6. Kinematic GPS and Applications

Tectonic Geodesy

GEOS 655

Kinematic GPS

Development of Kinematic GPS

- Research on GPS on kinematic platforms dates to 1980s.
- With ambiguities resolved, change in phase relates mainly to change in position.
- Demonstrated roughly centimeter-level positioning
  - Requires a fixed reference receiver near moving receiver.
  - Near means within a few to few tens of kilometers
- If you can position a vehicle, why not a site that moves because of dynamic earth/ice movements?
  - It took a while to recognize how precisely you can do it.
- But if you are interested in change in position over time, you may not need to resolve ambiguities.

Present Applications

- Rapid surveying/vehicle tracking
  - At UAF: positioning the plane for glacier laser altimetry
- Seafloor geodesy (buoy tracking)
- Ice motion
  - sub-daily, diurnal, tidal fluctuations
- GPS Seismology
- Tidal studies (e.g., ocean loading)

Ambiguity Resolution

- One way to estimate the ambiguities is to use a combination of phase and pseudorange, because the difference has only the ambiguity
- The difficulty with this is the noise level in the pseudorange data – you need to average for a while.
- The "float" solution has a real-valued estimate of ambiguity
  - The other complication is that there is an ambiguity for each frequency, but the ionosphere-free combination gives only one real-valued estimate (1 equation in 2 unknowns).

Widelaning and Narrowlaning

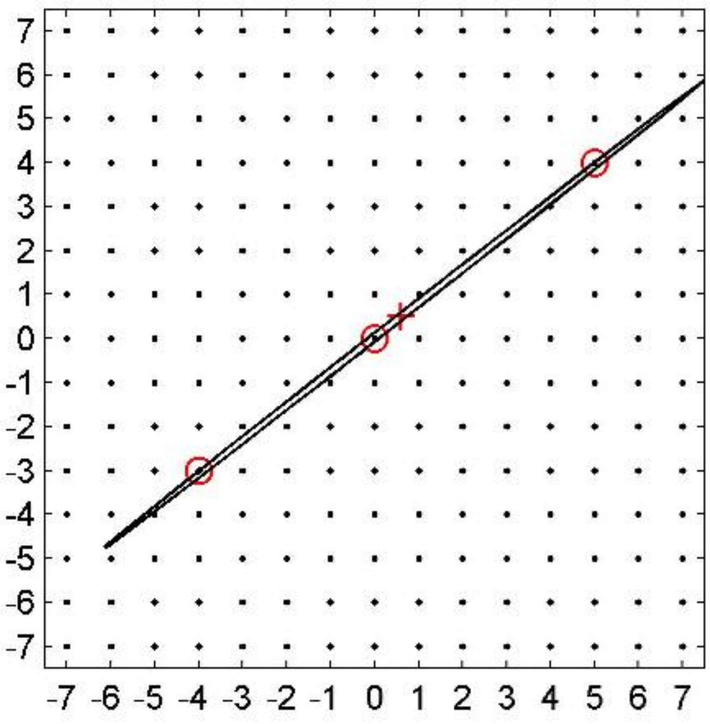
- There are some other linear combinations of the observables that are useful
  - Widelane: $\phi_1 - \phi_2$ has wavelength ~86 cm
  - Narrowlane: $\phi_1 + \phi_2$ has wavelength ~10 cm
  - The widelane ambiguity is particularly useful for ambiguity resolution, because it is relatively easy to average the pseudorange data down to give an estimate of the widelane ambiguity.
  - You can also estimate the widelane ambiguity by assuming that the (double-differenced) ionospheric delay is zero

Static Solution Ambiguity Resolution

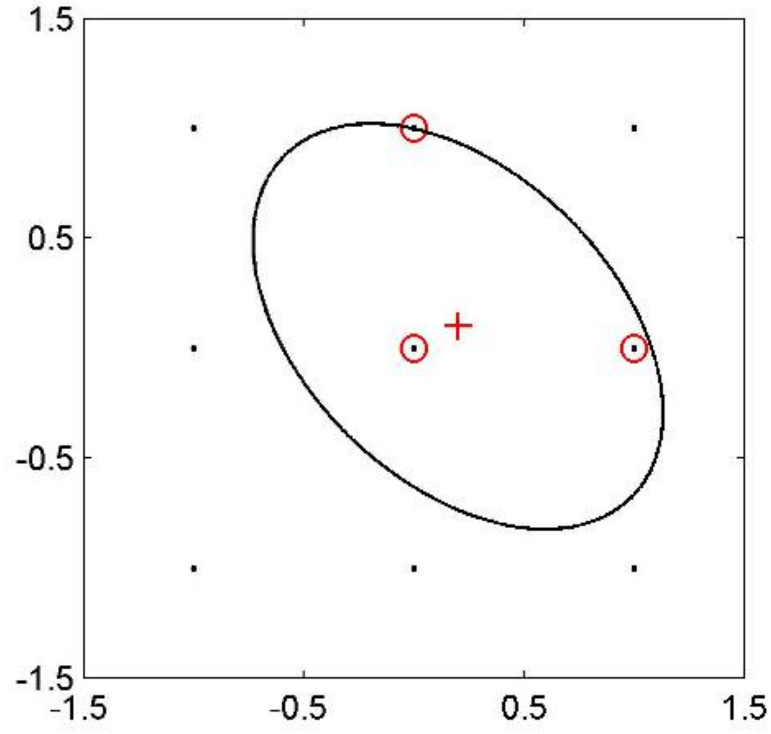
- Estimate float solution
- Resolve widelane ambiguities using
  - Pseudorange data
  - Ionosphere constraint
- Use fixed widelane bias and ionosphere-free bias estimate:
  - $B_{LC} = -n_1 f_1^2/(f_2^2 - f_1^2) + n_2 f_2^2/(f_2^2 - f_1^2)$
- Rewrite the above equation in terms of the widelane ambiguity: $n_W = n_1 - n_2$

Search-based Schemes

Identify possible candidate integer ambiguities based on "float" solution and covariance. Search all plausible candidates and find optimal.



True error ellipse

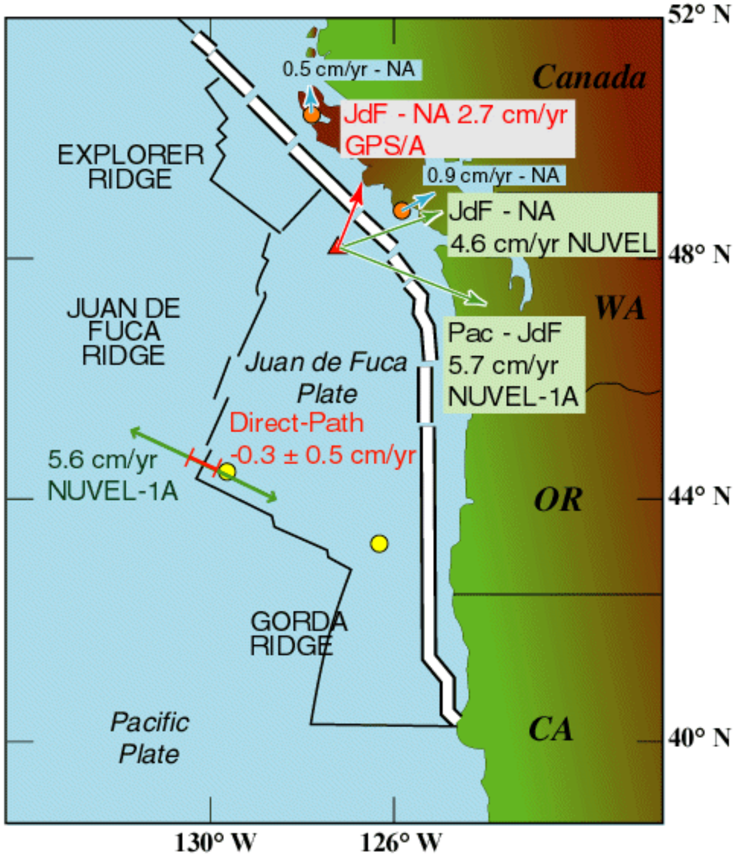


Decorrelated error ellipse

Ambiguity Searches 2

- Ambiguity function
  - Maximize sum over all satellites and all epochs of data of function
    - $Cos(2*pi*[\ \phi_{obs} - \phi_{pred}(x,y,z)])$
    - This term = 1 when predicted phase matches observed
  - Search is made by varying station position
- The key to any search-based method is to limit the number of candidates that must be searched.

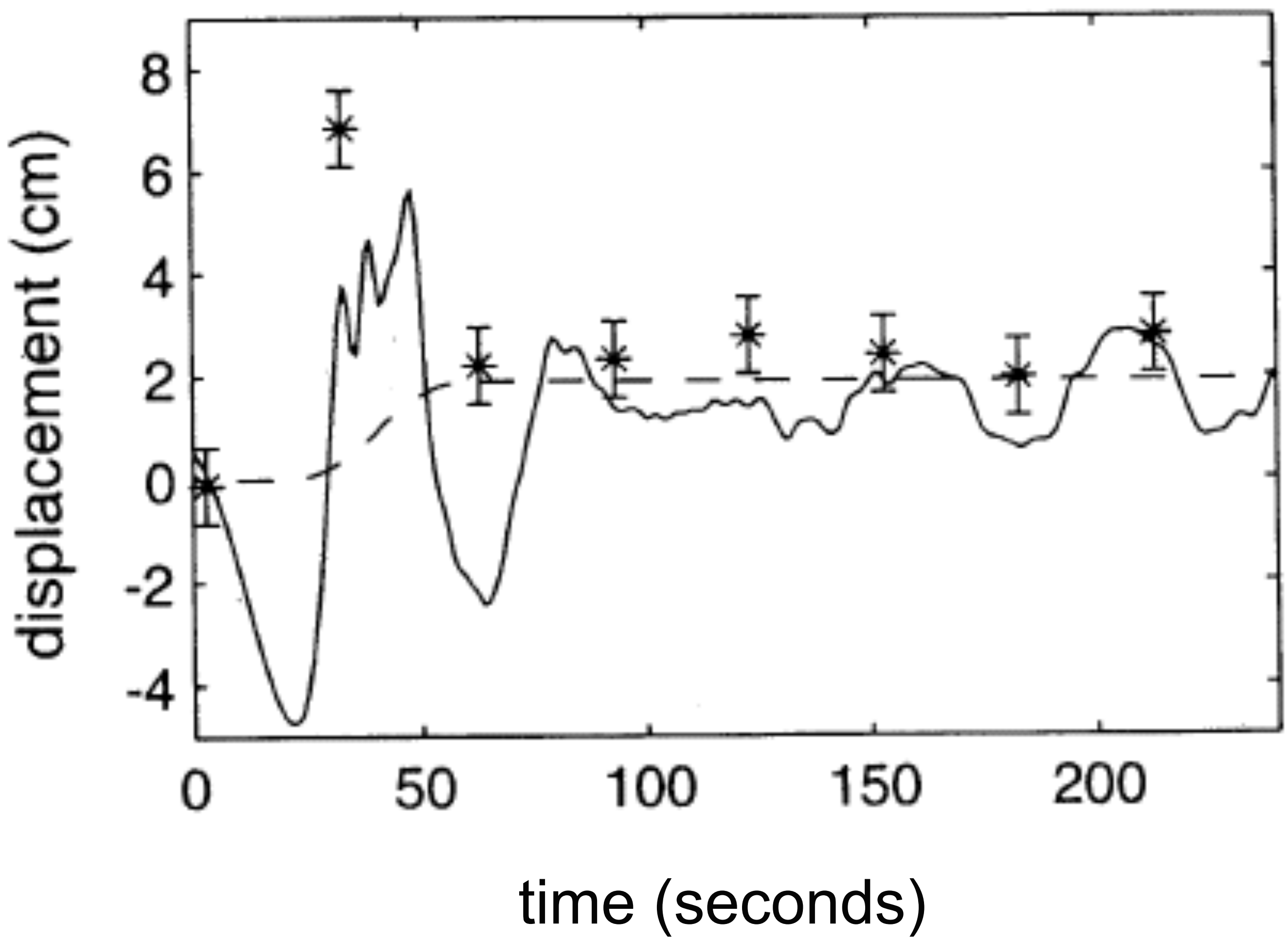
Seafloor Geodesy



Chadwell et al., 1999

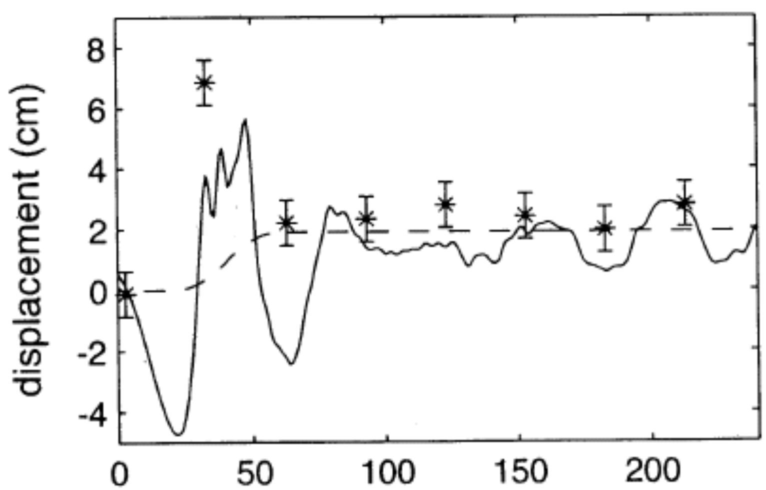
- Seafloor GPS project begun in early 1990s.
- GPS on buoy or ship
  - Positioned relative to satellites (GPS)
  - Positioned relative to seafloor transponders (acoustic)
  - Error mostly in water column velocity
- Measured Juan de Fuca convergence rate

GPS Seismology - 30 s



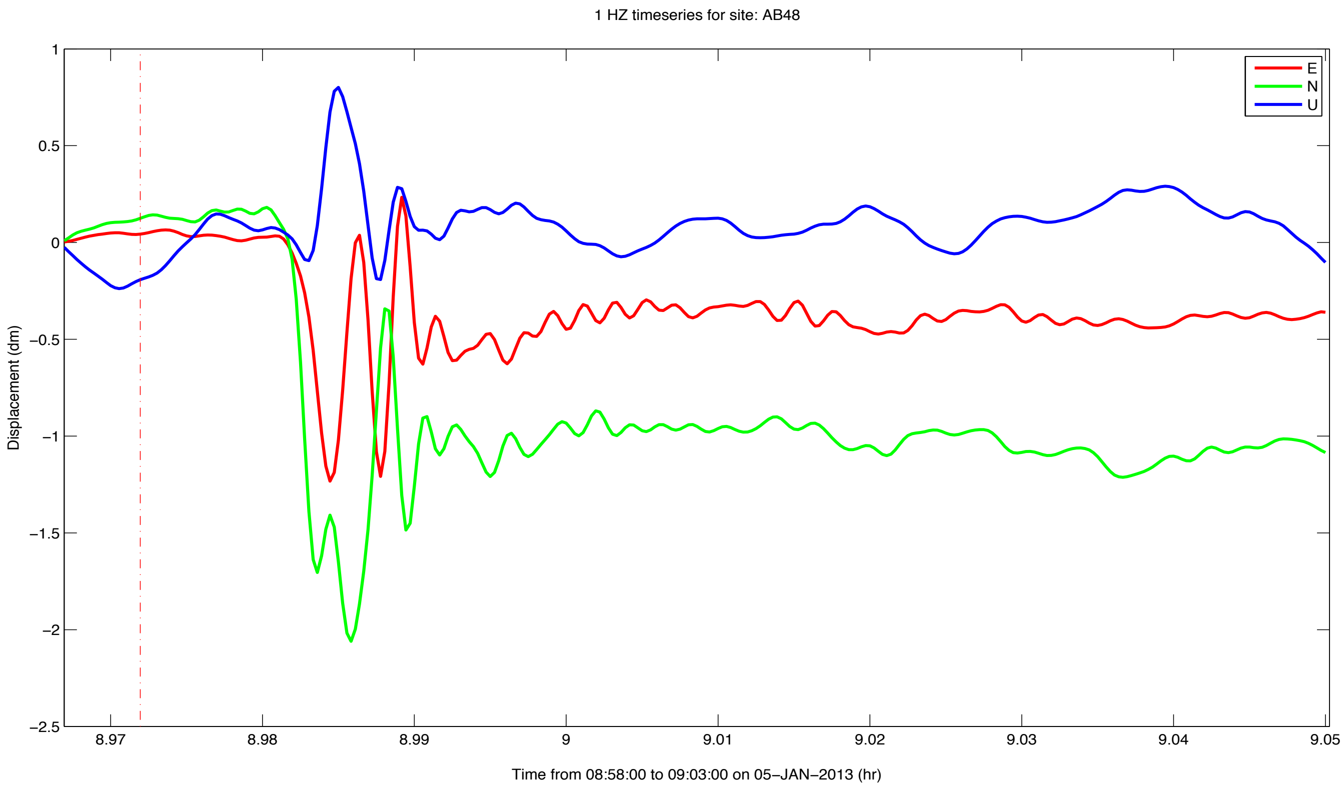
Hector Mine Earthquake *Nikolaidis et al.,* 2001 (JGR).

Nikolaidis and Bock result



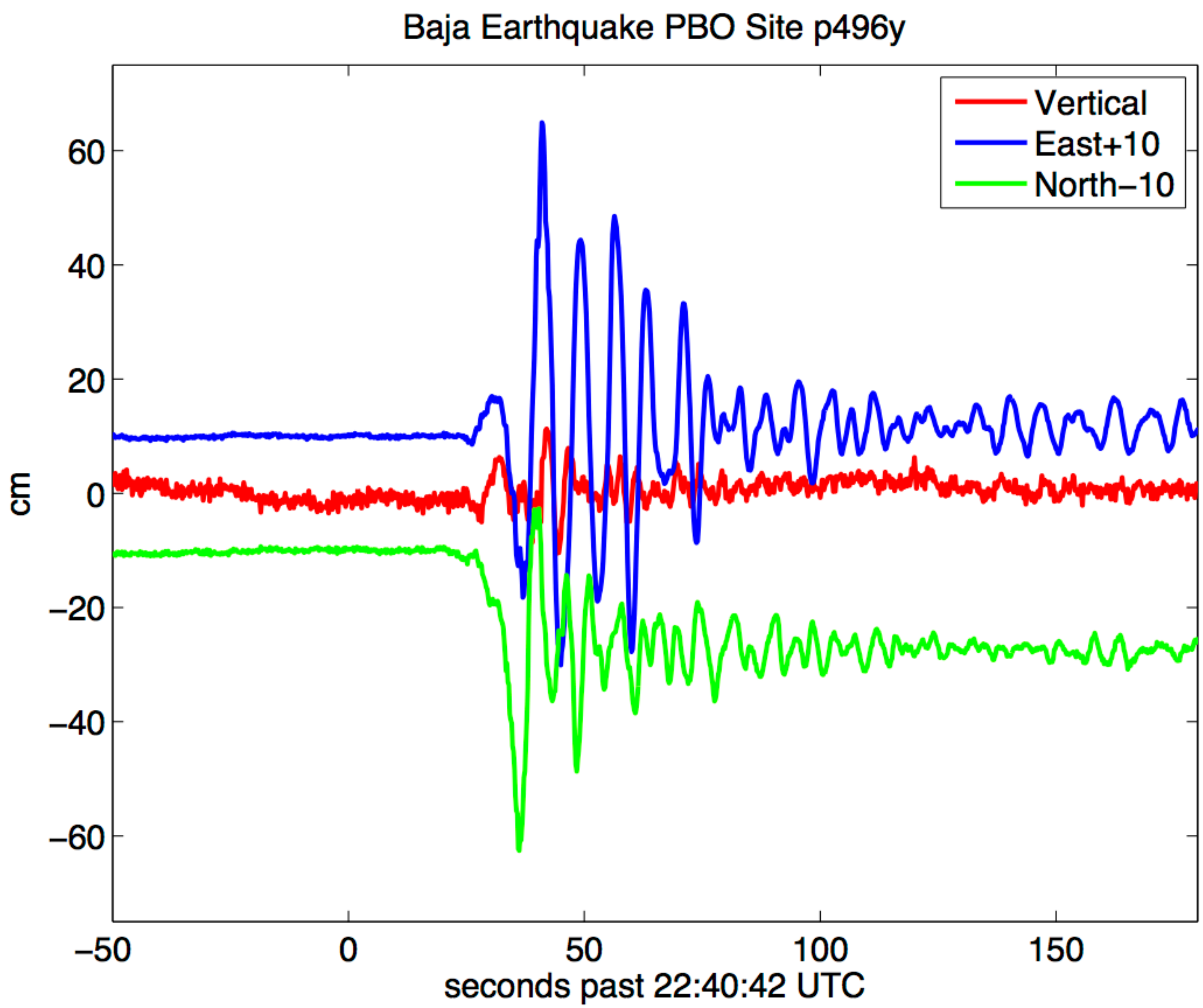
- Analyzed southern California data from time of 1999 Hector Mine earthquake
- Resolved ambiguities every epoch!
- Detected static displacement and transient point at time of seismic wave passage.

2013 Craig Earthquake

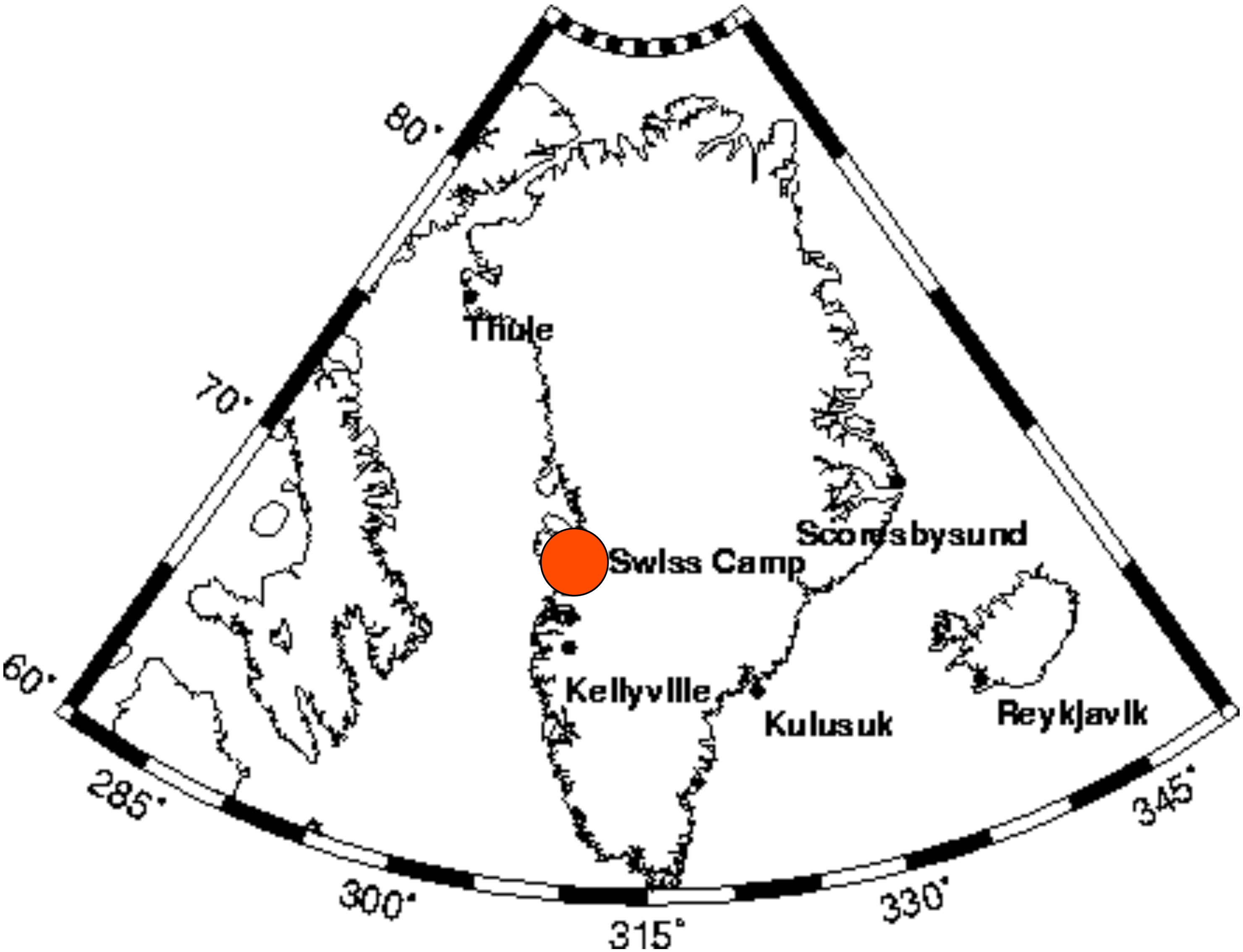


Kristine Larson
University of Colorado

El Mayor-Cucapah Earthquake



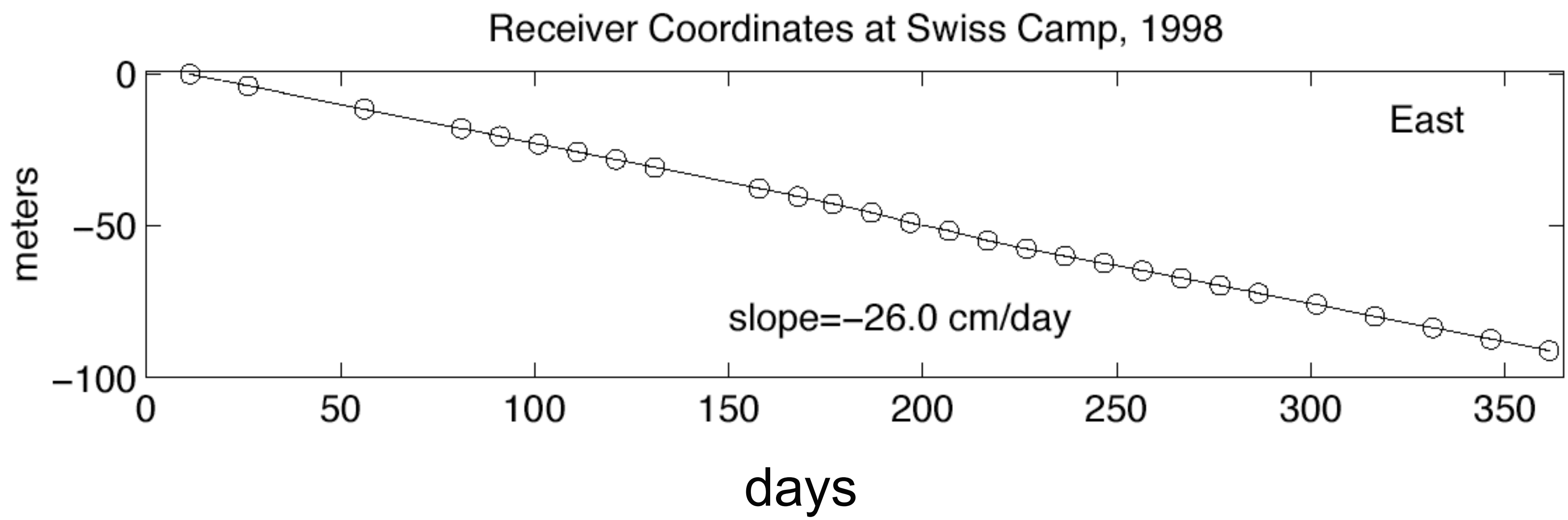
Greenland Ice Sheet



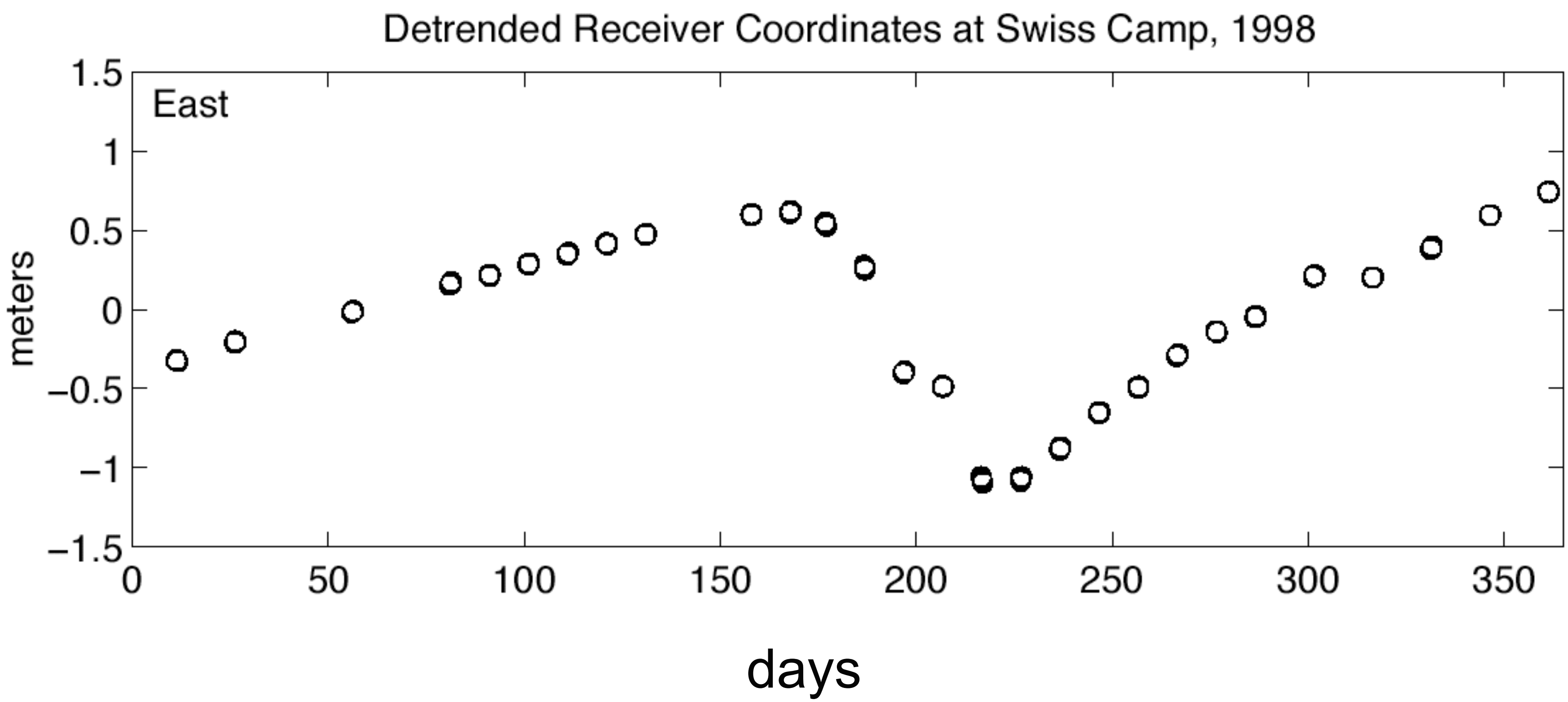
Swiss Camp

Zwally et al., 2002, *Science*

Full constellation; observations 10 hours every 10 days;
Remove assumption that the receiver doesn't move.

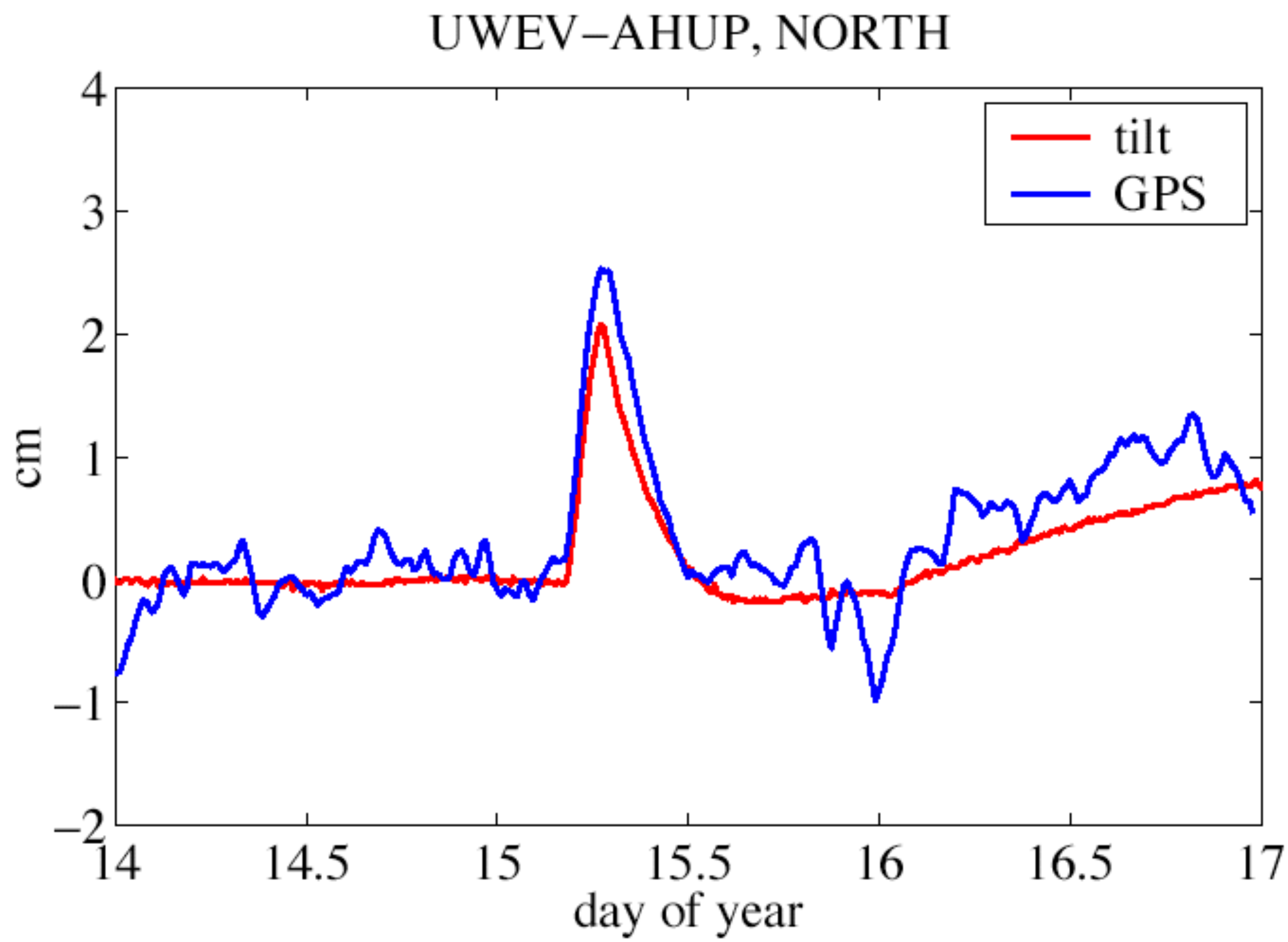


Seasonal variations related to melt-water at the ice-rock interface.



Volcano Monitoring

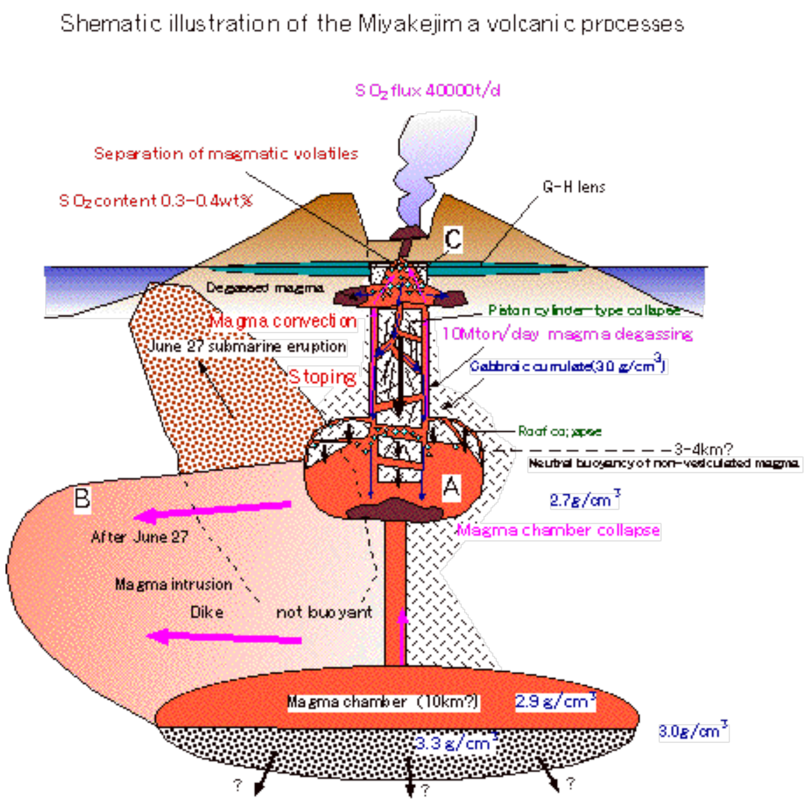
15 minute (filtered) averages of 5 minute observations



Kilauea Volcano

Larson et al. (2001).

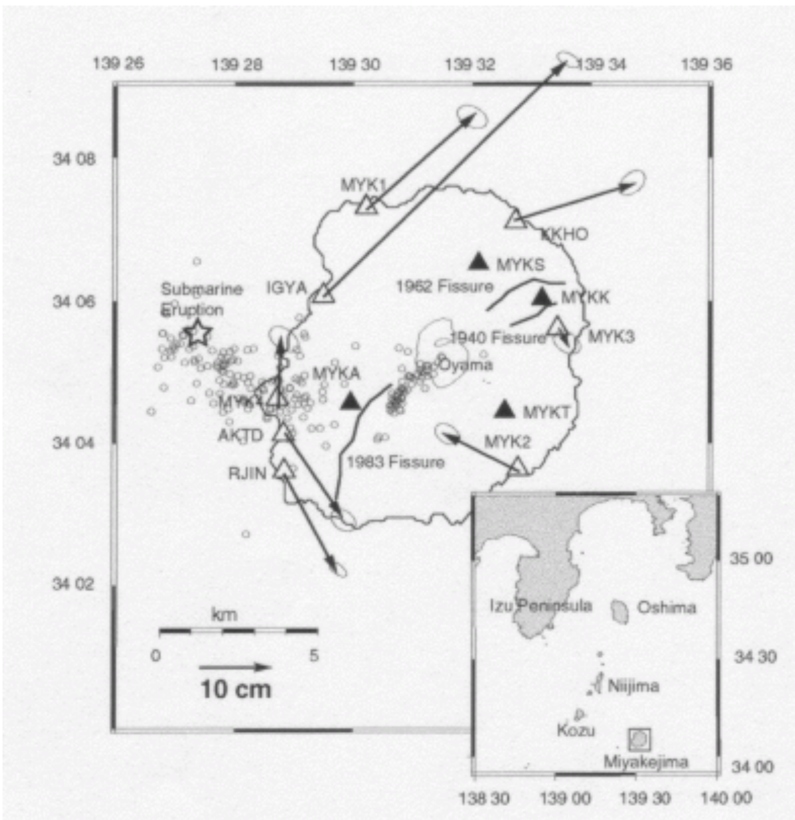
Miyakejima 2000 Eruption



Kazahaya et al., 2000

- Miyakejima in Izu Islands, off Japan
- Major volcanic event or year 2000 (June-August)
  - Seismic swarm
  - Small seafloor eruption
  - Large dike intrusion
  - Caldera collapse

GPS Displacements

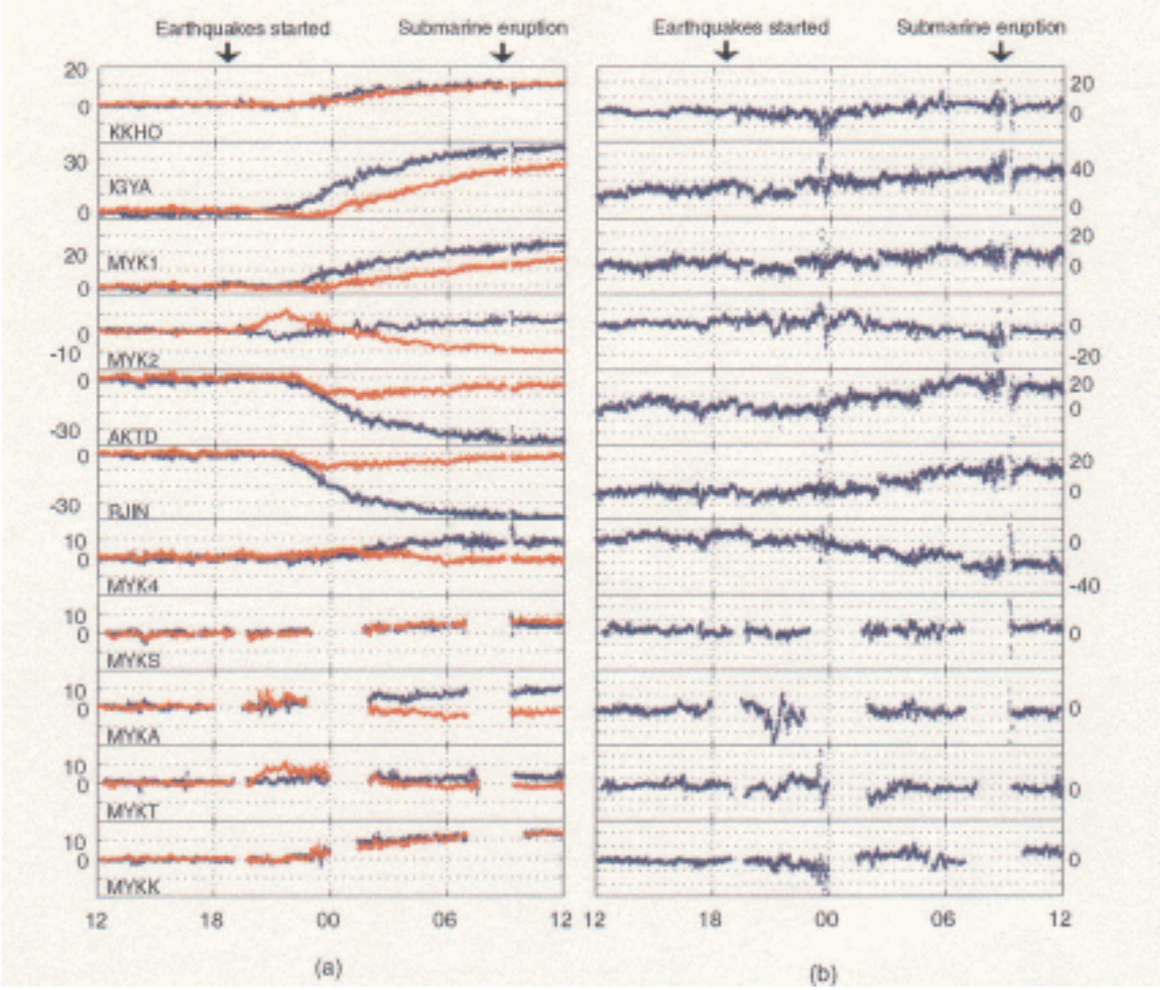


Irwan et al., 2003

- Several continuous GPS sites on island, and on nearby islands
- Identified mulitple phases in eruption from changes in deformation pattern
- Dramatic changes took place in first several hours.

Kinematic Displacement Records

Displacment components Residuals



- Analyzed GPS data on an epoch-by-epoch basis.
- Provides a kinematic displacement record with ~30 sec resolution

Why are GPS sites running at 1-Hz?

- NASA: low Earth orbit science missions.
- NGS: surveyors.
- Coast Guard (NGS): low precision navigation.
- FAA WAAS (wide area augmentation system): high precision real-time navigation.
- PBO Cascadia Initiative

IGS Real-time Network

GPS Static

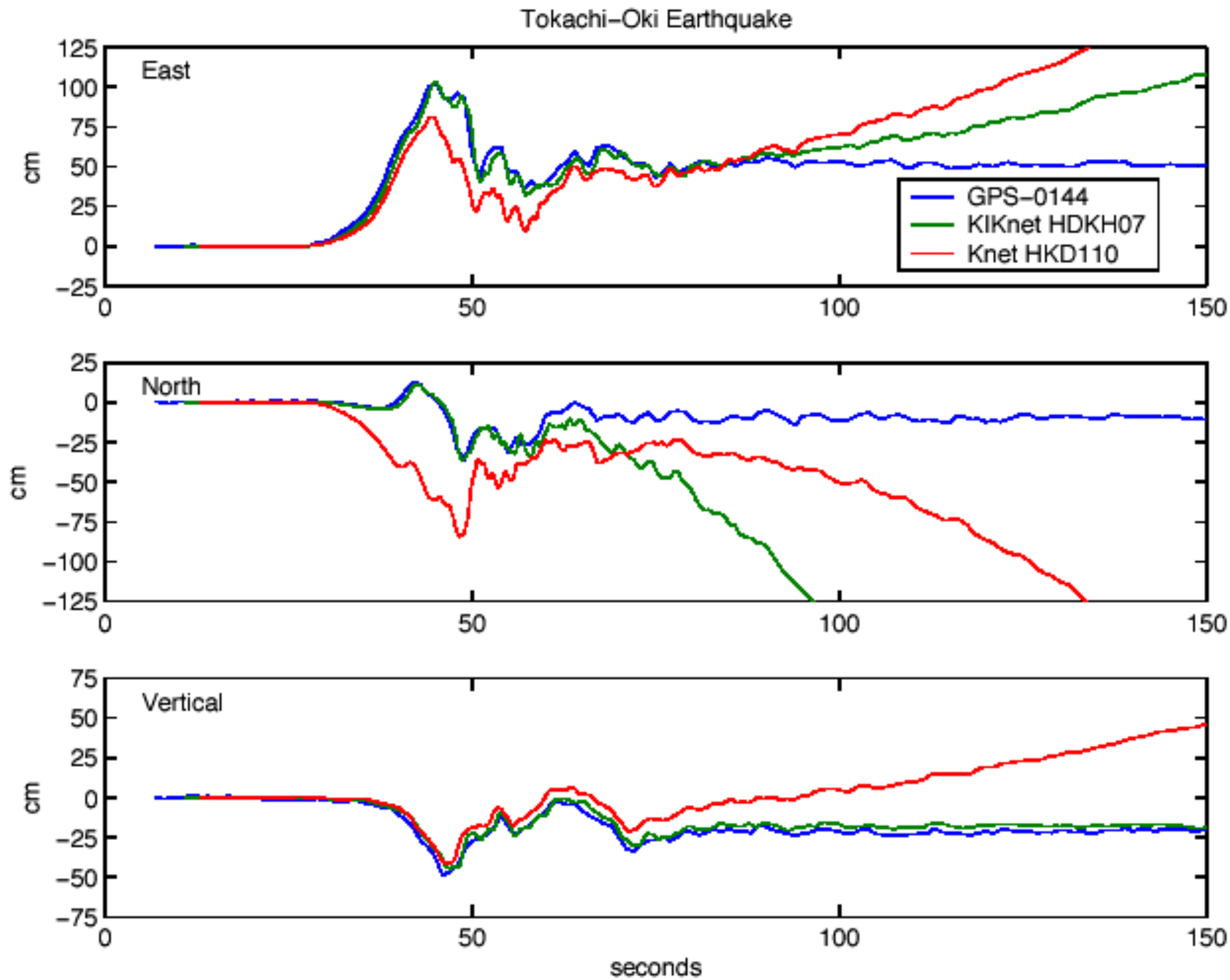
- Sample at 30 sec.
- Edit data.
- Decimate to 5 min.
- Orbits are held fixed.
- Estimate one position per day.

1 Hz Kinematic

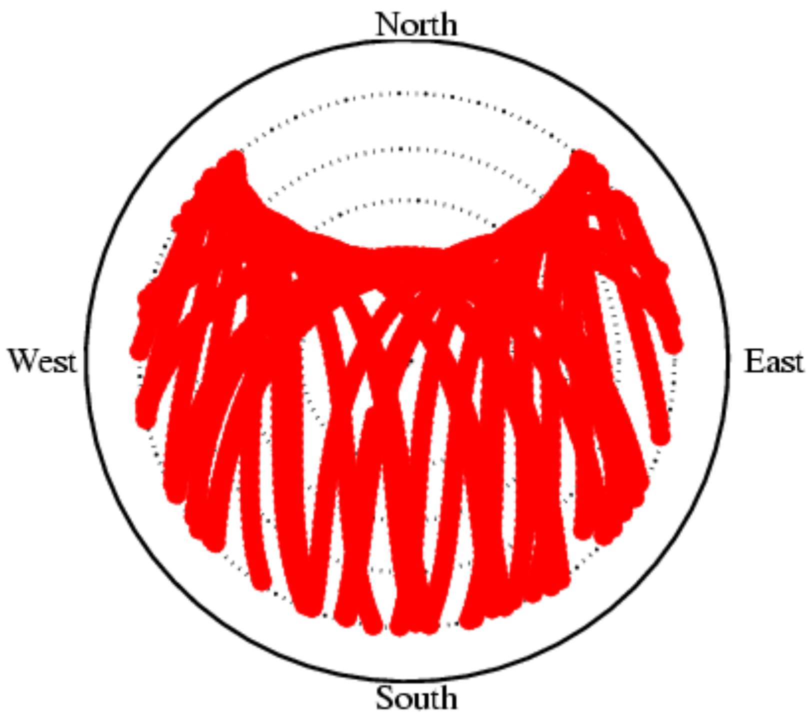
- Sample at 1 Hz
- Edit data.
- No decimation.
- Orbits are held fixed.
- Estimate one position per second.

The same software can be used to analyze the data in post-processing mode. There are also specialized kinematic solvers. Real time requires different software.

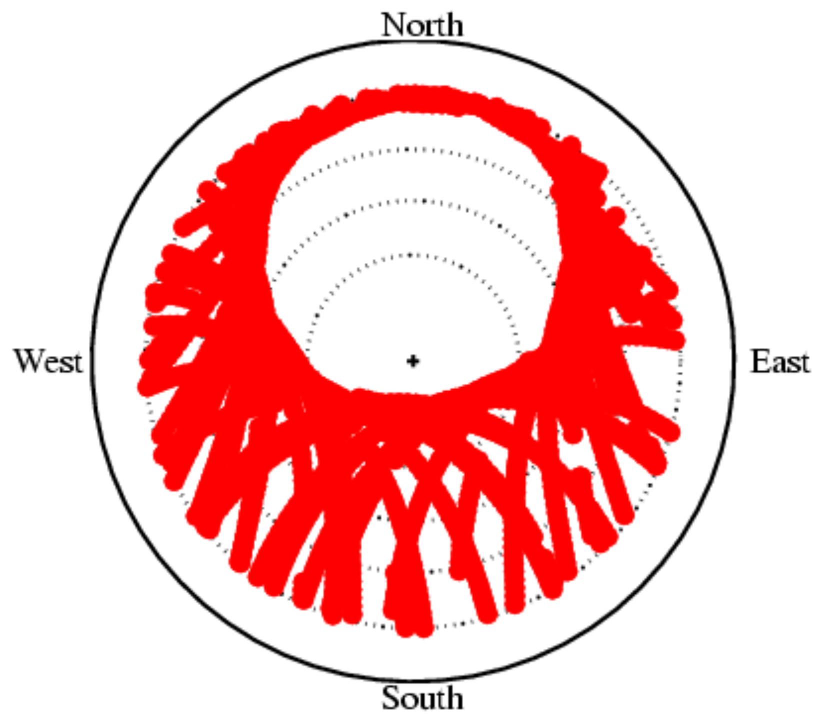
1 Hz GPS	Seismology
• Relative ground motions [i.e. to a site held fixed]	• Inertial local reference frame ground motions
• *Displacement* estimated	• *Acceleration* measured
• Insensitive to small ground motions, but (almost) no upper limit…	• Sensitive to small ground velocities or large accelerations


Tokachi-Oki Earthquake
East
cm
125
100
75
50
25
0
−25
0
50
100
150
GPS-0144
KIKnet HDKH07
Knet HKD110
North
25
0
−25
−50
−75
−100
−125
Vertical
75
50
25
0
−25
−50
−75
seconds

24 hours of GPS Data

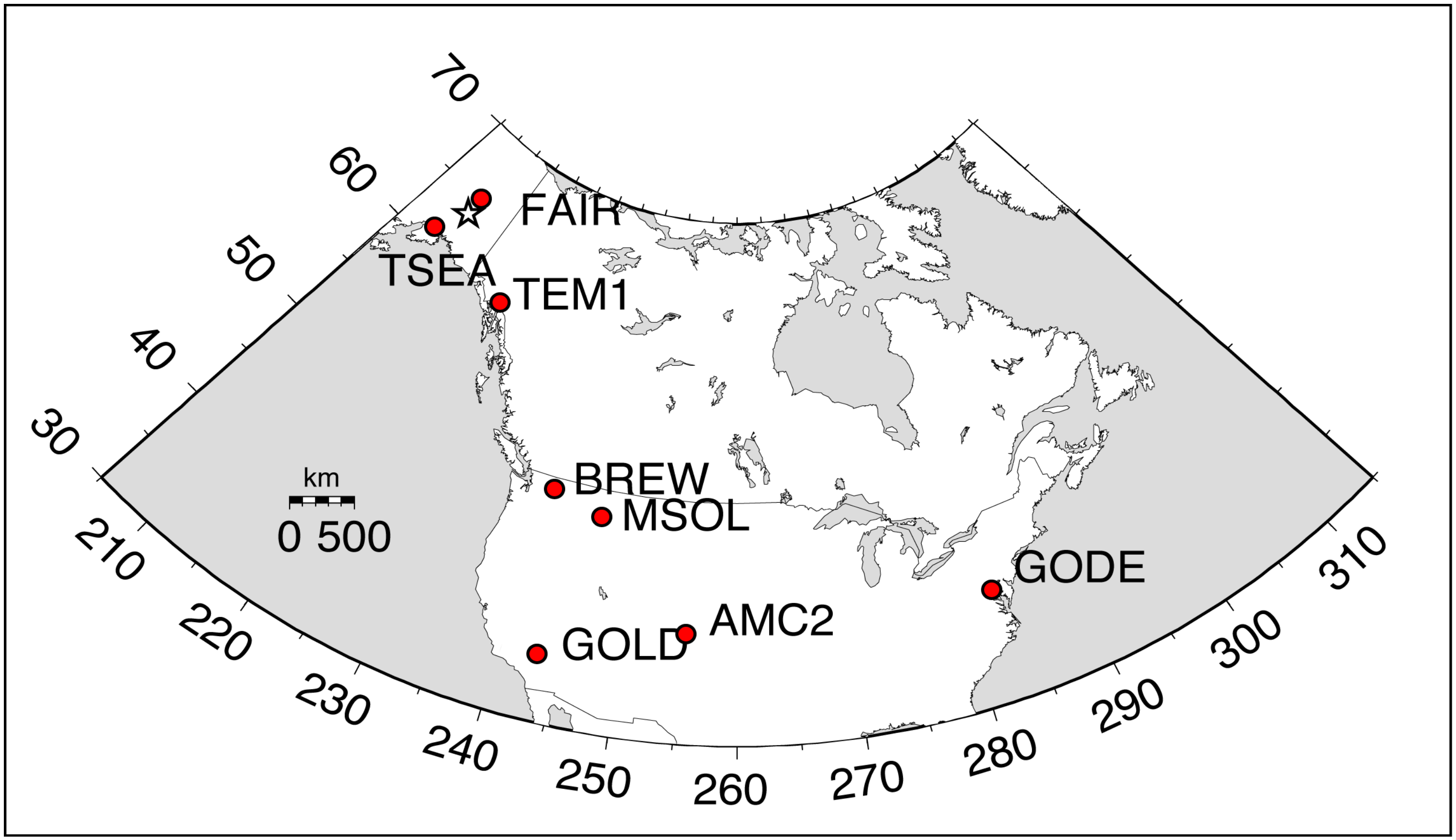


Southern California

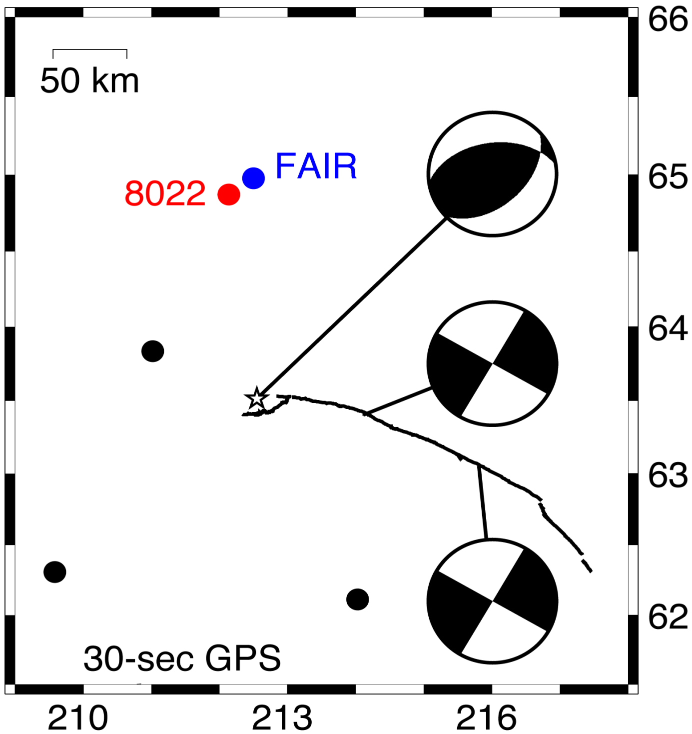


Fairbanks

Original Denali GPS Network

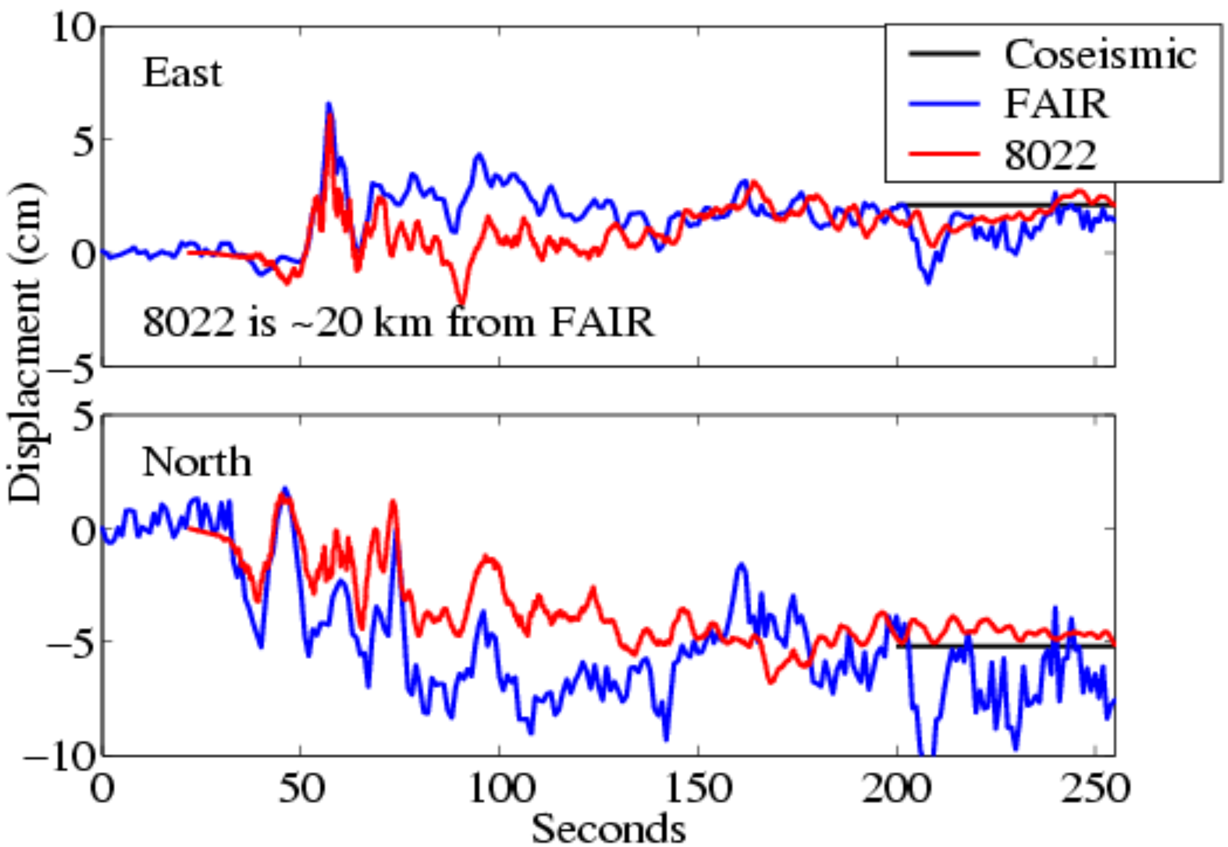


Denali Fault earthquake

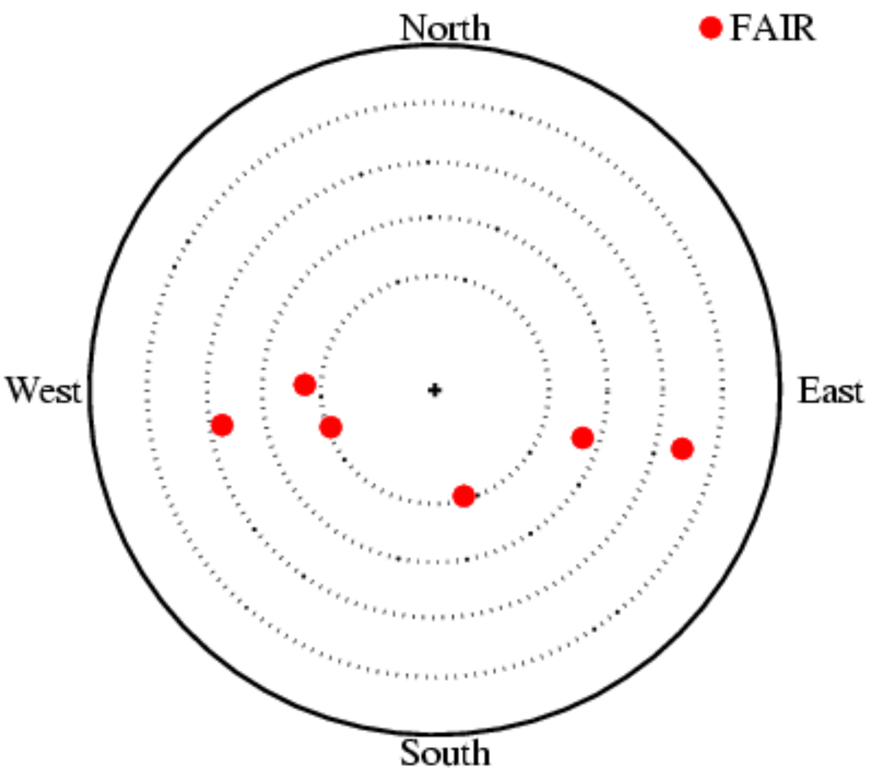


- 1 Hz GPS FAIR
- Strong motion 8022
- High-pass filtered to remove baseline drift.
- Fix co-seismic offset [*Eberhart-Phillips et al*., 2003]

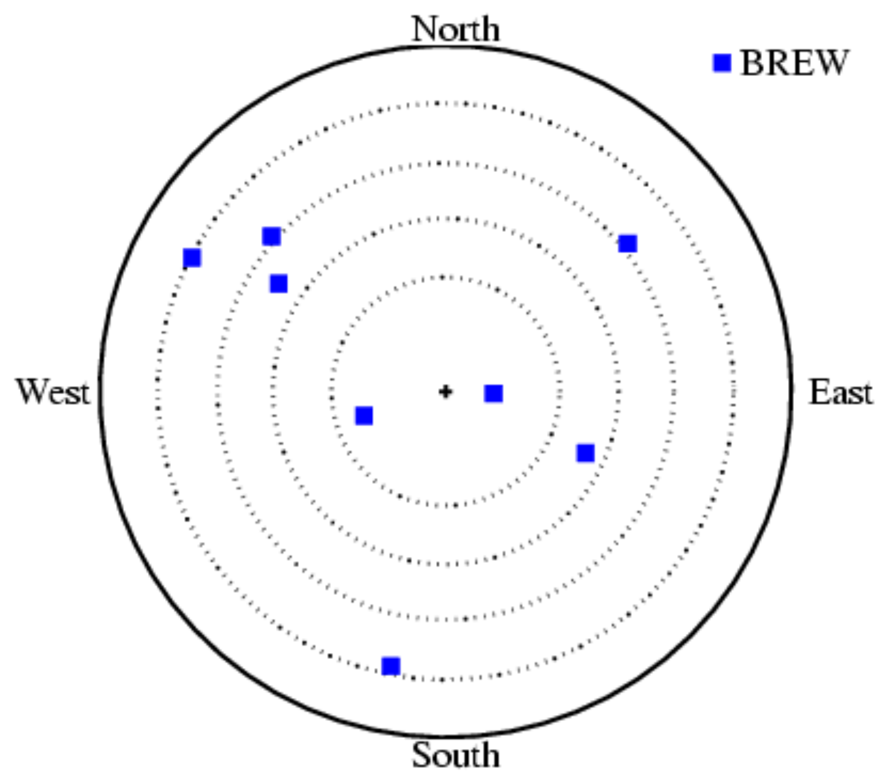
1 Hz GPS at FAIR



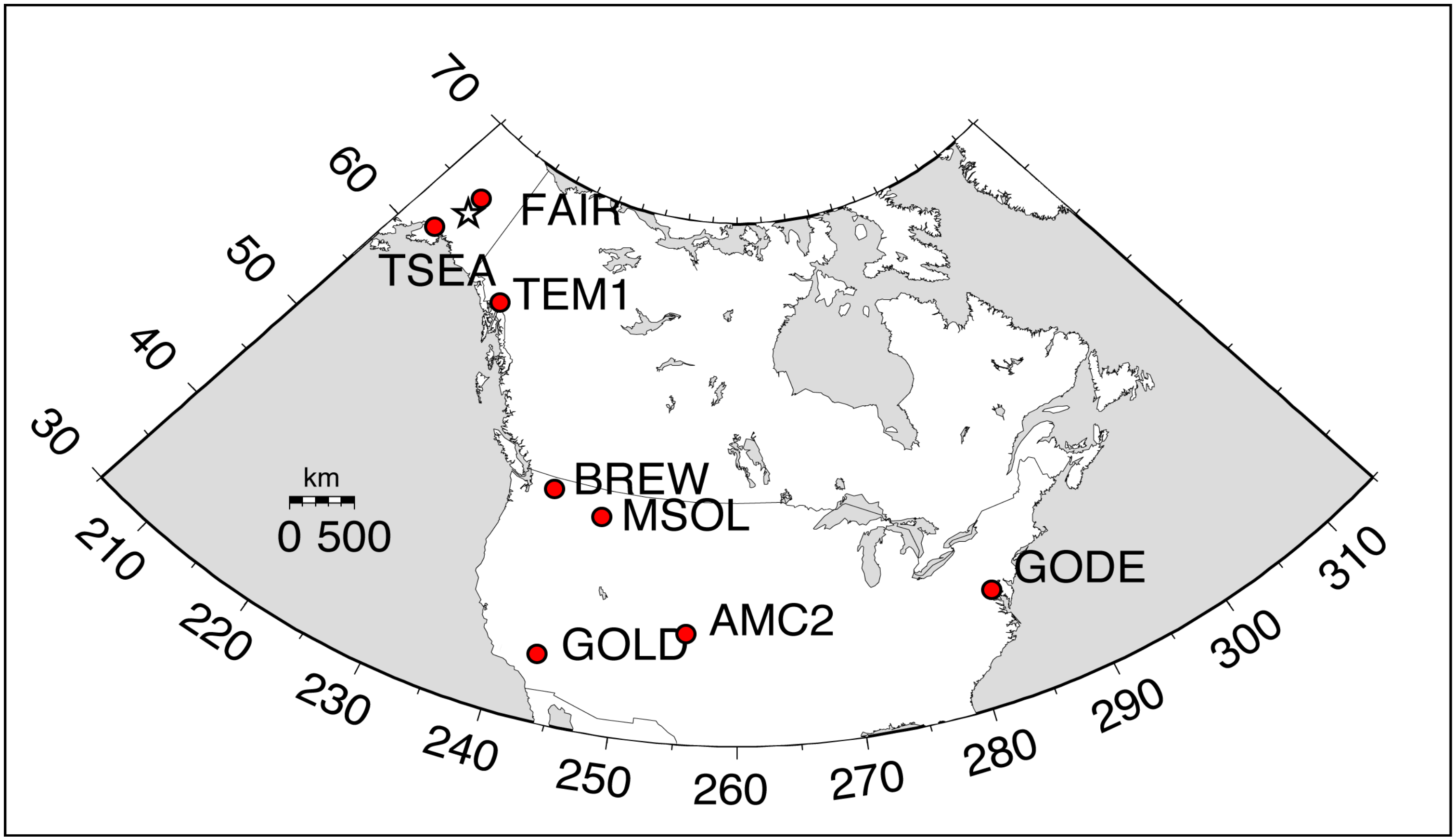
FAIR



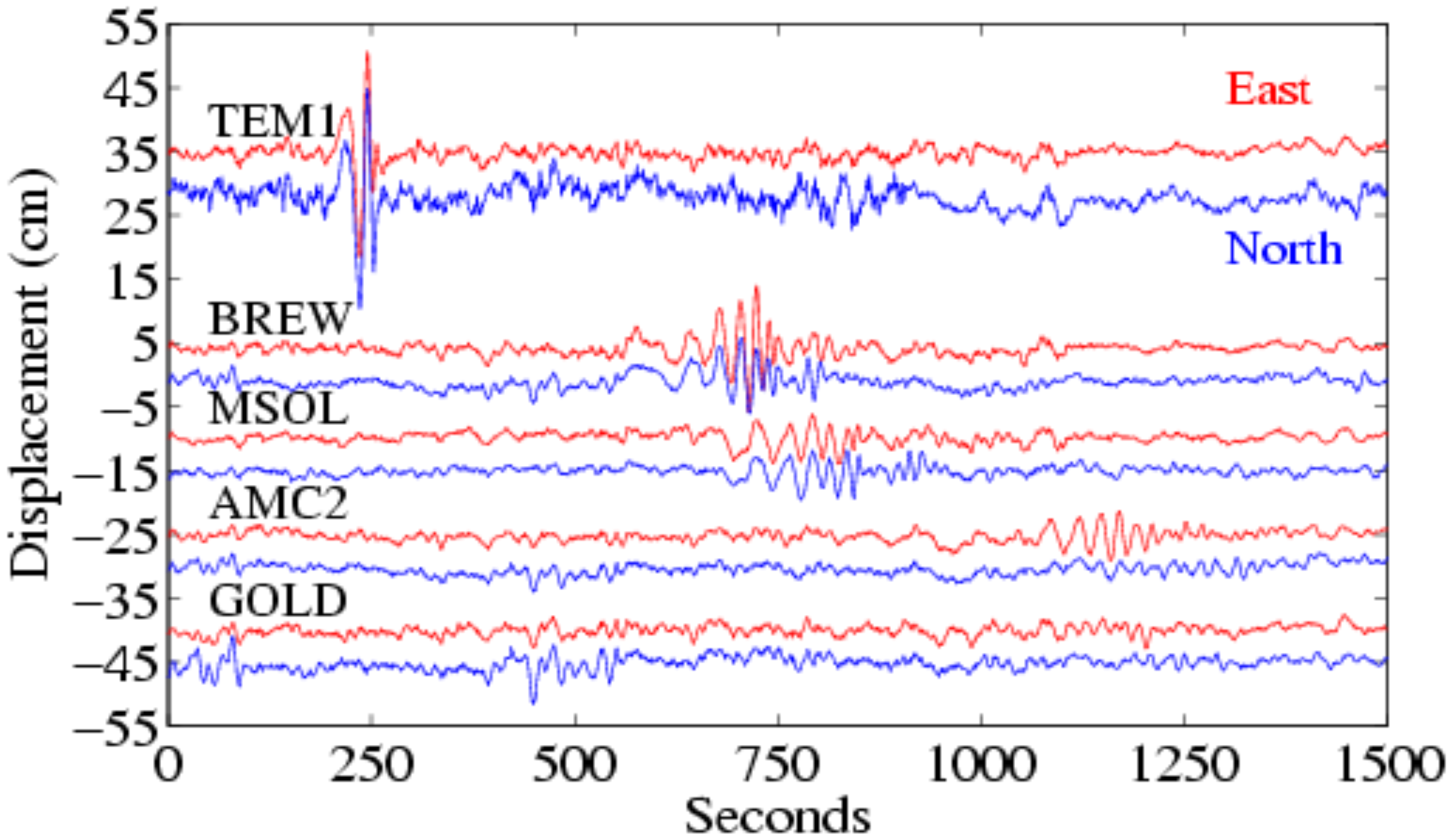
BREW



Surface Wave Observations

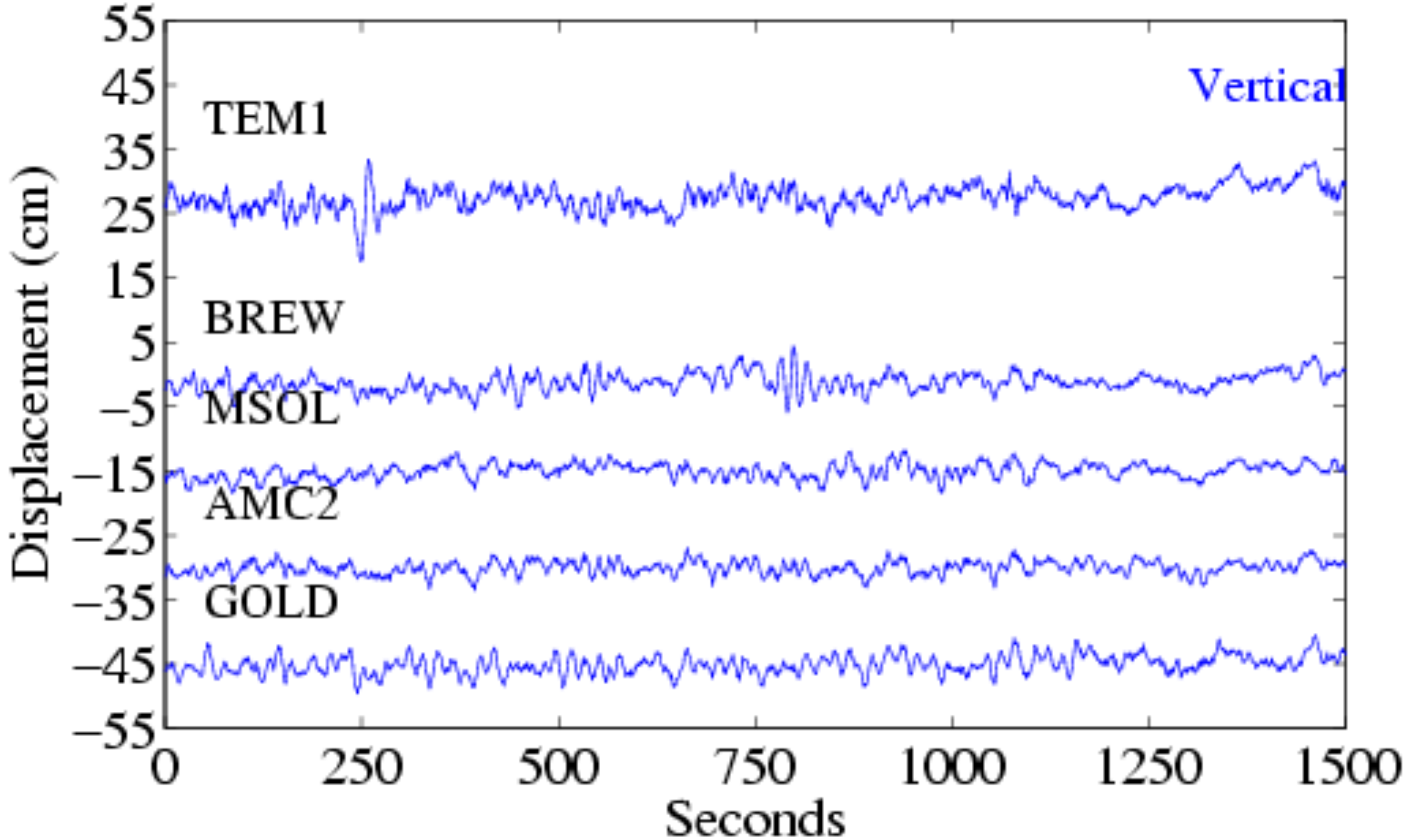


GPS Surface Waves



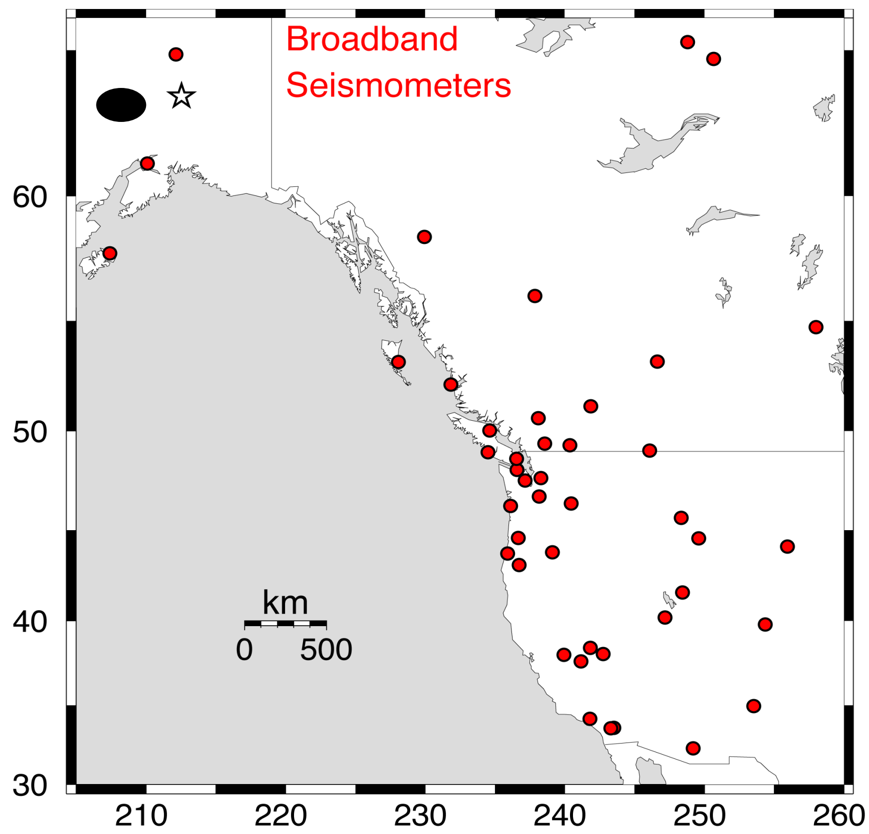
Larson et al., 2003, *Science*

Can GPS do the vertical?

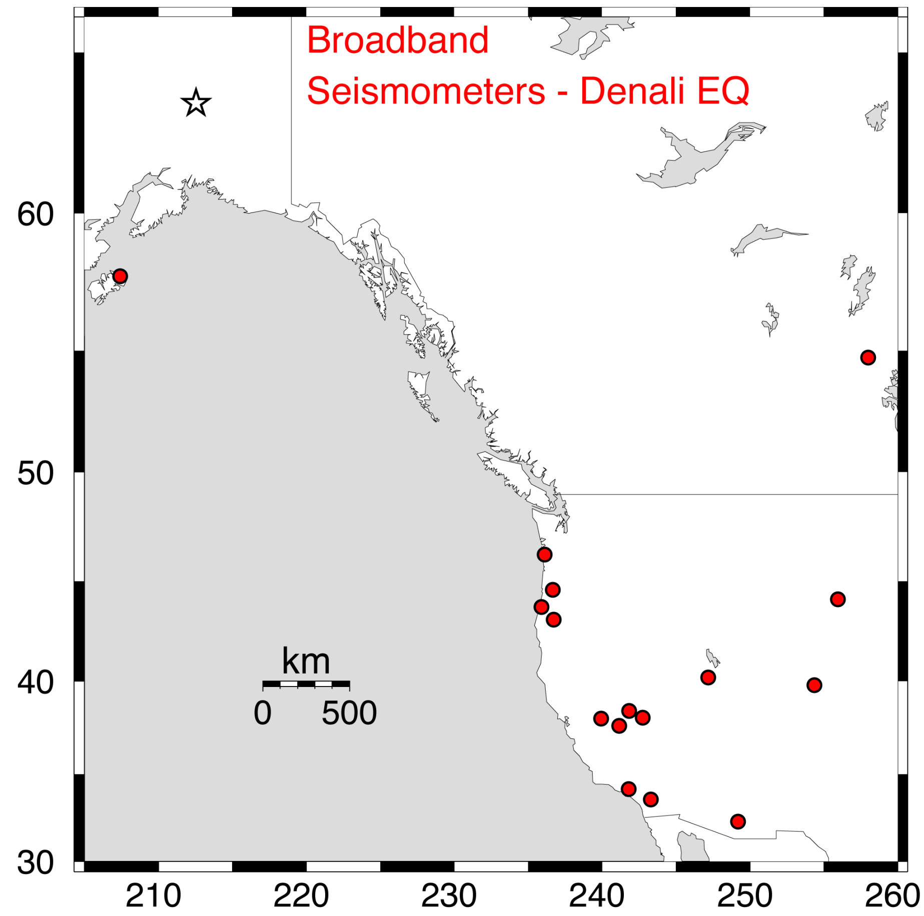


Yes, but not as well as the horizontals.

Denali Seismic Instrumentation

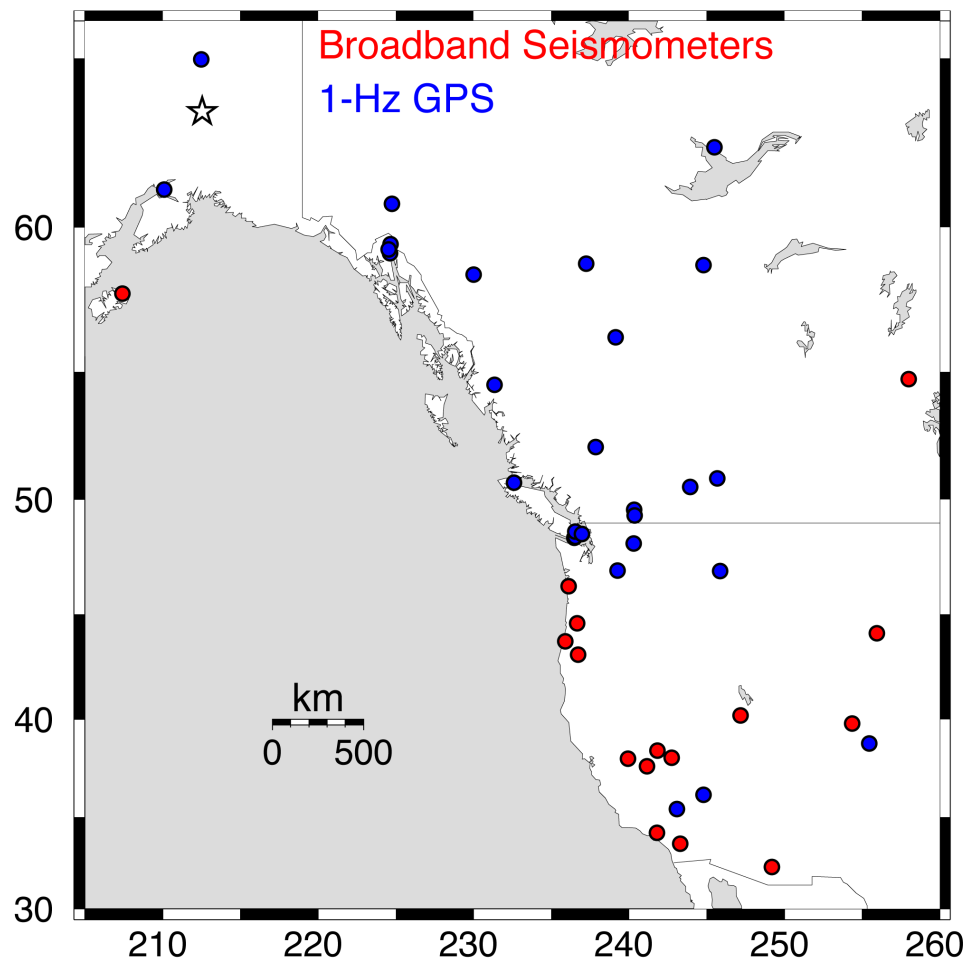


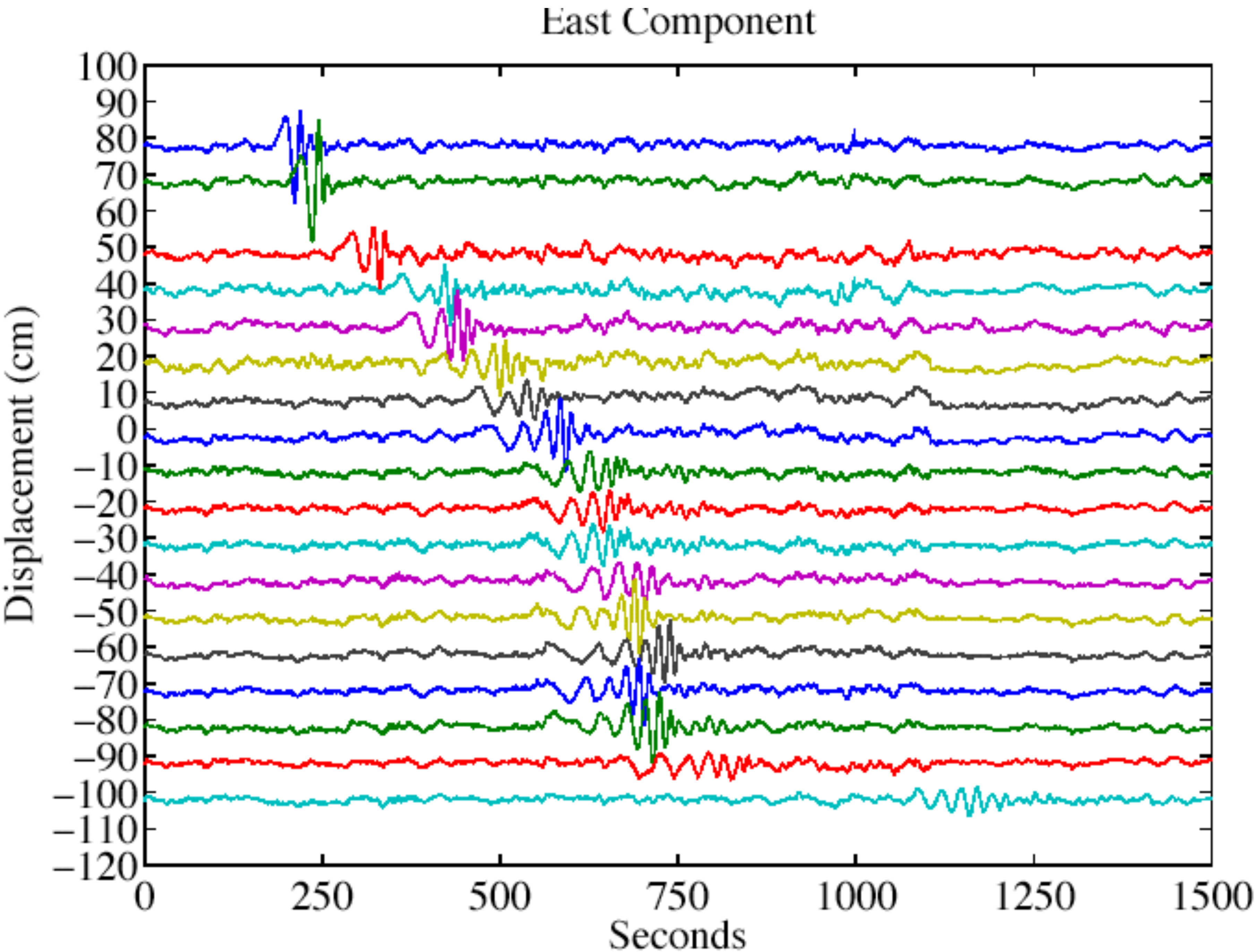
Denali Seismic Instrumentation



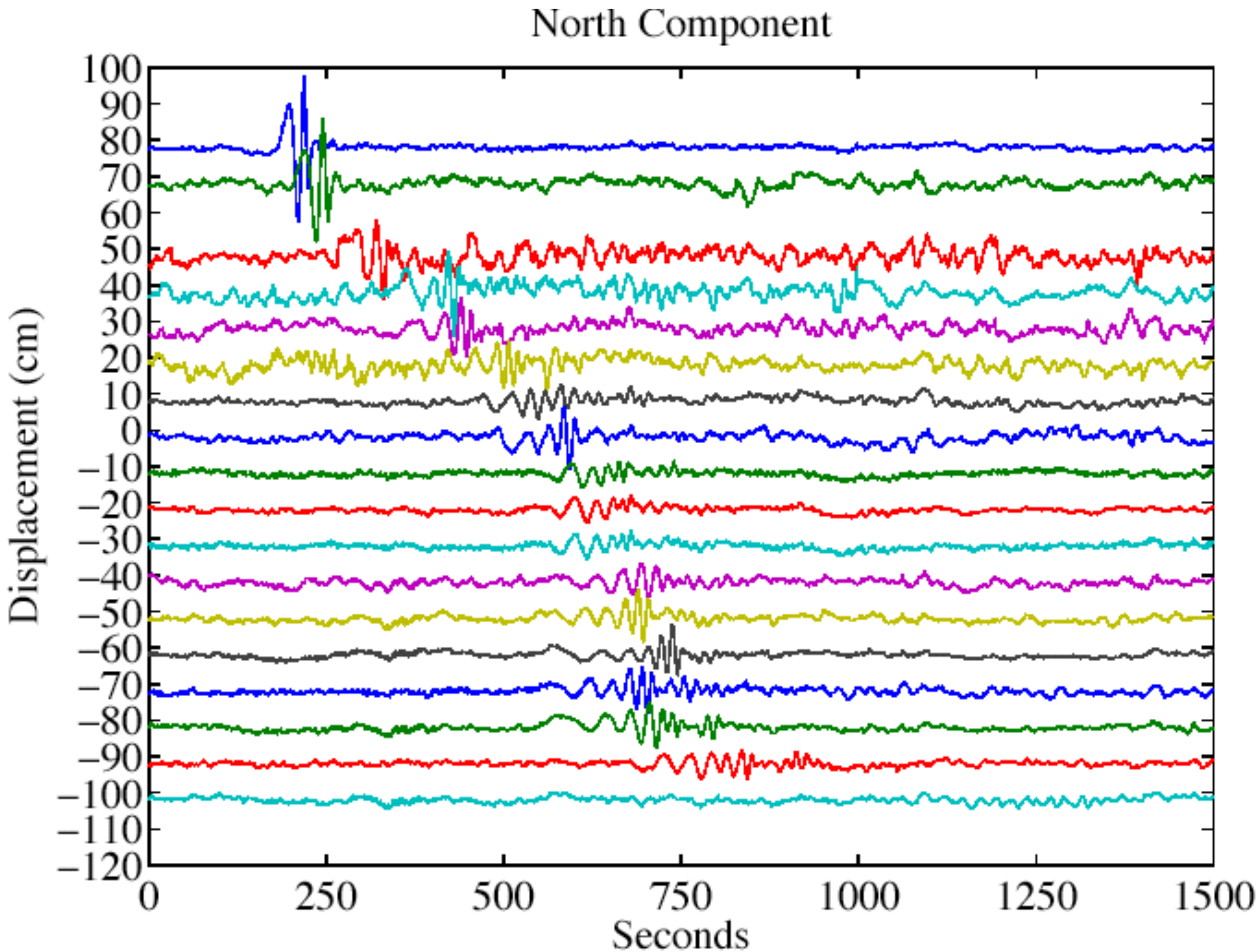
Sites that clipped (went off scale) removed

Denali Seismic Instrumentation

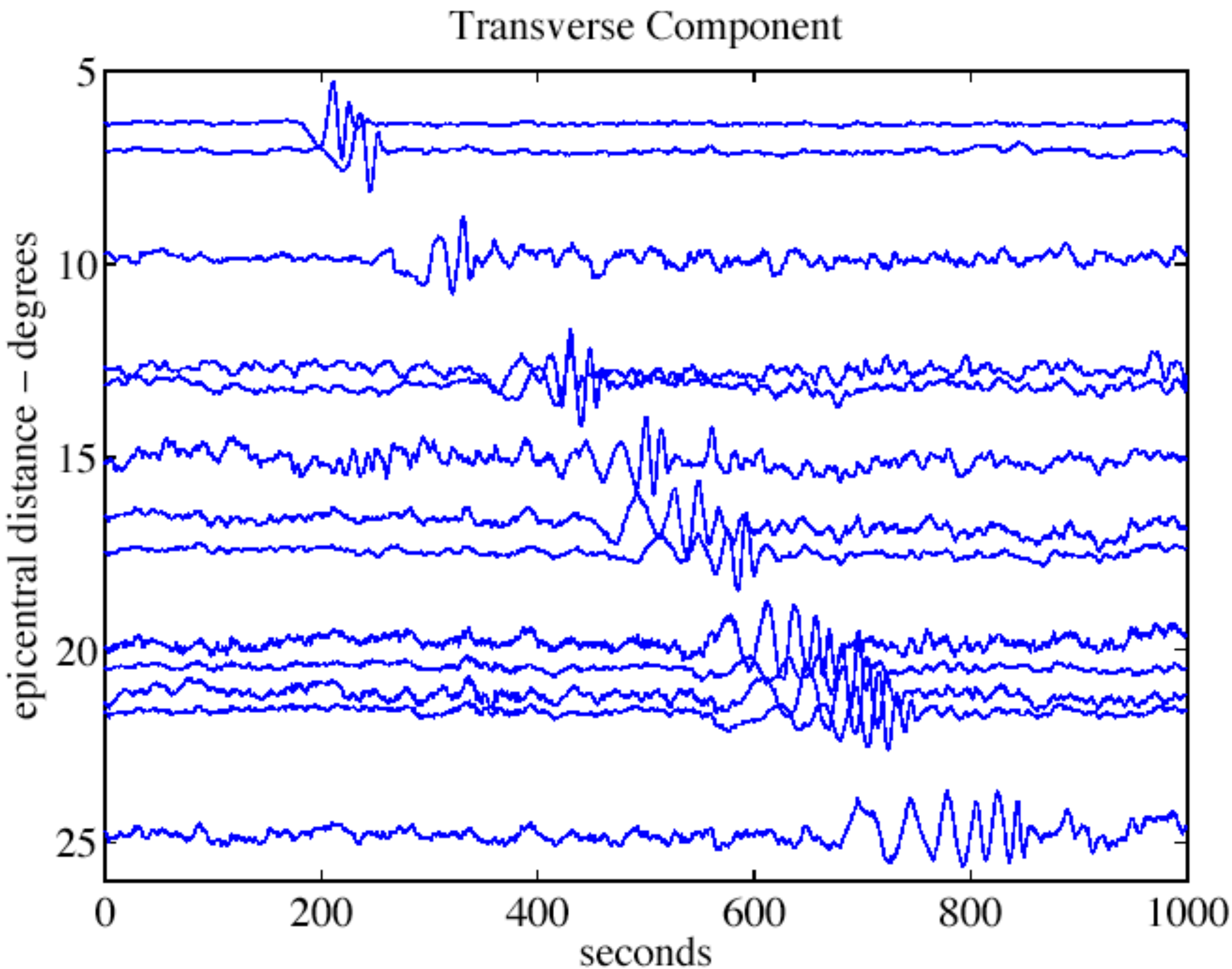


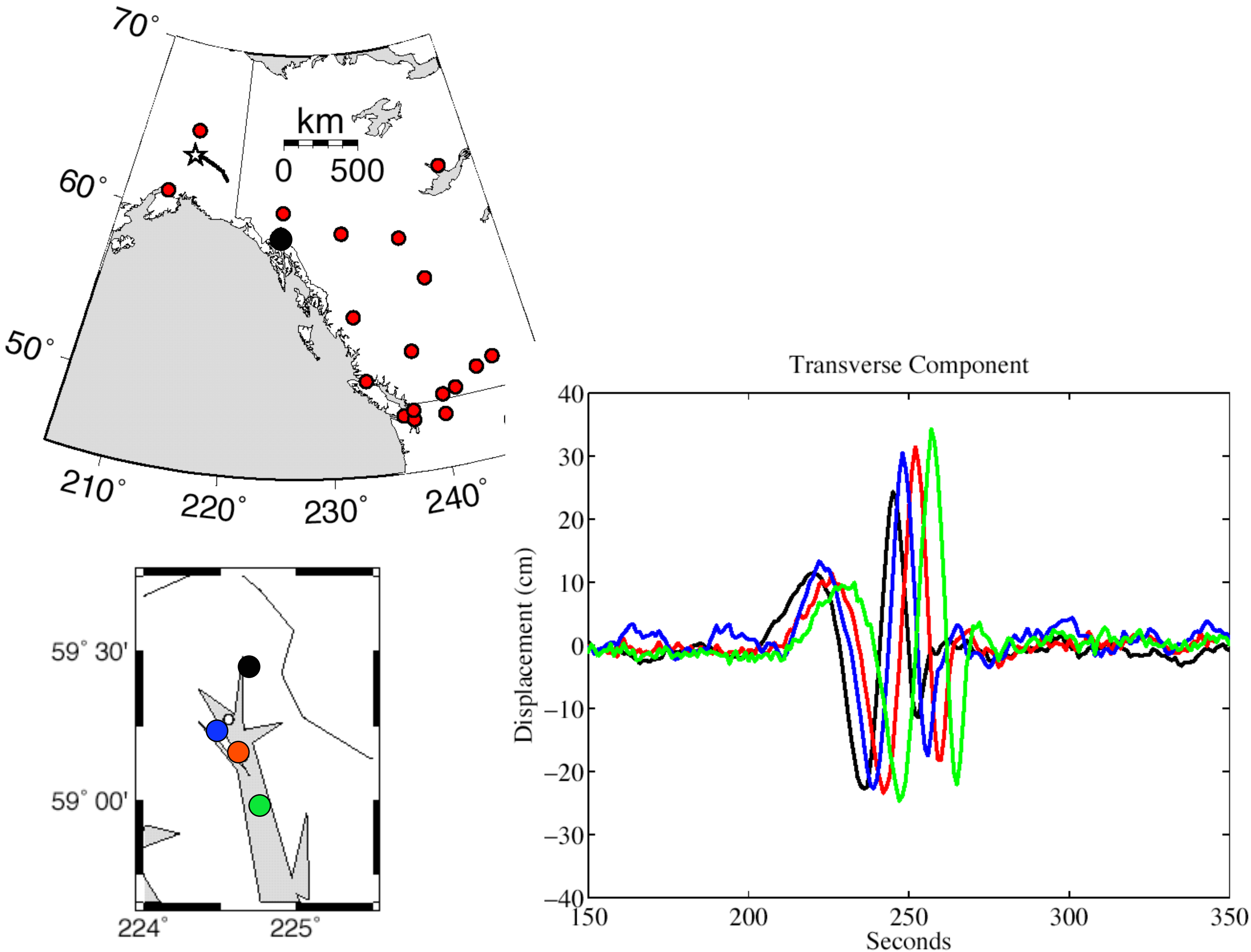


East Component
Displacement (cm)
Seconds
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
−110
−120
0
250
500
750
1000
1250
1500



North Component
Displacement (cm)
Seconds
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
−110
−120
0
250
500
750
1000
1250
1500


Transverse Component
5
10
15
20
25
epicentral distance – degrees
0
200
400
600
800
1000
seconds

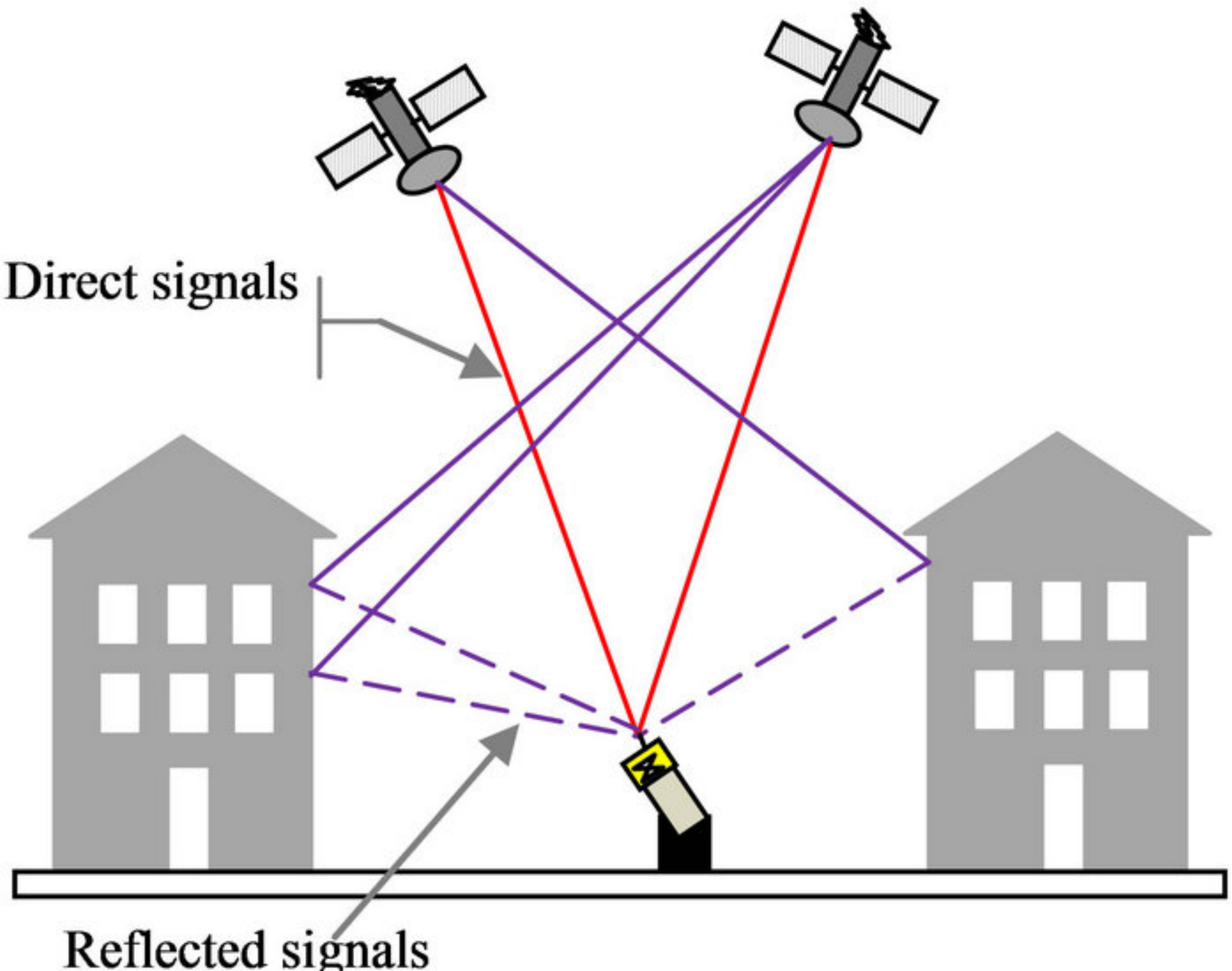


70°
60°
50°
km
0 500
210°
220°
230°
240°
59° 30'
59° 00'
224°
225°
Transverse Component
Displacement (cm)
Seconds
40
30
20
10
0
−10
−20
−30
−40
150
200
250
300
350

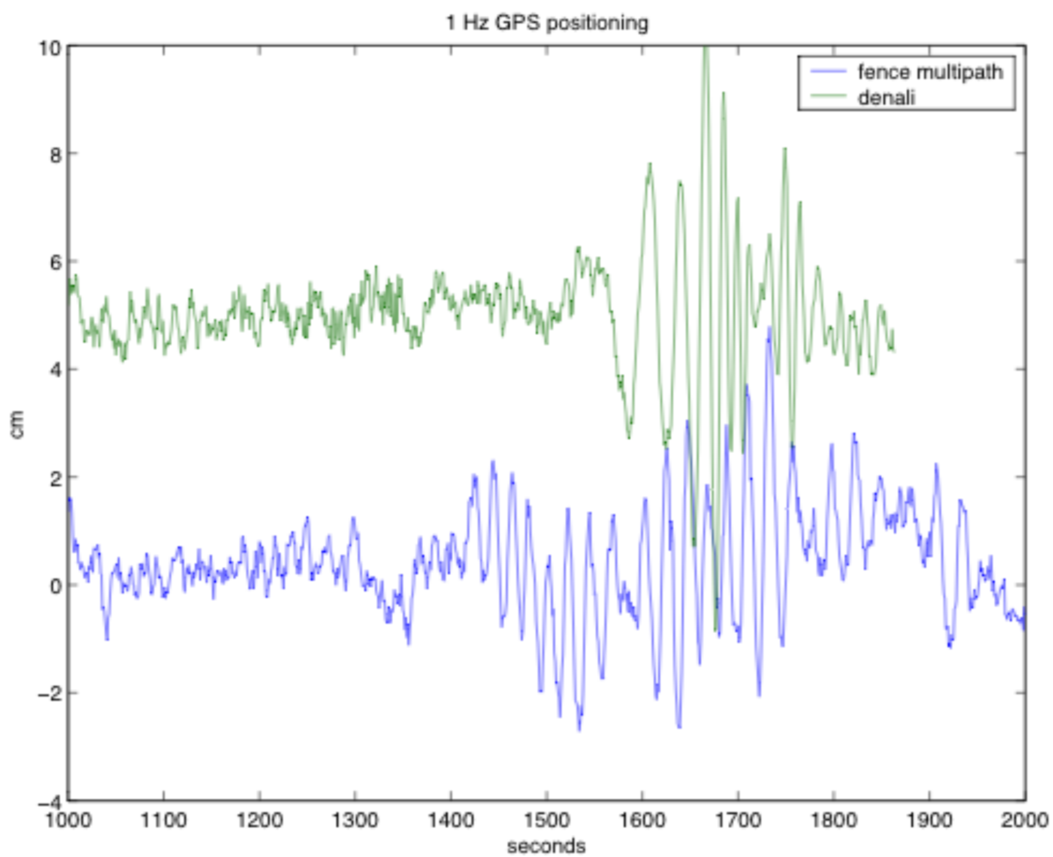
Capabilities

- Precise enough to supplement traditional strong motion in earthquake source model inversions (Chen et al., 2004).
- No maximum displacement limit
  - But receivers may have tracking problems at extreme accelerations (e.g., 2010 Maule eq)
- No drift or tilt (off-level) errors
- But higher noise level than seismometers at high frequencies.

Multipath



Multipath



1 Hz GPS positioning
fence multipath
denali
cm
seconds
10
8
6
4
2
0
−2
−4
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

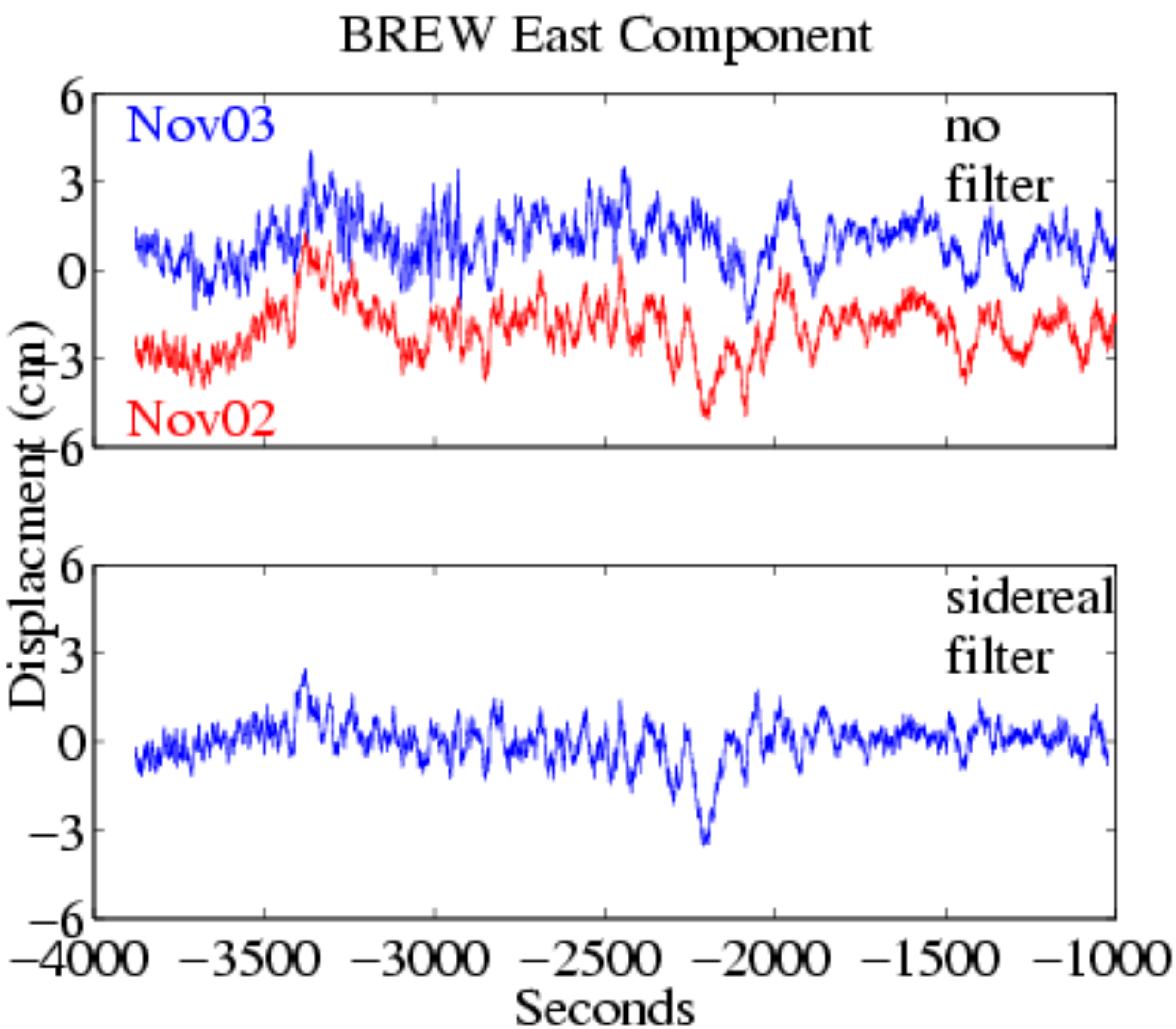
Multipath and Sidereal Filtering

- The GPS orbital period => identical constellation geometry occurs 3 min 56 seconds earlier each day.

- Compute 1 Hz solutions for multiple days before and after the earthquake.

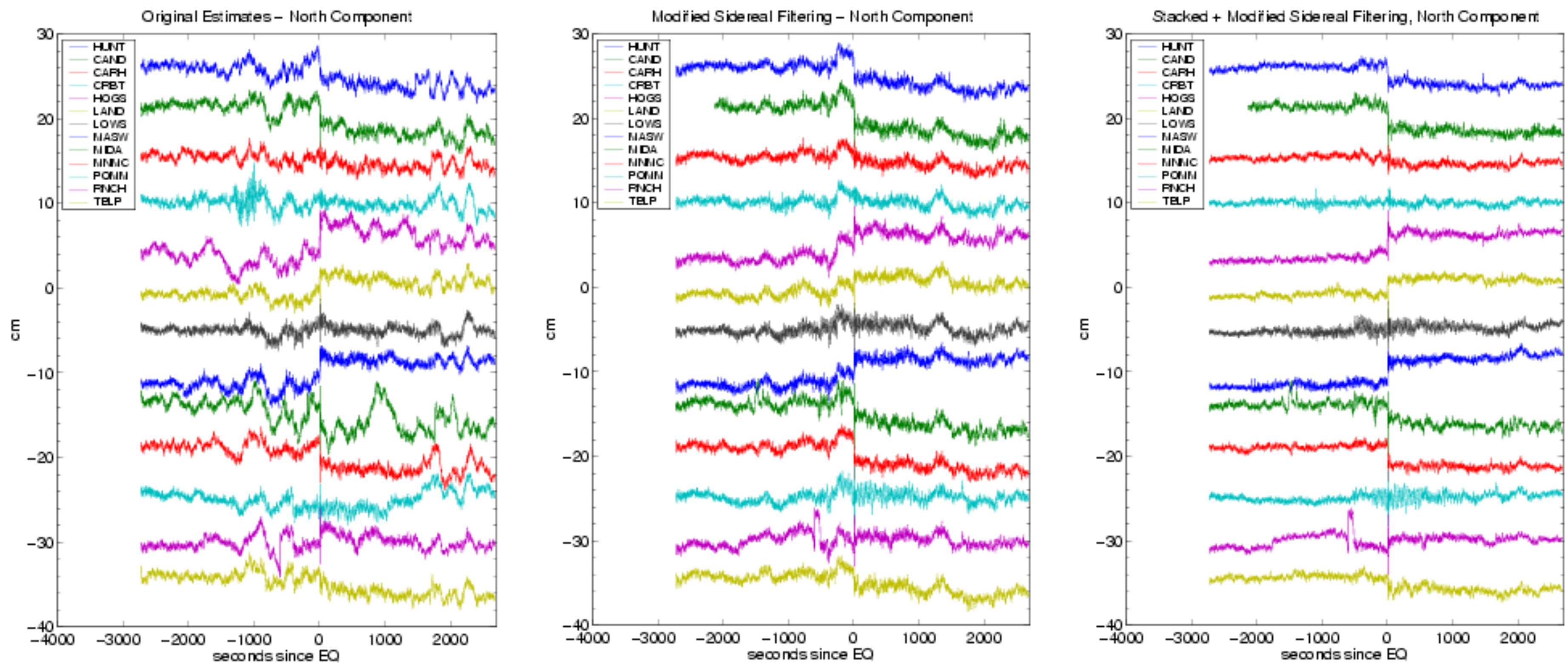
- Combine shifted solutions to remove “common” systematic errors.

Example of sidereal shifting:



Reducing Noise

Parkfield earthquake

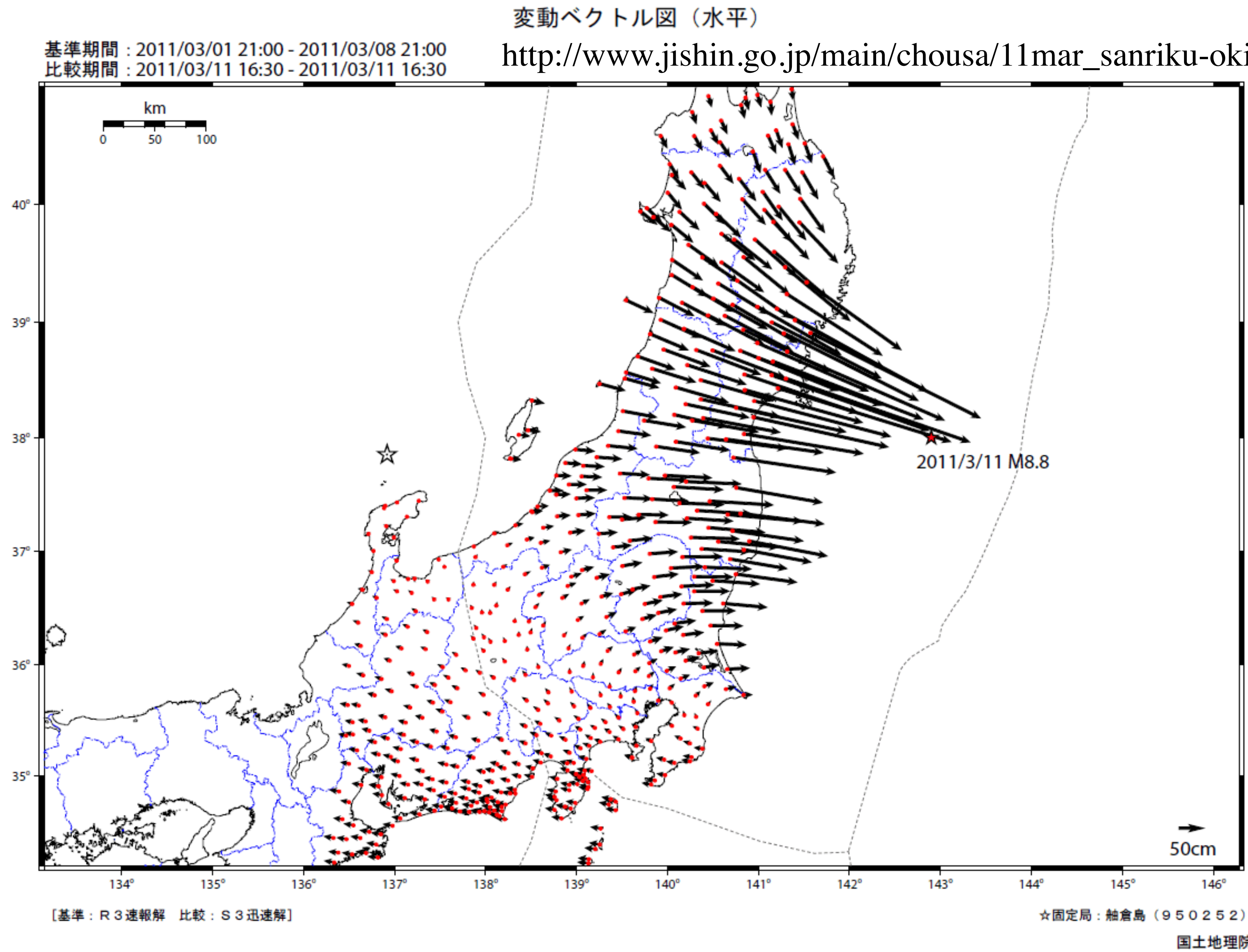


Andria Bilich, University of Colorado

2011 Tohoku-oki Earthquake

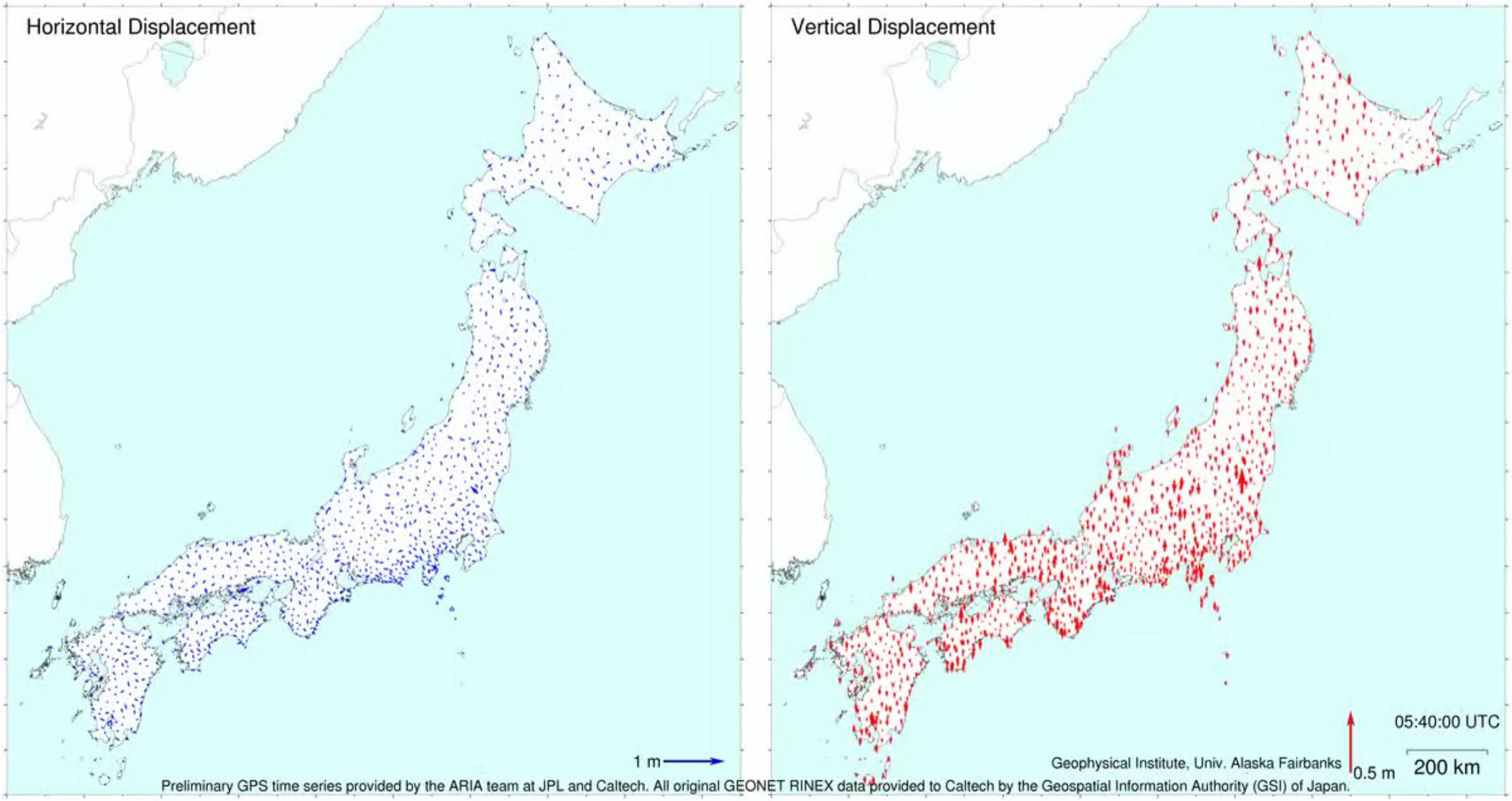
Observed GPS Displacements

http://www.jishin.go.jp/main/chousa/11mar_sanriku-oki/



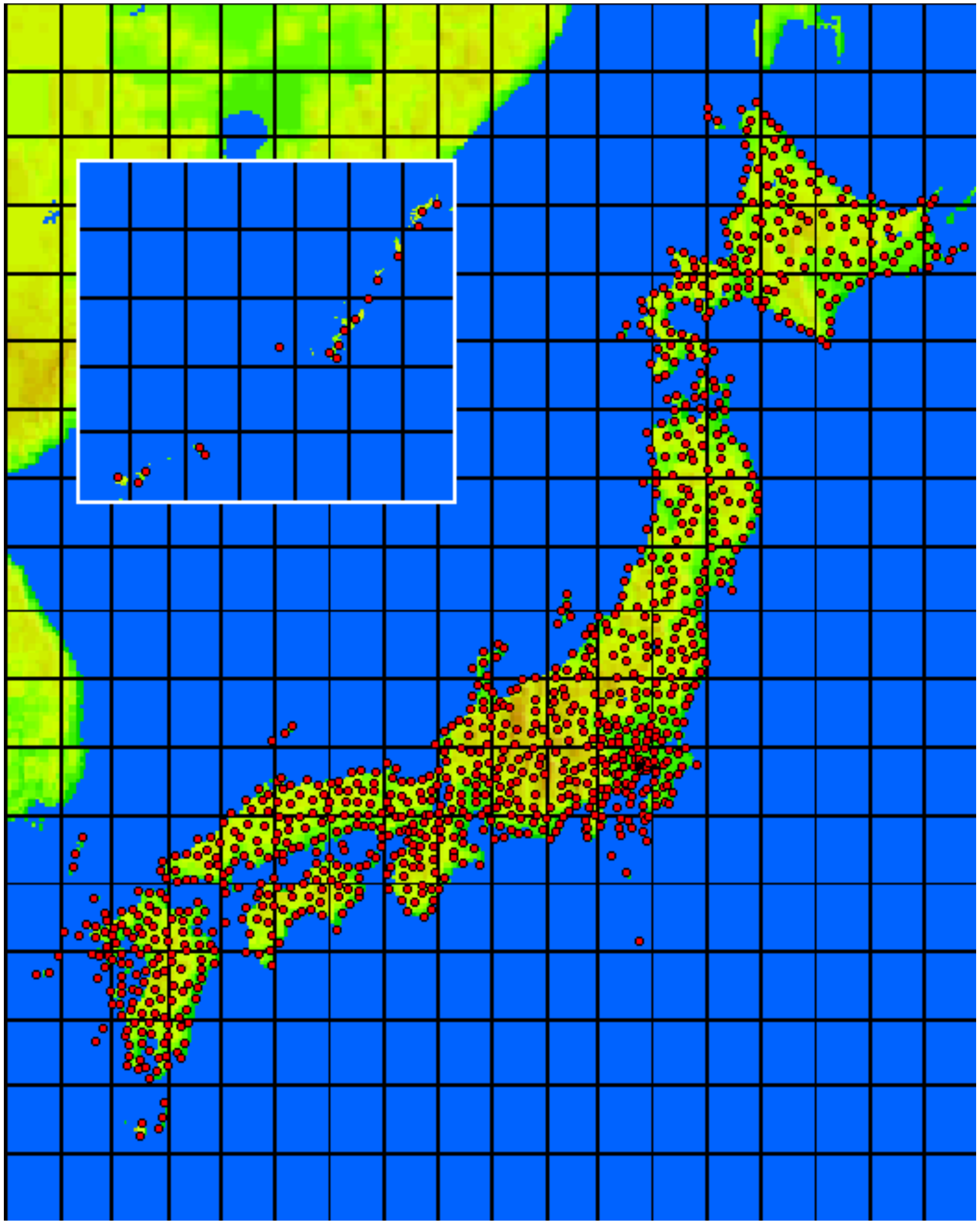
Ronni Grapenthin
University of Alaska Fairbanks

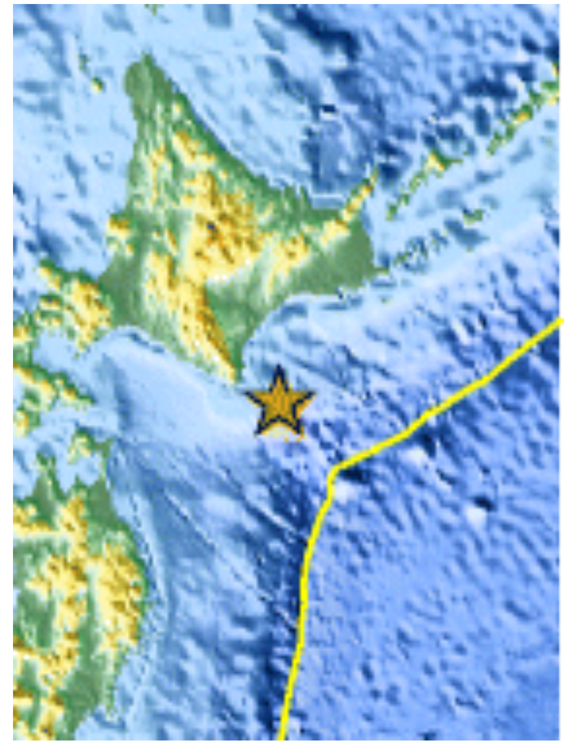
Movie of an Earthquake

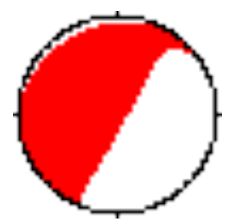


2003 September 25 Tokachi-Oki (Hokkaido) Earthquake

Strong Motion Network

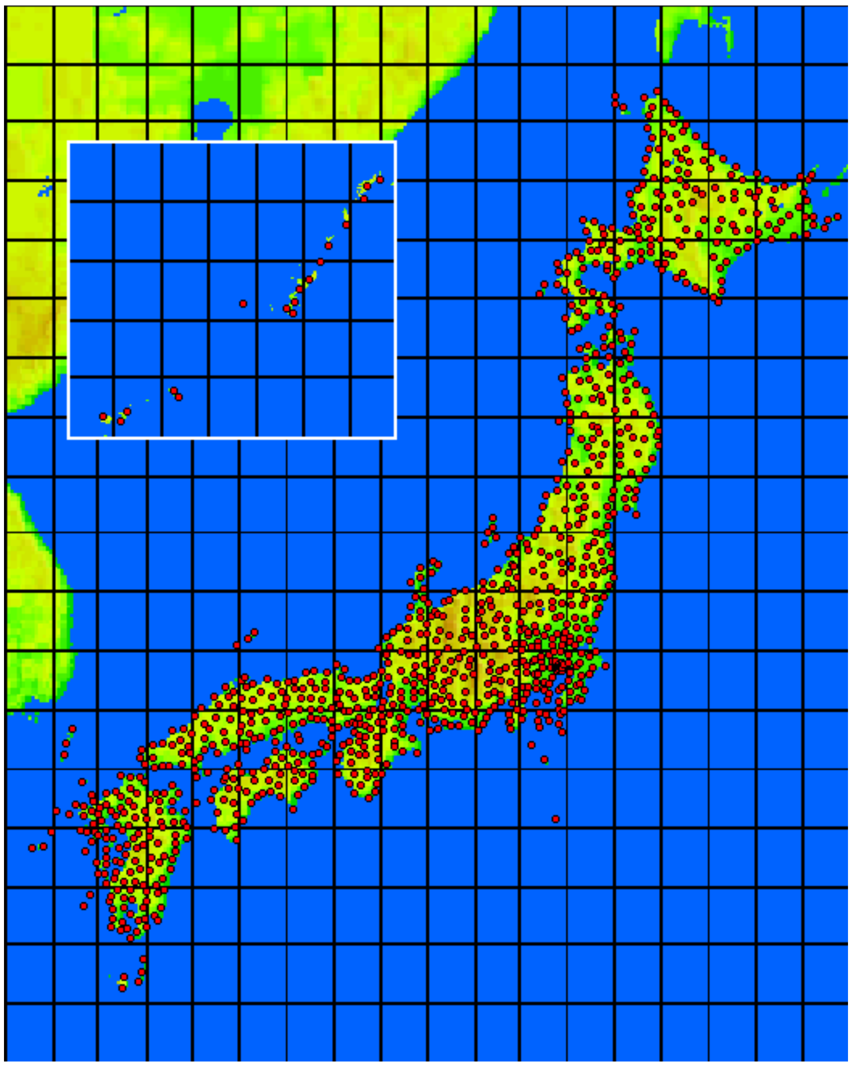




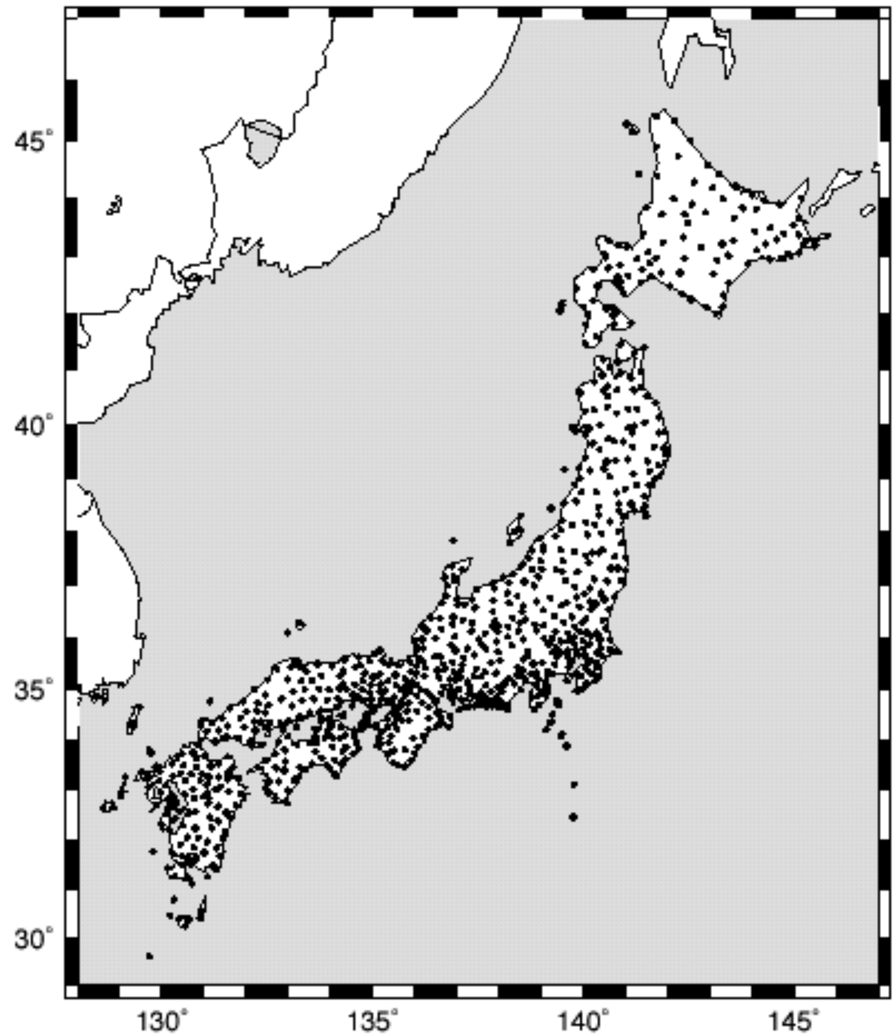


Harvard Mw 8.3

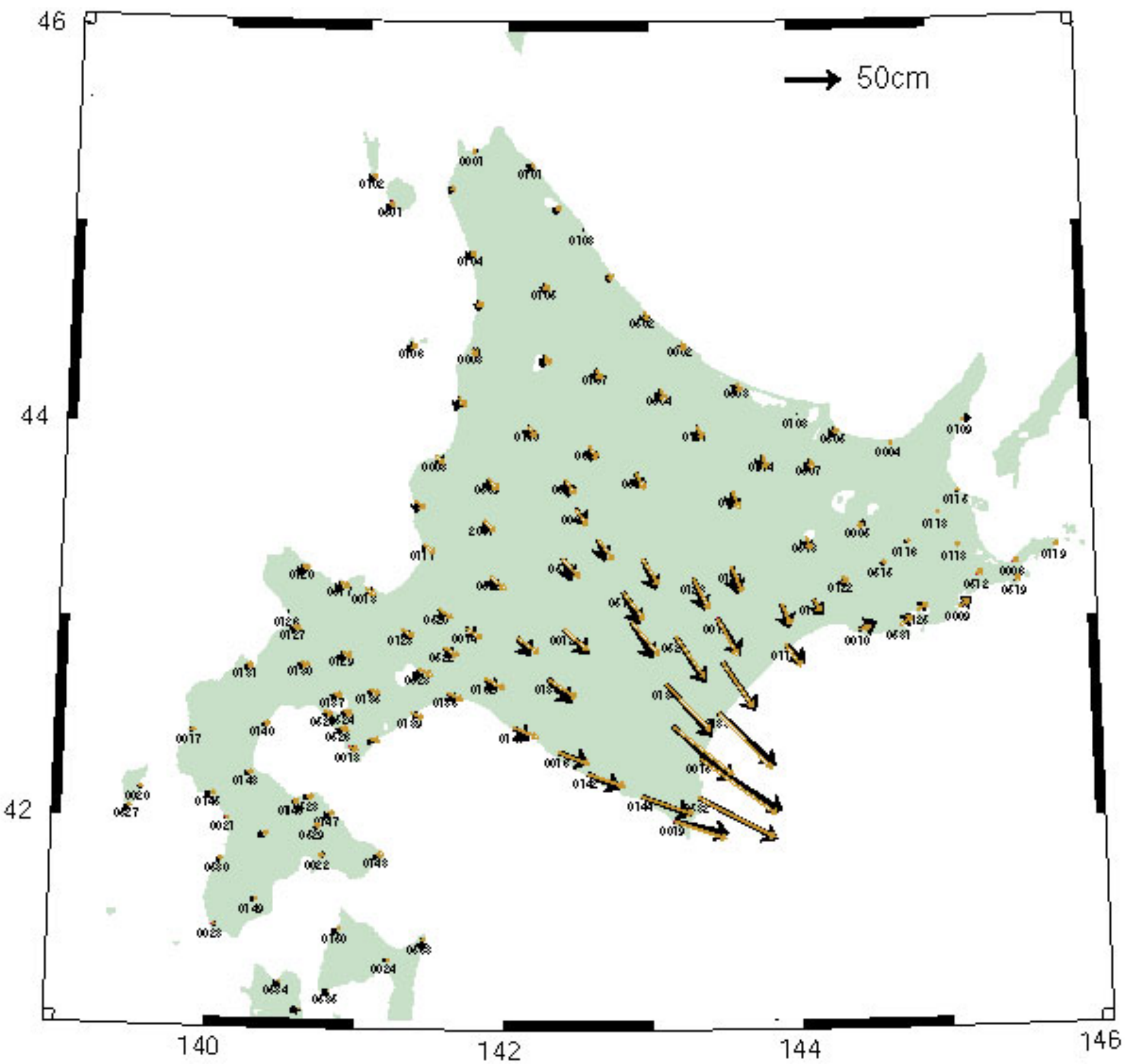
Strong Motion Network



GPS Network



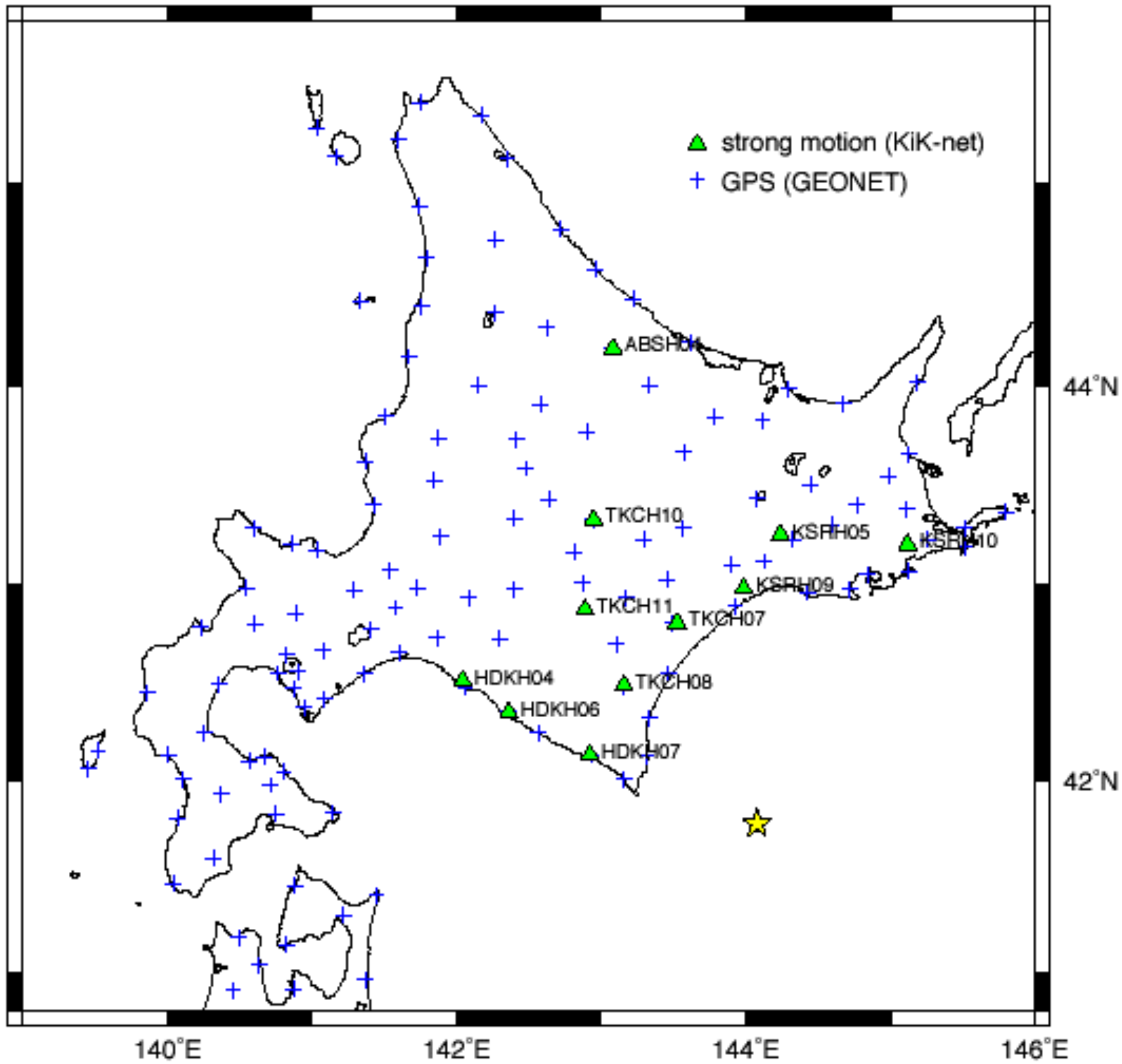
Coseismic Displacements: traditional GPS



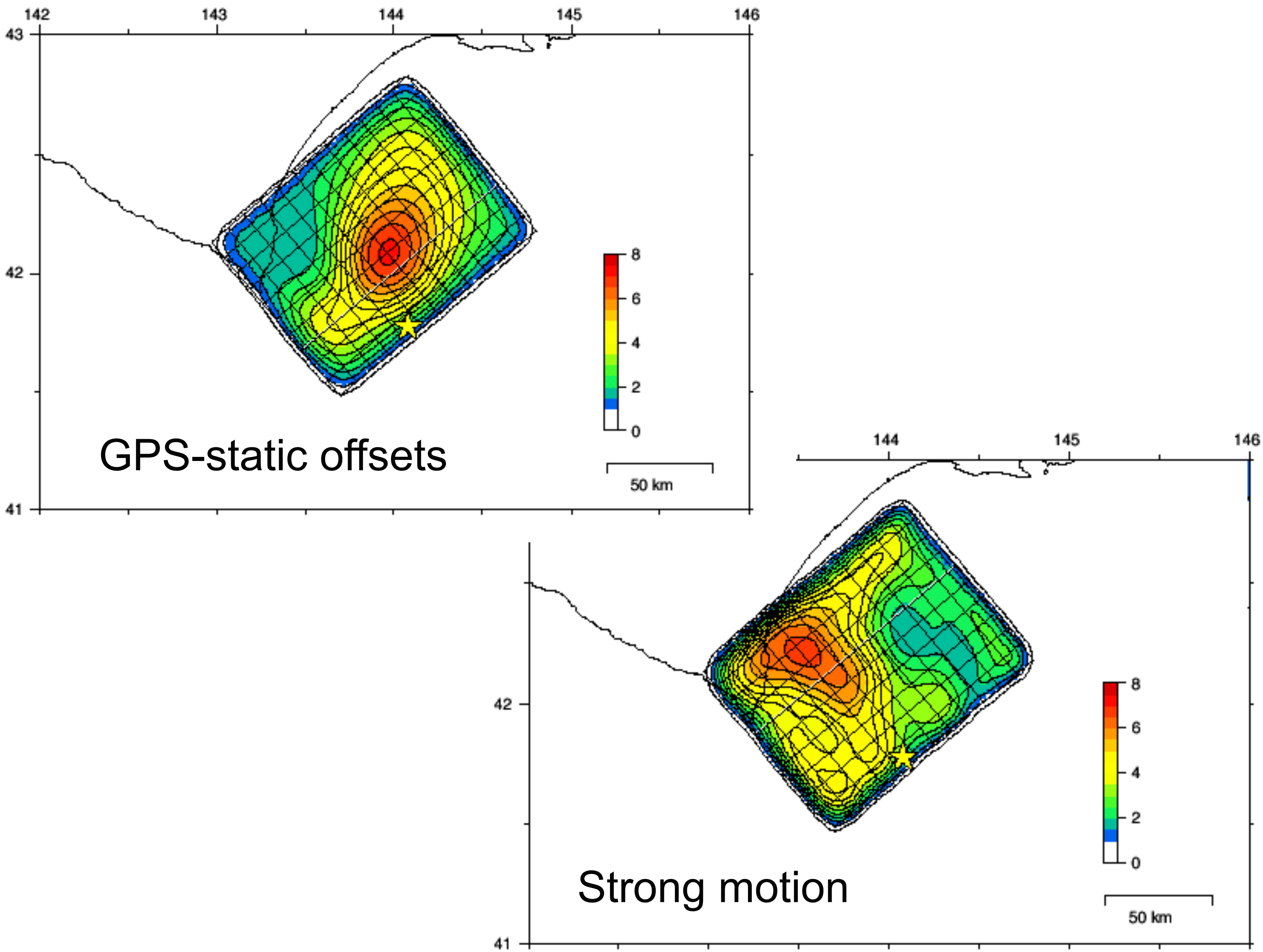
T. Kato
Tokyo University

図２：地震時水平変動の観測値と計算値の比較

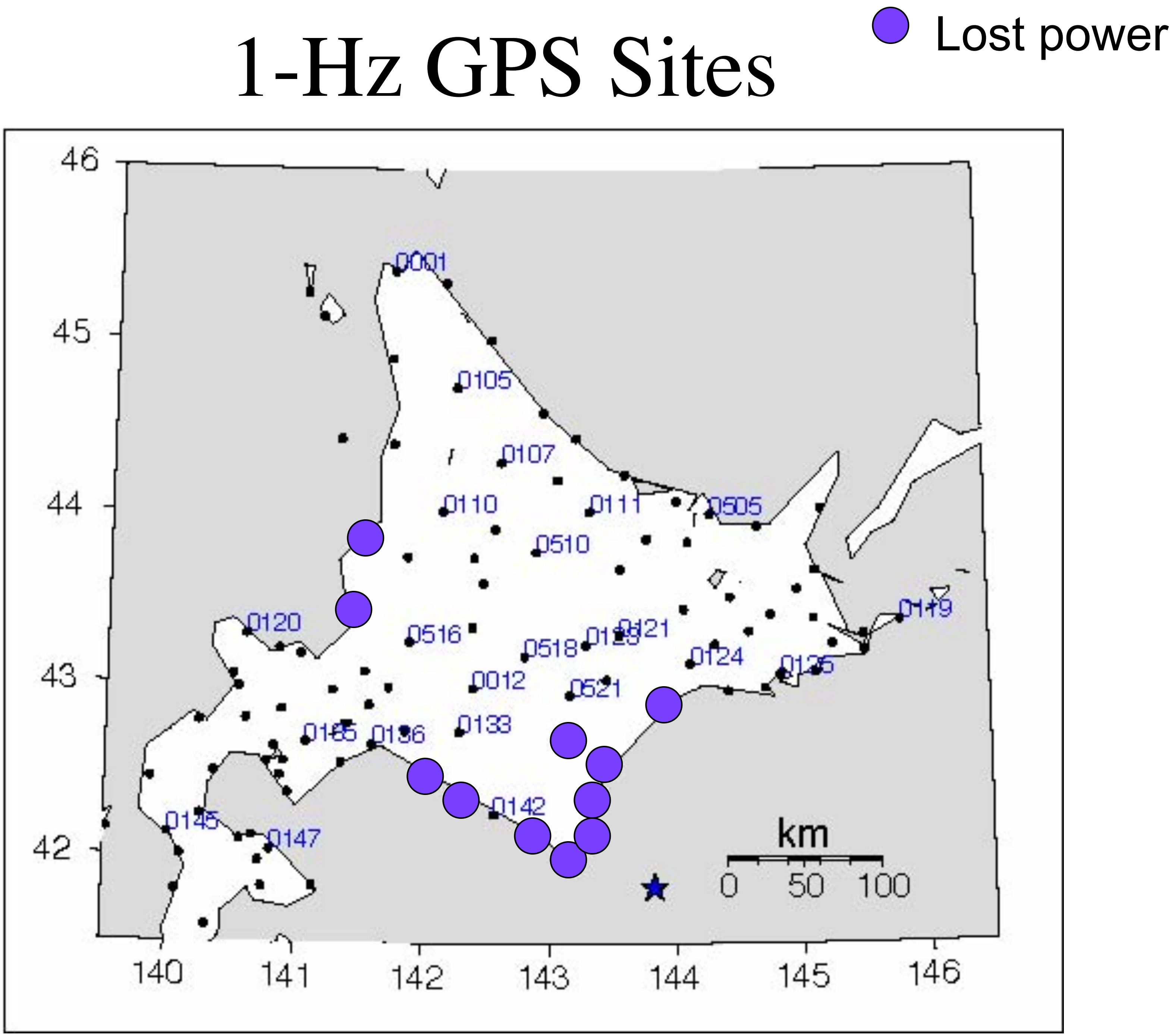
Inversion for Rupture



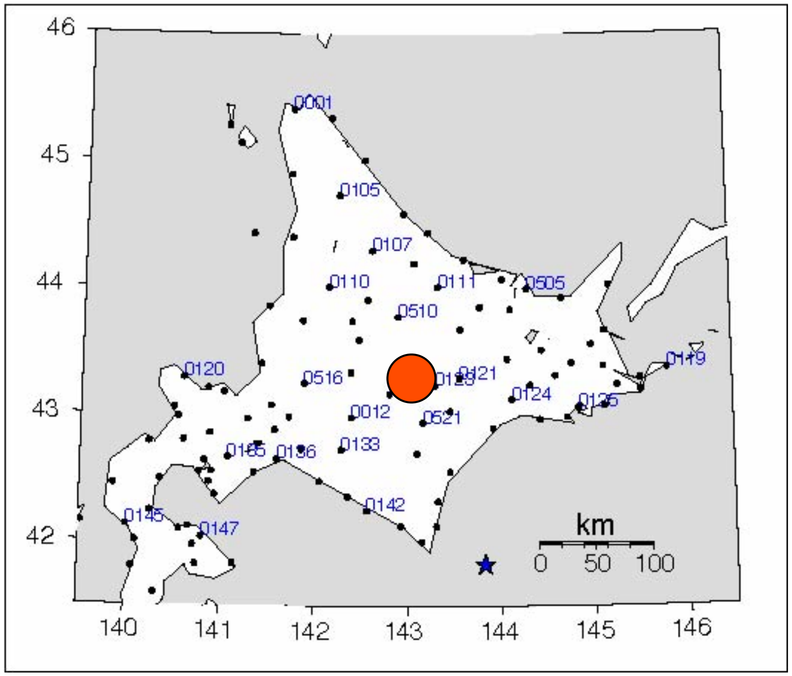
Koketsu et al.

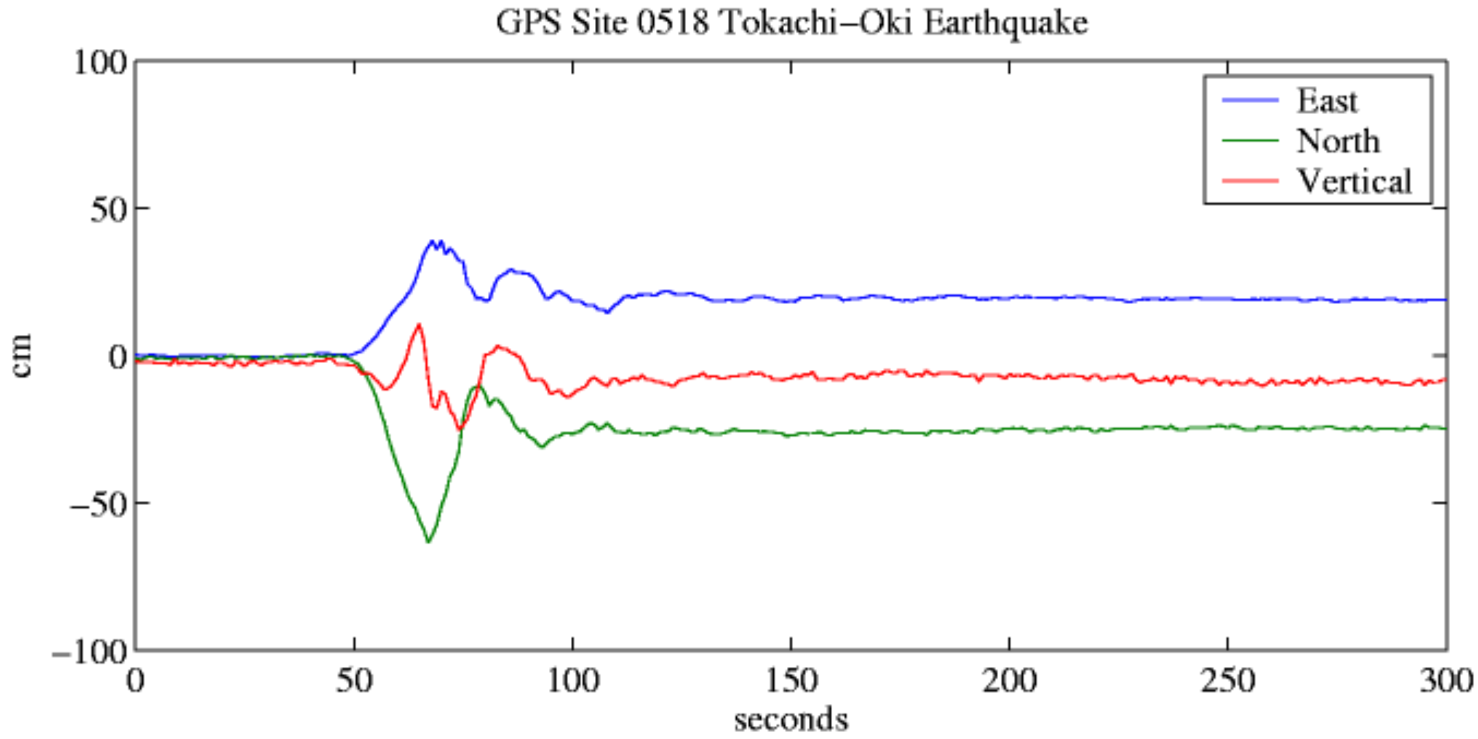

142
143
144
145
146
43
42
41
8
6
4
2
0
50 km
GPS-static offsets
144
145
146
42
41
8
6
4
2
0
50 km
Strong motion

1-Hz GPS Sites

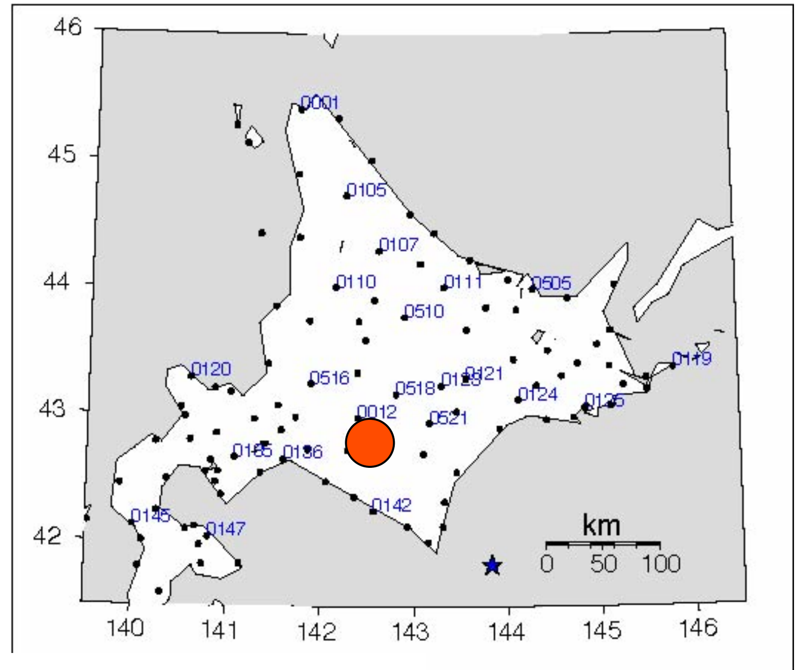


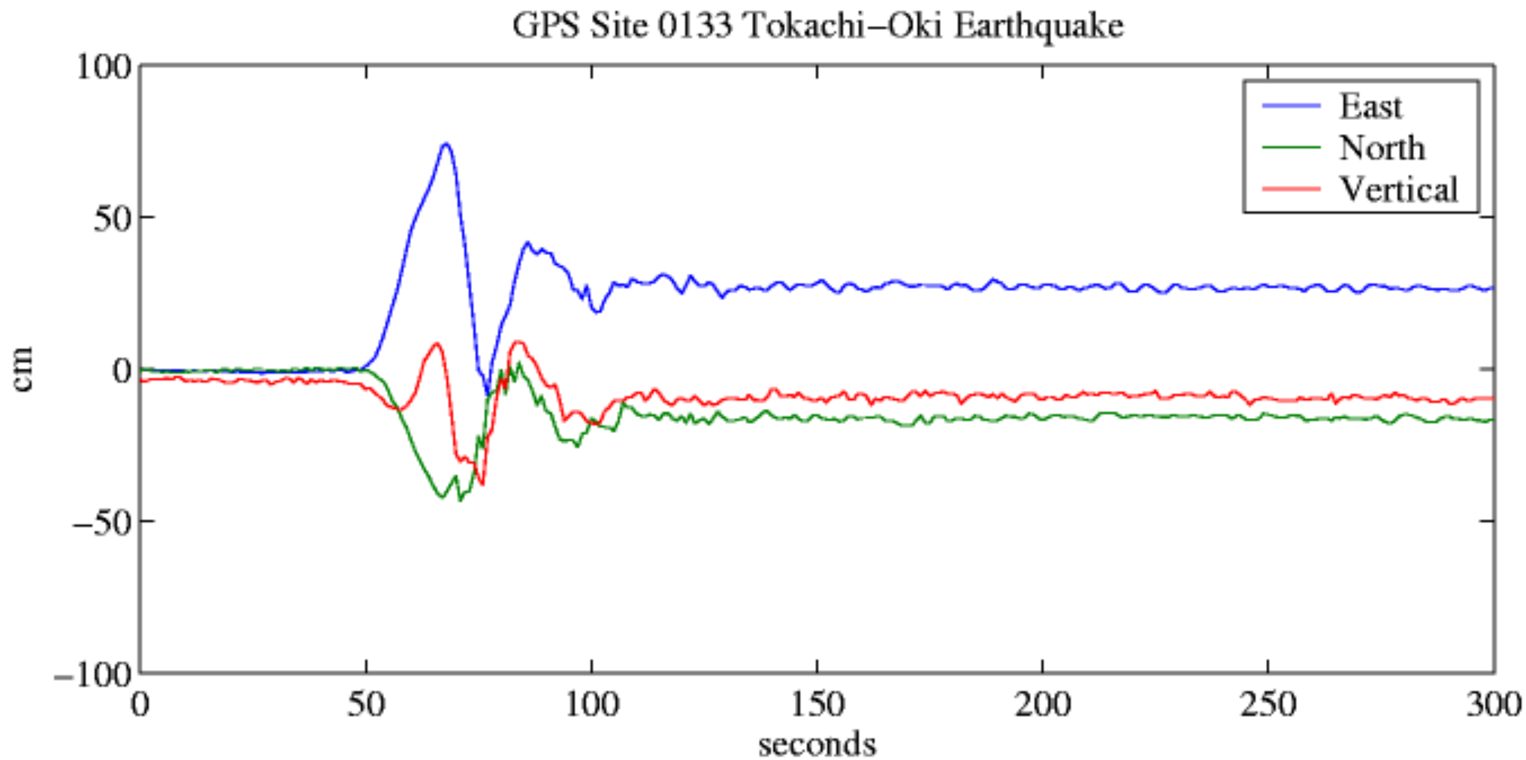
1 Hz GPS Position Estimates



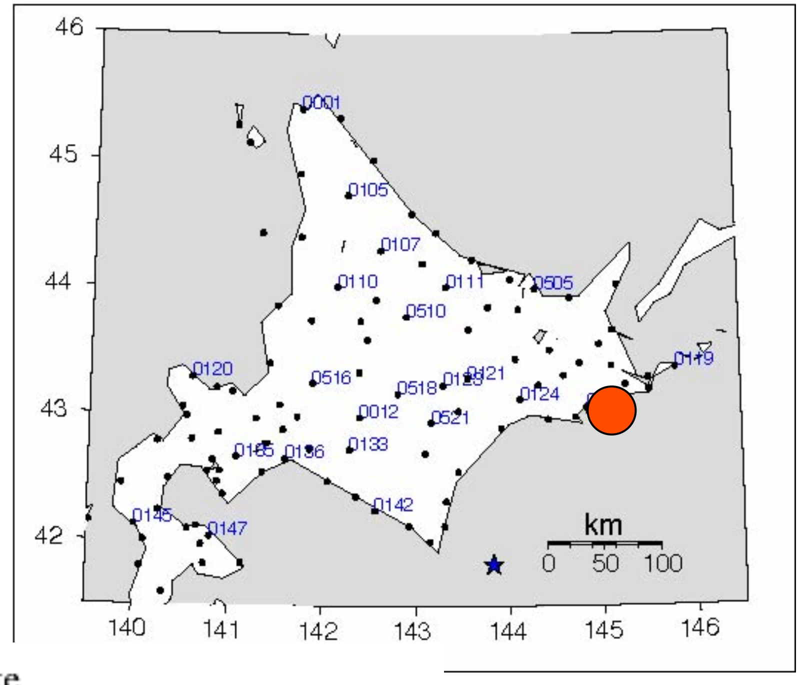


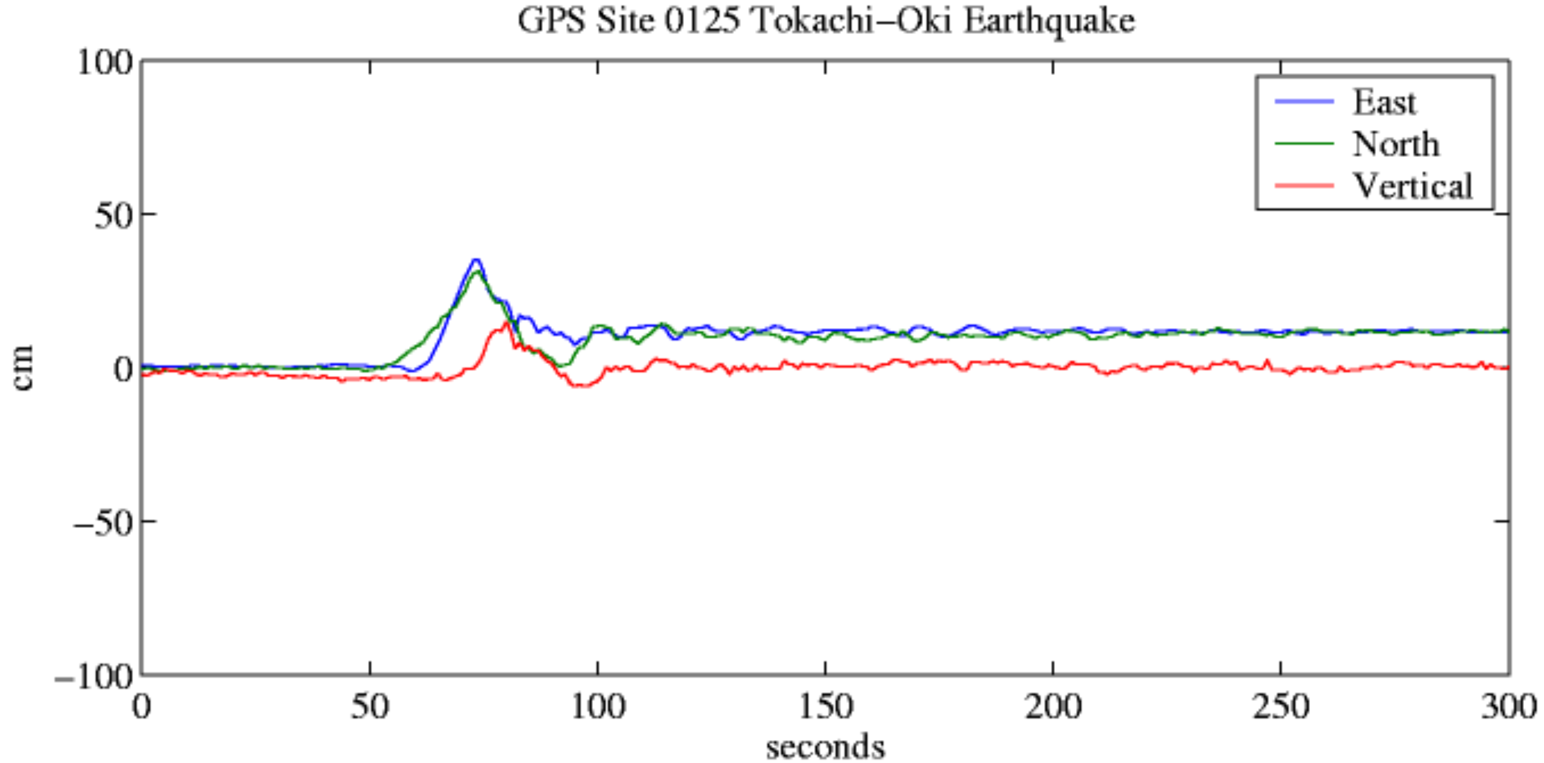
1 Hz GPS Position Estimates

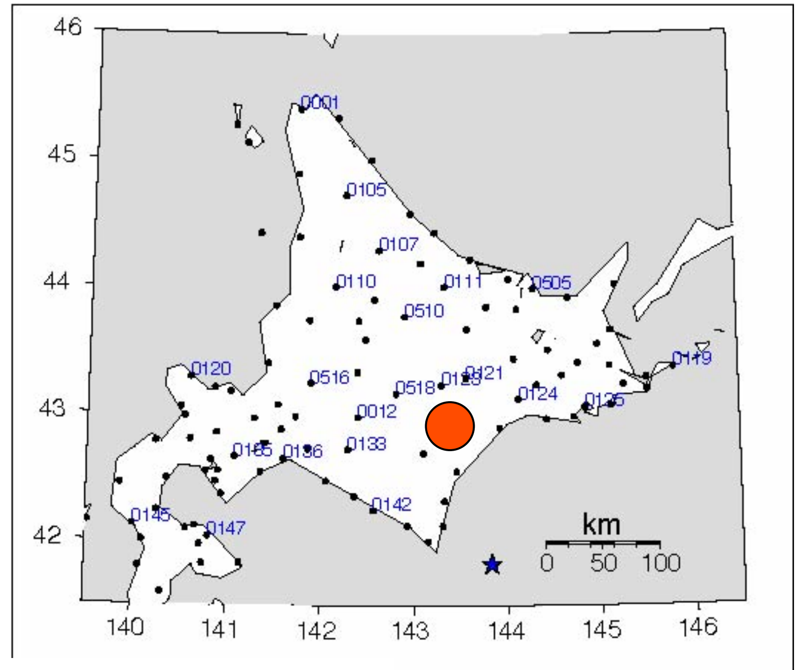


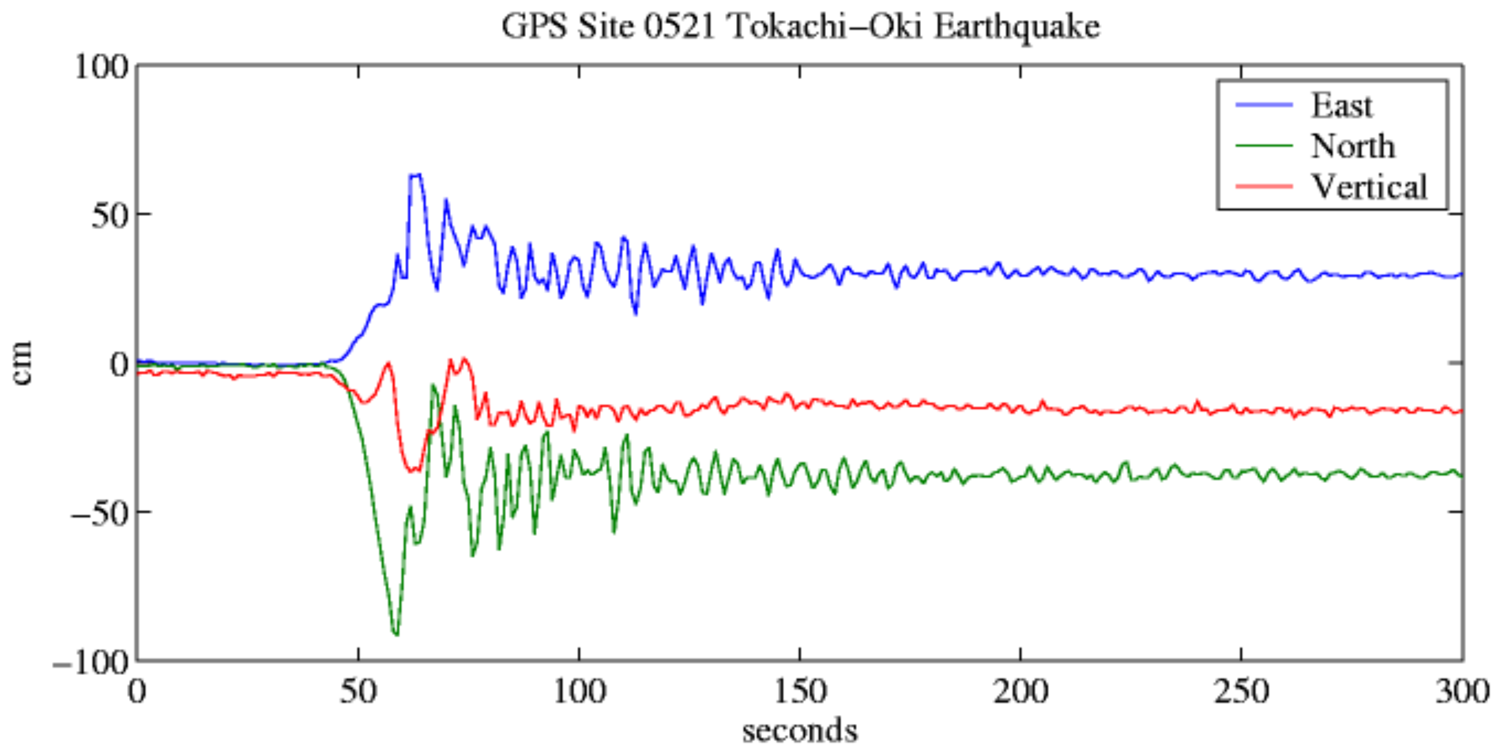


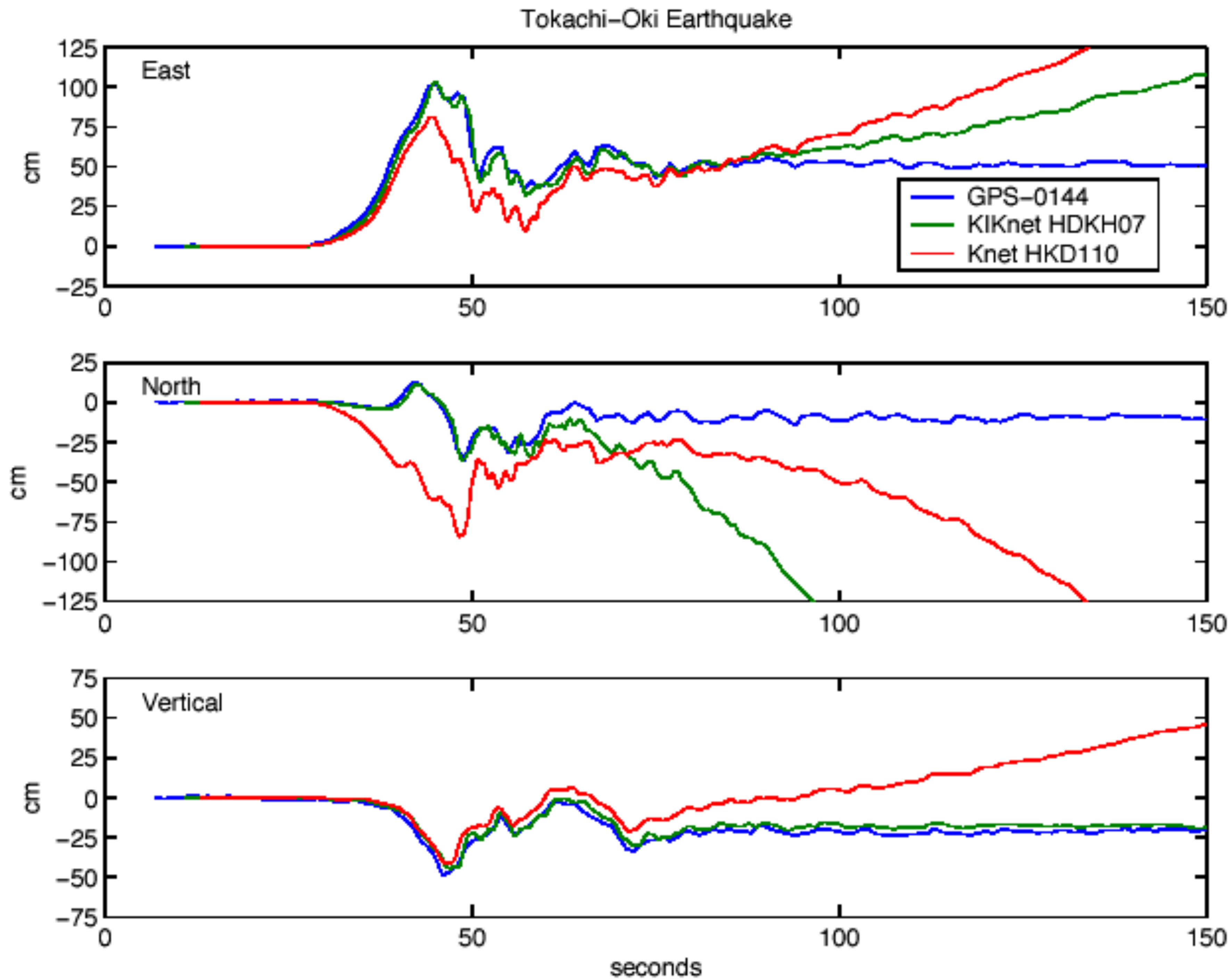
1 Hz GPS Position Estimates





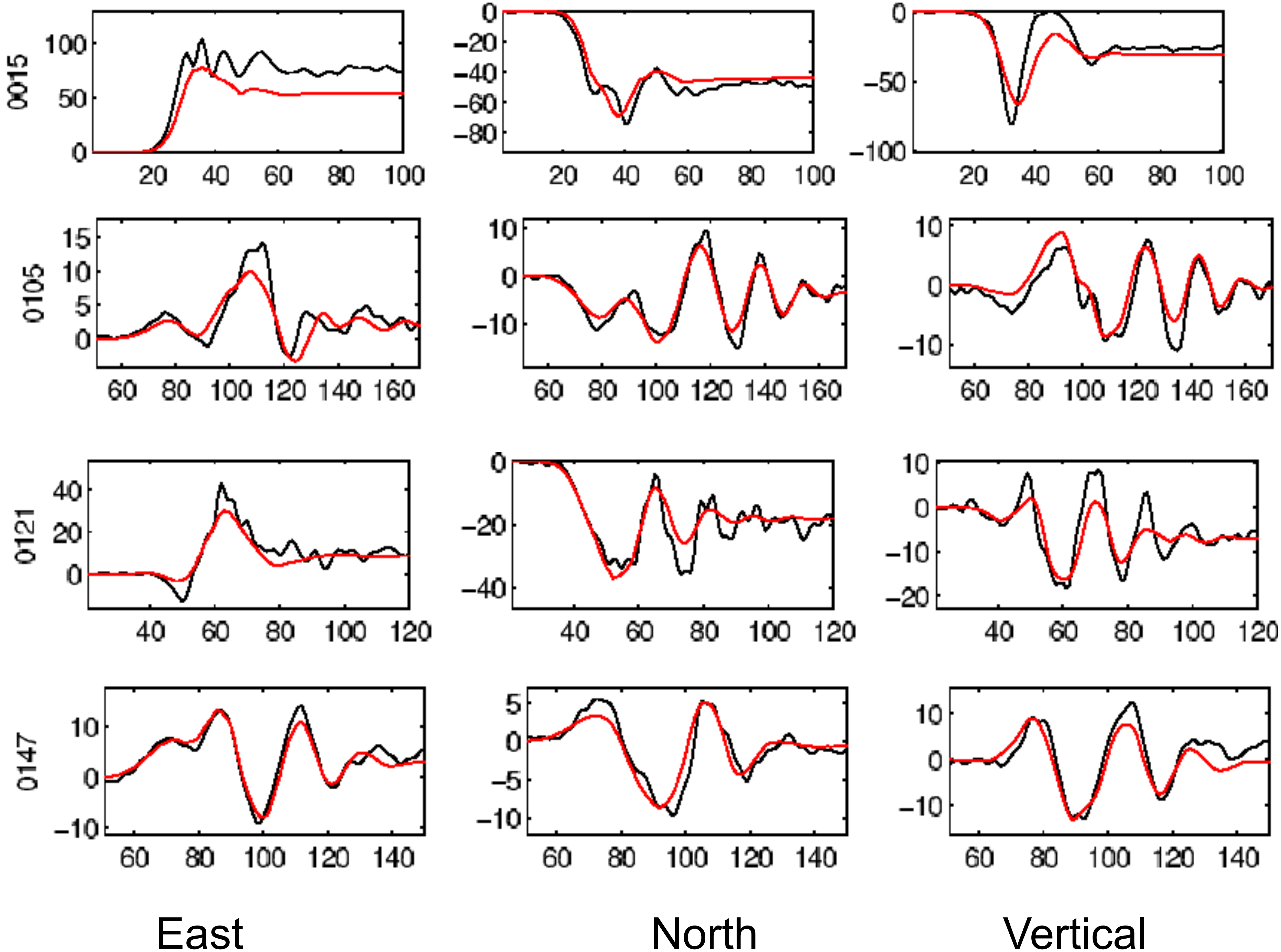

46
45
44
43
42
140
141
142
143
144
145
146
0001
0105
0107
0110
0111
0505
0510
0120
0516
0518
0124
0012
0133
0142
0145
0147
0119
km
0
50
100

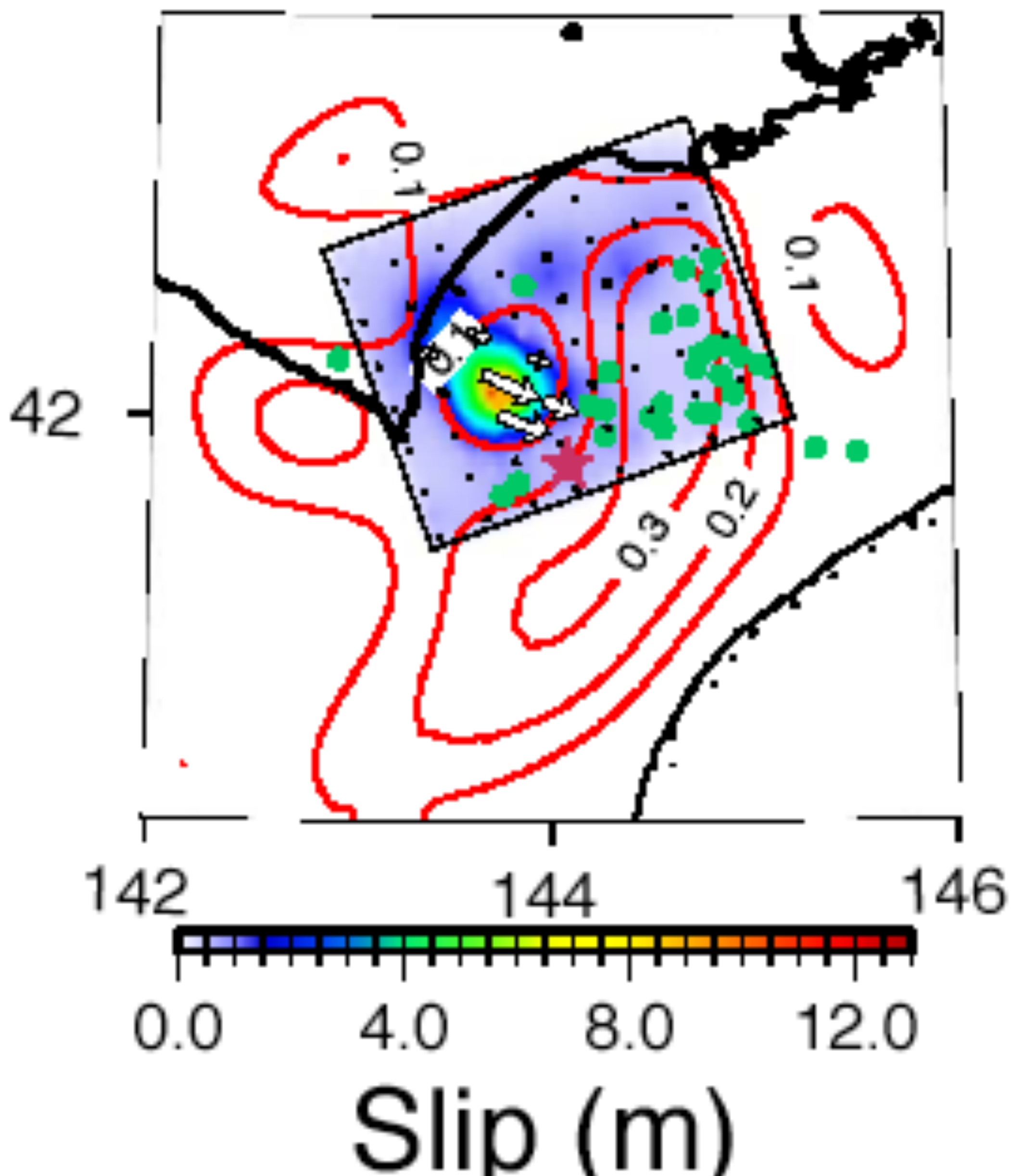

GPS Site 0521 Tokachi–Oki Earthquake
East
North
Vertical
cm
seconds
100
50
0
−50
−100
0
50
100
150
200
250
300


Tokachi-Oki Earthquake
East
North
Vertical
cm
seconds
GPS-0144
KIKnet HDKH07
Knet HKD110
125
100
75
50
25
0
-25
-50
-75
-100
-125
0
50
100
150

Methodology

- Multiple time window inversion
- Fault plane 10 x 10 km segments
- Frequency-Wavenumber (FK) of *Zhu & Rivera* [2003].
- Smoothness & positivity constraints.
- Velocity structure after *Yagi* [2004].


0015
0105
0121
0147
East
North
Vertical

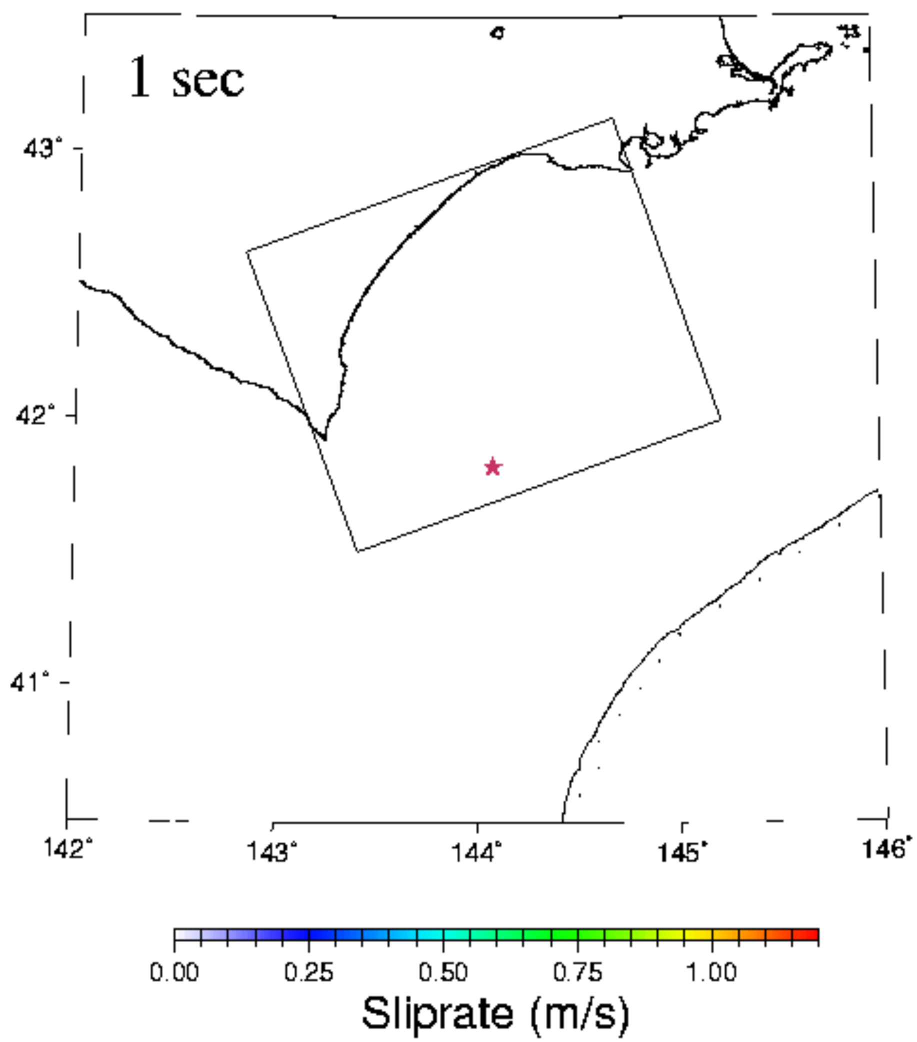


Mo=1.7×10^{21}Nm
（Mw8.1）
Peak Slip ~ 9.0m

Aftershocks

Ito et al. [2004]

Animated Slip Model



Miyazaki et al., 2004