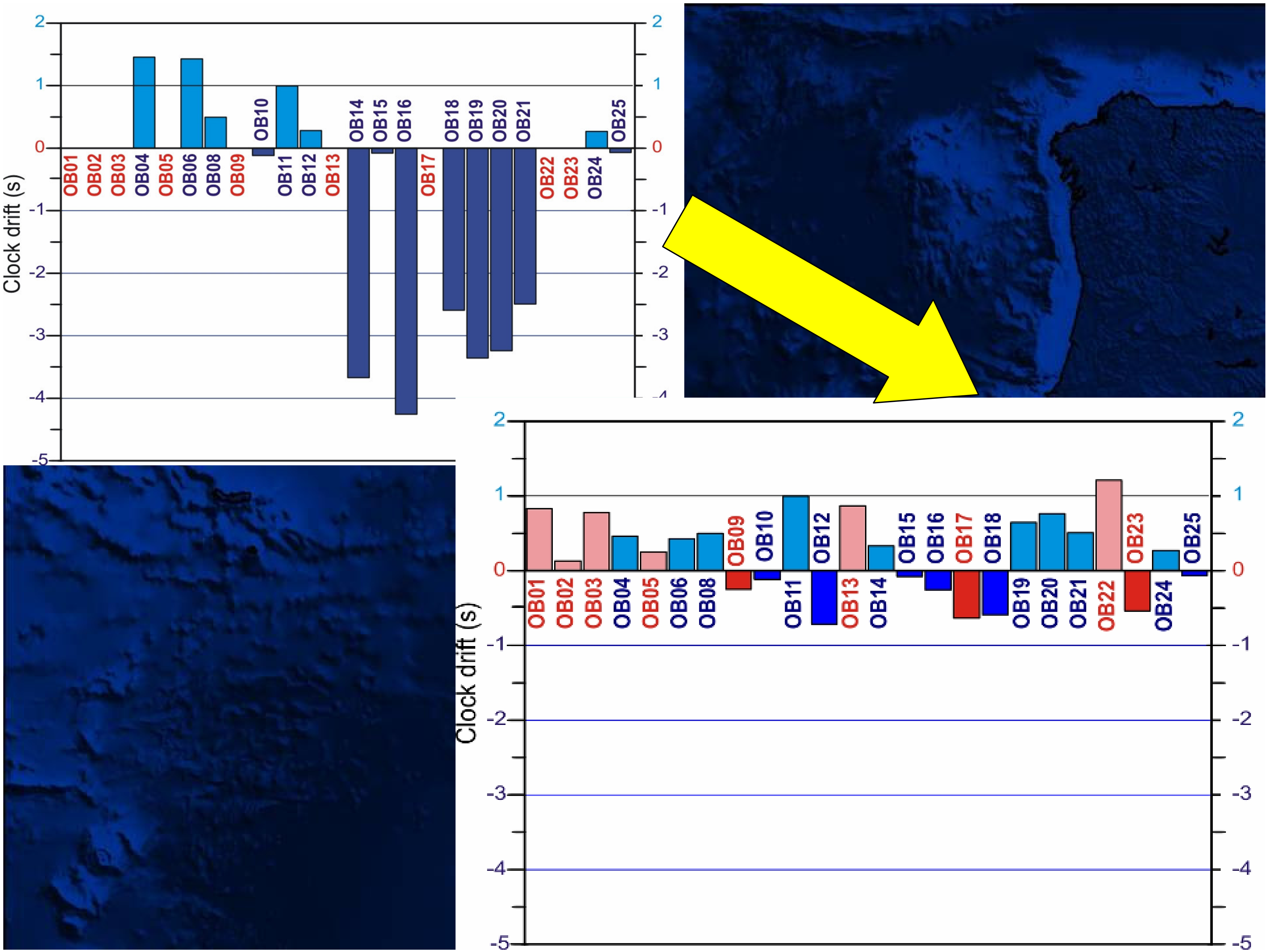
Station	Drift s/year	±σ	N	Station	Drift s/year	±σ	N
PBEJ	-0.721	0.328	38	PBAR	-0.615	0.220	77
PTEO	-0.523	0.199	88	PVAQ	-0.542	0.147	100
PBDV	-0.588	0.155	88	MORF	-0.574	0.140	87
PFVI	-0.521	0.126	96	MESJ	-.---	-.---	--
PDRG	-.---	-.---	--	All	-0.540	0.068	502

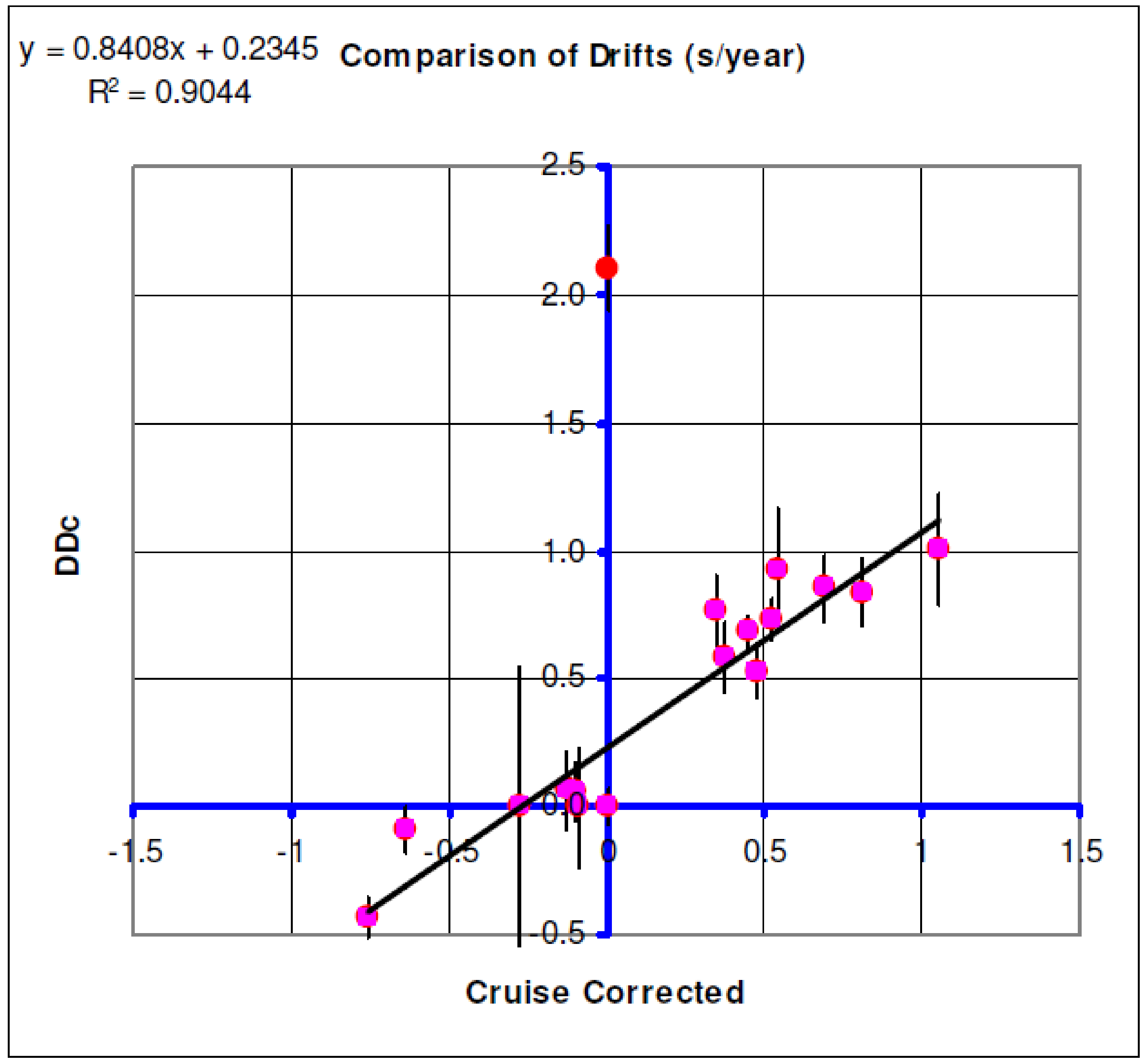
Table 9b – Clock drifts in seconds per year computed from the evolution of P-wave arrival residual double differences for the land stations, IM bulletins.

Station	Drift s/year	±σ	Station	Drift s/year	±σ
PBEJ	-0.377	0.040	PBAR	-0.515	0.027
PTEO	-0.541	0.021	PVAQ	-0.379	0.017
PBDV	-0.371	0.017	MORF	-0.428	0.017
PFVI	-0.400	0.017	Average	-0.430	-.---

A proposal of time drift corrections to be applied to the NEAREST dataset

- All 3 methods investigated fail to find any time drift greater than ±2 s as measured onboard
- All 3 methods are coherent with correlation slopes between 0.7 and 0.9
- The information provided by SEND allowed us to include in the problem the proposal of integer time corrections
- We use as absolute time-reference the land station P-wave arrivals and derive all other corrections using the double-difference time residuals method


Clock drift (s)
2
1
0
-1
-2
-3
-4
-5
OB01 OB02 OB03 OB04 OB05 OB06 OB08 OB09 OB10 OB11 OB12 OB13 OB14 OB15 OB16 OB17 OB18 OB19 OB20 OB21 OB22 OB23 OB24 OB25
Clock drift (s)
2
1
0
-1
-2
-3
-4
-5
OB01 OB02 OB03 OB04 OB05 OB06 OB08 OB09 OB10 OB11 OB12 OB13 OB14 OB15 OB16 OB17 OB18 OB19 OB20 OB21 OB22 OB23 OB24 OB25



y = 0.8408x + 0.2345
R^2 = 0.9044
Comparison of Drifts (s/year)
DDc
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.5
-1
-0.5
0
0.5
1
1.5
Cruise Corrected

Table 3 – Clock drifts in seconds per year after an integer second correction is applied to the skew time measured onboard.

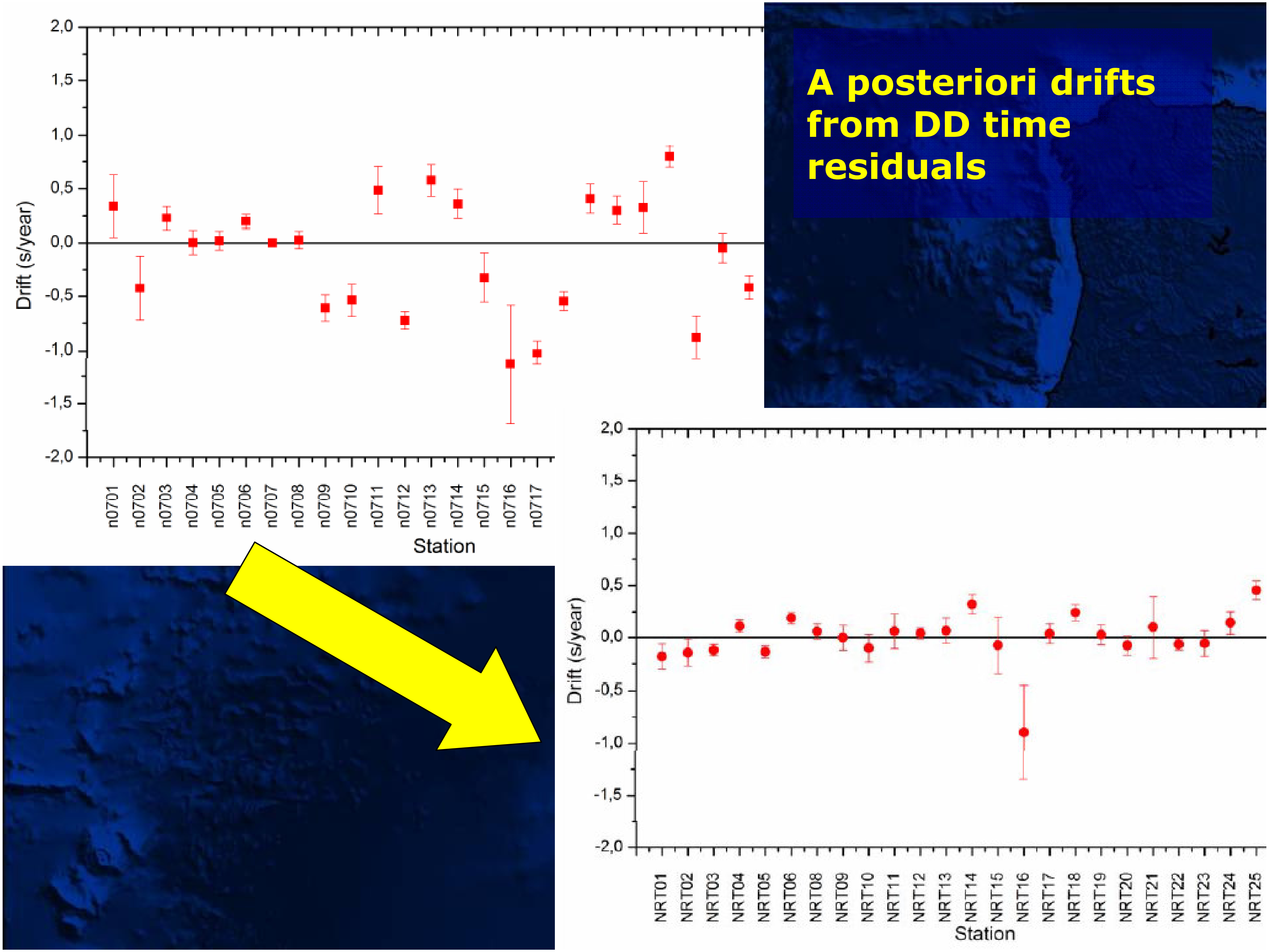
OBS	Drift s/year	Correction s	OBS	Drift s/year	Correction s
OBS01	--.—	--.—	OBS14	0.348	-4
OBS02	--.—	--.—	OBS15	-0.086	0
OBS03	--.—	--.—	OBS16	-0.277	-4
OBS04	0.482	1	OBS17	--.—	--.—
OBS05	--.—	--.—	OBS18	-0.633	-2
OBS06	0.451	1	OBS19	0.688	-4
OBS08	0.522	0	OBS20	0.816	-4
OBS09	--.—	--.—	OBS21	0.542	-3
OBS10	-0.123	0	OBS22	--.—	--.—
OBS11	1.053	0	OBS23	--.—	--.—
OBS12	-0.761	1	OBS24	0.377	0
OBS13	--.—	--.—	OBS25	-0.099	0

A posteriori drifts from DD time residuals

Table 11b – Clock drifts in seconds per year computed from the P-DD method, fixing the land station drifts to zero and the synchronized OBS to Table 3 values.

Station	Drift s/year	±σ	Station	Drift s/year	±σ
PBEJ	-0.003	0.017	PBDV	-0.003	0.012
PBAR	-0.046	0.016	MORF	-0.034	0.012
PTEO	-0.081	0.014	PFVI	-0.021	0.012
PVAQ	-0.006	0.012	Average	-0.028	-.---

A posteriori drifts from DD time residuals



Preliminary evaluation: average residuals for the 296 events

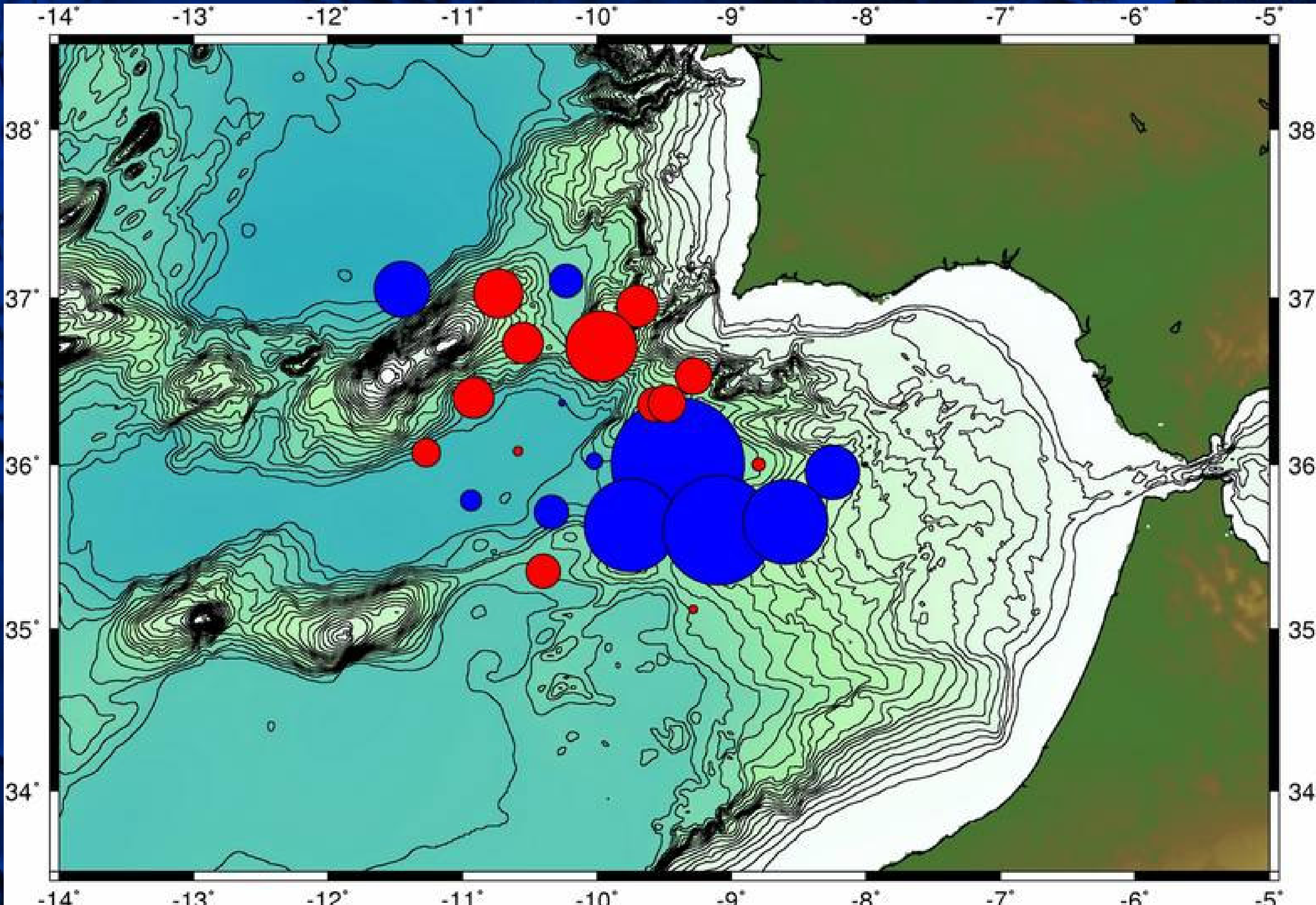
Location is performed adjusting Vp/Vs and finding the best station time delays that account for local structure differences

- NO Correction: RMS=0.4[illegible] s
- CRUISE Correction: R[illegible]45[illegible]
- NEW Correction: [illegible]6 s

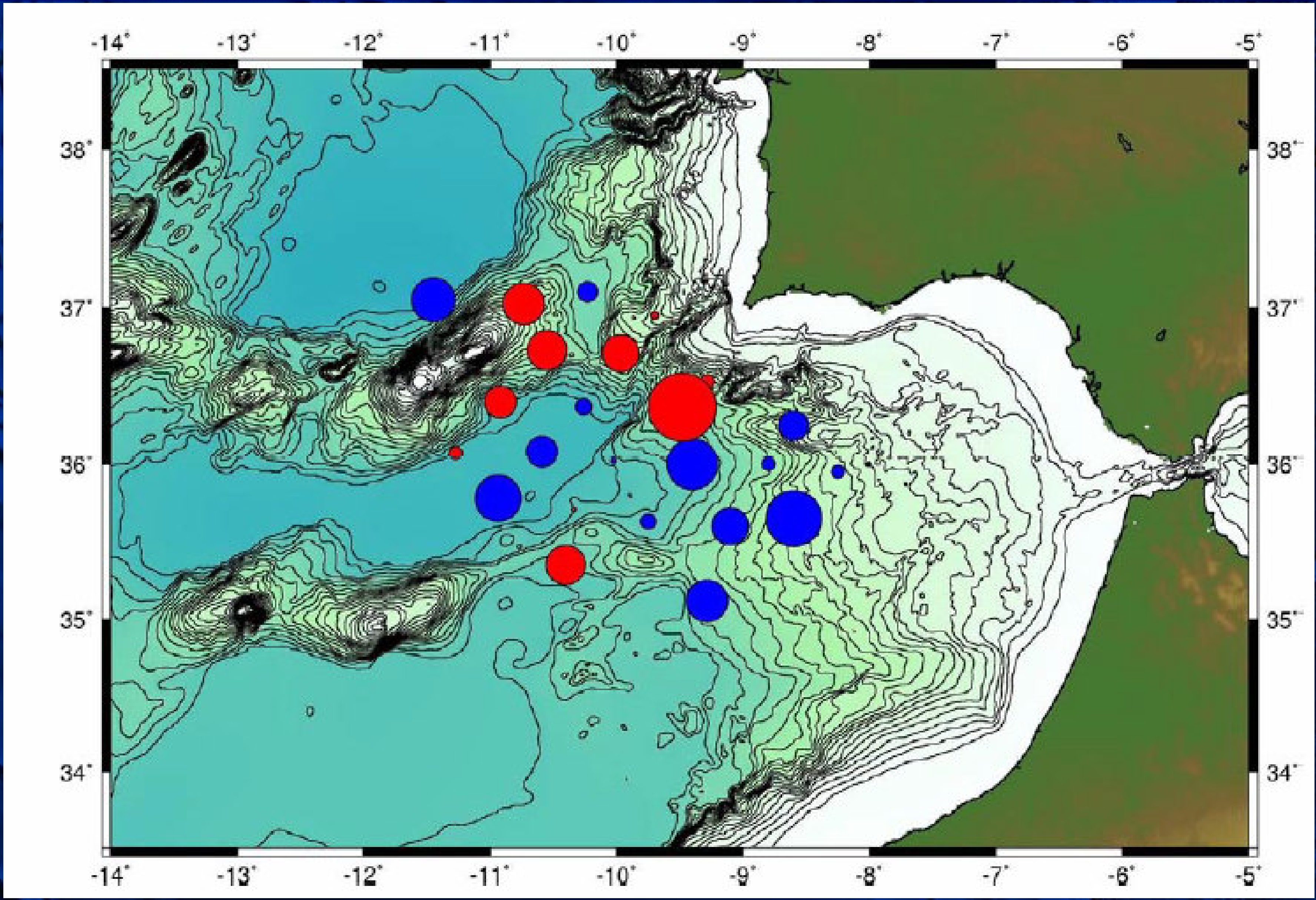
Success?

After all this wo[illegible] 3.5% improvement over NO correction and 13[illegible]provement over CRUISE corrections

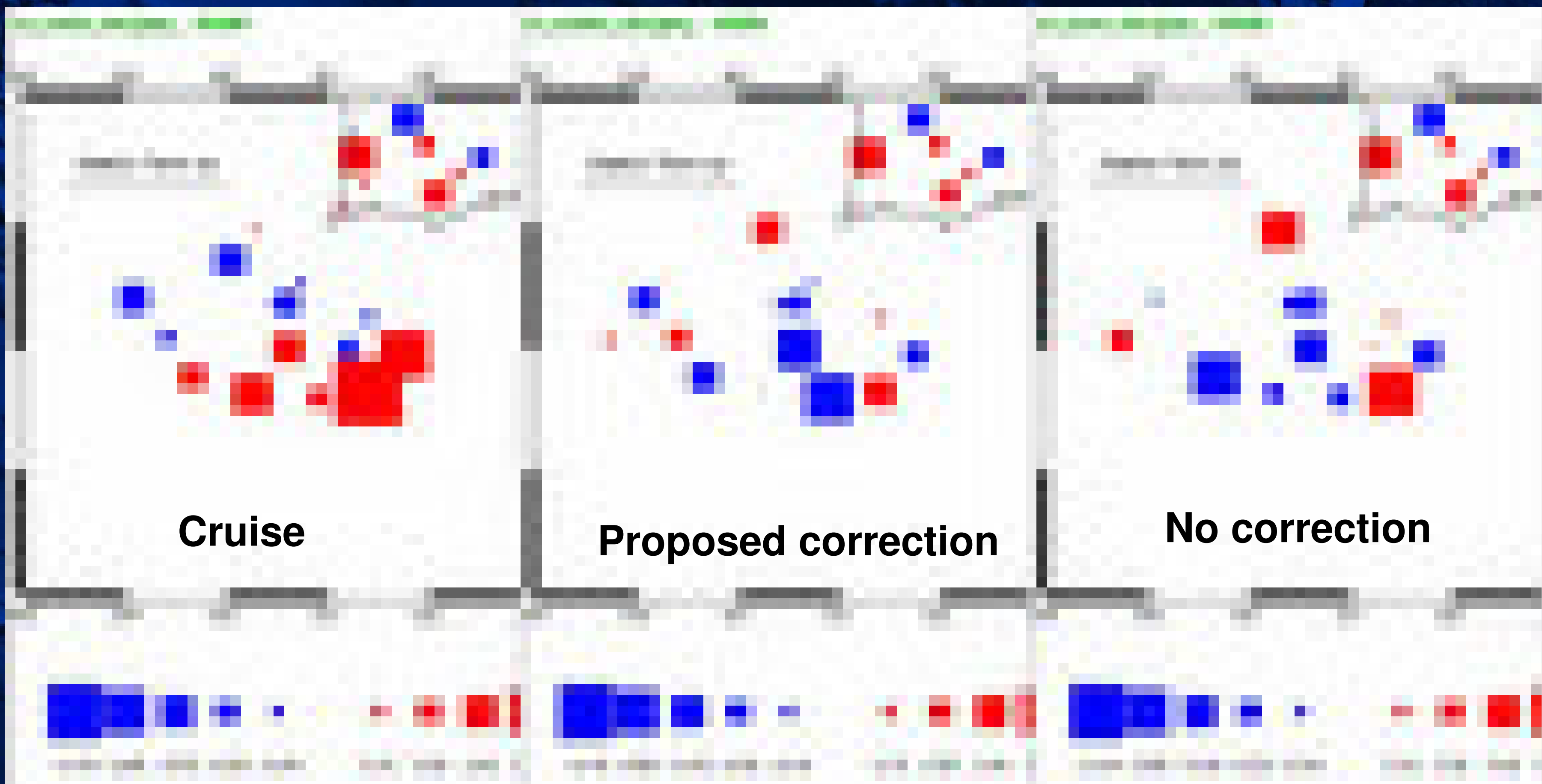
Average station delays



Average station delays



Station terms from tele-seismic tomographic inversion




Success?
Thank You!