GNSS Applications in Monitoring Crustal Deformation

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Content

1. GNSS observations on crustal deformations in China
2. Data processing and analyses
3. Results from GNSS observations in China
4. Conclusions

Advantages of GNSS in Monitoring Crustal Deformation for Detection of Precursors to Strong Earthquakes
1. GNSS observations on crustal deformations in China

GNSS networks in China
— Crustal Movement Observation Network of China (CMONOC) — Major scientific engineering project for 12th Five Year plan, the second phase of the CMONOC — Major scientific engineering project for 9th Five Year plan, mainly aimed at earthquake predictions.

— Modern Geodetic Datum System in China
(360 CORS stations, 4500 GNSS stations)
an undergoing project by National Administration of Surveying, Mapping and Geoinformation of China
Continuous GNSS observation stations in the Crustal Movement Observation Network of China (CMONOC)
1000 regional GPS stations, occupied once every 2-3 years from 1999 to 2007

Position and geodetic height at regional stations
2000 regional GPS stations, occupied about every 2 years since 2009

Position and geodetic height at regional stations
2. Data processing and Analysis

Data processing software

Assessment of the GNSS data processing results

Displacement analysis: regional RF

Strain studies:

Global plate motion model:

Time Series studies:
Data processing software packages

GAMIT/GLOBK    DD positioning
BERNESE        DD and PPP positioning
GIPSY/OASIS     PPP positioning

Single receiver phase ambiguity resolution
PANDA           PPP positioning
Assessment of the GNSS data processing results

High precision of the GNSS data processing results

Daily solutions
1mm in horizontal component and
3mm in vertical component as shown in statistics of the.

Epoch specific GPS positioning
10mm in horizontal component
30mm in vertical component.
Orbit WRMS
Assessment of the GNSS data processing results

**RMS and chi**2**2**

**BERNESE**

A posteriori RMS of unit weight: 0.00116 m
Chi**2/DOF: 1.35

**GAMIT/GLOBK**

Postfit nrms: 0.15820E+00
The prefit chi**2 for 642 input parameters is 0.900

**RMS of individual components**

From GLOBK

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Value (m)</th>
<th>Standard Deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46. ALGO_GPS X coordinate</td>
<td>918129.34983</td>
<td>0.00104</td>
</tr>
<tr>
<td>47. ALGO_GPS Y coordinate</td>
<td>-4346071.28104</td>
<td>0.00419</td>
</tr>
<tr>
<td>48. ALGO_GPS Z coordinate</td>
<td>4561977.85544</td>
<td>0.00498</td>
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<tr>
<td>Loc. ALGO_GPS N coordinate</td>
<td>5115776.28764</td>
<td>0.00038</td>
</tr>
<tr>
<td>Loc. ALGO_GPS E coordinate</td>
<td>21818305.16091</td>
<td>0.00015</td>
</tr>
<tr>
<td>Loc. ALGO_GPS U coordinate</td>
<td>200.91682</td>
<td>0.00658</td>
</tr>
</tbody>
</table>
Coseismic displacement

mm

YANC

TOHOKU M9.0

Antenna Ht. changed
Horizontal displacements at the YANC station

Green from 1999 to June, 2009
Red From July, 2009 to March, 2011 (Tohoku M9.0 earthquake)
Displacement analysis

Basic theory: Free network adjustment

Basic method: Similarity transformation

For coordinate transformations or displacement fields

Basic results: Solutions in regional reference frames from the global reference frames
Similarity transformation is used
– to get the displacements in the regional reference frame from the results of positioning in the global reference frame
– to get independent national coordinate systems
– to get locally independent coordinate systems.
Crustal movements and similarity transformation

**Basic principle**: Movements are relative. Different results of movements can be realized through similarity transformations with shifts, rotations and scaling if different reference frames are used.
Similarity transformation is the basic method used in coordinate transformations and displacement transformations to obtain relative displacements in GNSS data processing.

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}_{N} = s \cdot \begin{bmatrix}
  1 & \omega & -\omega \\
  -\omega & 1 & \omega \\
  \omega & -\omega & 1
\end{bmatrix} \begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}_{O} + \begin{bmatrix}
  \Delta x \\
  \Delta y \\
  \Delta z
\end{bmatrix} + \begin{bmatrix}
  v \\
  x \\
  y \\
  z
\end{bmatrix}
\]

\[
X_{N} = s \cdot R \cdot X_{O} + \Delta X + v
\]

Red parts are used in estimating the transformation parameters. Similarity transformation is a mathematical method, its application in GNSS must be adapted to the practical geodetic observations.
Application of the similarity transformation in the analysis of displacements

Displacements in 3D space (not appropriate for the displacements of crustal movements, because of different characteristics of the horizontal and the vertical displacements. There are significant annual variations in the vertical component at a lot of GPS stations (an example in the next slide). In NA12 some requirements for the station displacements are added when the 3D similarity transformation is used.

Crustal movements could be decomposed into the horizontal and the vertical components usually with the ellipsoid as the reference surface for both components.

The similarity transformations should be performed separately for the horizontal and the vertical displacements so as to avoid the mutual conversion of the 2 components in analyzing the crustal deformations in China.
Similarity transformation for horizontal displacements on the ellipsoid used by the author:

If the 3D coordinates X'Y'Z' of the projection of station positions XYZ on the ellipsoid are obtained, then similarity transformation of X'Y'Z' can be used to get the horizontal displacements on the ellipsoid.

X'Y'Z' can be obtained as follows

Convert XYZ to NEU (N, E, U)
Convert NEU '(U' =0) to X ' Y' Z '. U' =0 is the key step.
All stations are divided into 2 groups X1 and X2. Stations in X1 are core stations. Similarity transformation of X'Y'Z' in X1 can be performed to get the parameters of the similarity transformation and the displacements \(v_x, v_y\) and \(v_z\) in 3D and \(v_N, v_E\) and \(v_U\) (\(v_U\) is almost 0) on the ellipsoid.

With parameters of the similarity transformation, perform similarity transformation on X2 and get \(v_x, v_y\) and \(v_z\) in 3D and \(v_N, v_E\) and \(v_U\) (\(v_U\) is almost 0) on the ellipsoid. Then horizontal displacements of all stations on the ellipsoid are obtained.
Advantage of displacements in the regional reference frames:

Physically or tectonically meaningful.
Low noise level than the results in the global reference frames.

Examples: regional reference frame in China SNARF and NA12 in north America

Plate-fixed reference frames
Horizontal displacement in the regional RF from 1999 to 2007 in China
Horizontal Displacements in north America in NA12

From 2007-04-11(1422) to 2014-8-14(1806)
Comparison of time series of 2 results for E
Comparison of time series of 2 results for $N$
Similarity transformation for the vertical component:
Similarity transformation in 1D.

\[ H_{2Oi} = H_{1Oi} + \Delta H + v_{Hi} \]

Red part is used in estimating the transformation parameters.
Vertical displacement time series at LHAS:

**Blue dots**: observed result in regional RF.

**Pink dots**: Best fit with annual variations.

**Yellow dots**: Residuals of the best fit.

-35 -30 -25 -20 -15 -10 -5 0 5 10 15 20


**mm**
Strain studies on crustal deformation

3 GPS stations can perform as a strainmeter. Strain components in each triangle formed with 3 GPS stations can be estimated. Rocks can be easily broken by shear stress and the earthquake occurrences are the most closely related with shear strains.
Strain estimation: Automatically form triangles through Delauney triangulation and estimate the strain components on the ellipsoid.

**Strain components:**
- Areal dilation $\Delta$,
- Maximum shear strain $\gamma_{\text{max}}$,
- First shear strain $\gamma_1$,
- Second shear strain $\gamma_2$,
- Principle strains $\varepsilon_1$, $\varepsilon_2$ and spin.

**GMT (Generic Mapping Tool) mapping is used for:**
- Mapping of the discrete values in each triangle
- Contour mapping
- Trend surface mapping with color codes with better visual effect.

Statistic analysis
Strain

Principal strain $\varepsilon_1$

Principal strain $\varepsilon_2$

45° Azimuth of the major axis of the principal strain

Maximum shear strain

$\theta$ Azimuth of the major axis of the principal strain
The first shear strain $\gamma_1$ represents left lateral shear in N45°E or right lateral shear in N45°W under north-south compression and east-west extension; the second shear strain $\gamma_2$ represents left lateral shear in N or right lateral shear in E under compression in NW and extension in NE.
Global Plate Motion Model

— a remarkable achievement in Earth sciences, dreamed by many scientists

Euler vector (Euler's rotation theorem)
**EULER vector** $\vec{\Omega}$ for plate motion

Here $\vec{V}$ must be tangent to the sphere. The 3D displacement(s) or velocities directly obtained from GPS observations are usually not tangent to the sphere.
On the plate $i$, with the position vector $r_j$ at station or point $j$ and the Euler rotation vector $\tilde{\Omega}_i$, the velocity at $j$ is \[ \dot{v}_j = \tilde{\Omega}_i \times \vec{r}_j \] or \[ \tilde{\Omega}_i = \Omega_i \cos(\phi_i) \cos(\lambda_i) \cdot \vec{e}_x + \Omega_i \cos(\phi_i) \sin(\lambda_i) \cdot \vec{e}_y + \Omega_i \sin(\phi_i) \cdot \vec{e}_z \]

\[ \Omega_x = \Omega_i \cos(\phi_i) \cos(\lambda_i) \]

\[ \Omega_y = \Omega_i \cos(\phi_i) \sin(\lambda_i) \]

\[ \Omega_z = \Omega_i \sin(\phi_i) \]

$\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$ : the unit vectors along the axis.

\[ u = +z\Omega_y - y\Omega_z \]
\[ v = -z\Omega_x + x\Omega_z \]
\[ w = +y\Omega_x - x\Omega_y \]

**Problem:** they are non linear equations.
Table 2. Major plate angular velocities relative to ITRF2000

<table>
<thead>
<tr>
<th>Plate</th>
<th>Latitude (deg.)</th>
<th>Longitude (deg.)</th>
<th>( \omega ) (deg/Myr)</th>
<th>Error Ellipse (deg.)</th>
<th>( \chi^2 )</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anta</td>
<td>69.683</td>
<td>-125.655</td>
<td>0.222 ± 0.006</td>
<td>0.77</td>
<td>1.6</td>
<td>6</td>
</tr>
<tr>
<td>Aust</td>
<td>33.472</td>
<td>37.590</td>
<td>0.618 ± 0.003</td>
<td>0.93</td>
<td>1.2</td>
<td>9</td>
</tr>
<tr>
<td>Eura</td>
<td>57.019</td>
<td>-99.868</td>
<td>0.260 ± 0.002</td>
<td>0.74</td>
<td>1.0</td>
<td>21</td>
</tr>
<tr>
<td>Noara</td>
<td>-3.583</td>
<td>-84.702</td>
<td>0.200 ± 0.003</td>
<td>0.87</td>
<td>1.3</td>
<td>22</td>
</tr>
<tr>
<td>Pacf</td>
<td>-63.832</td>
<td>110.161</td>
<td>0.670 ± 0.003</td>
<td>0.59</td>
<td>1.2</td>
<td>5</td>
</tr>
<tr>
<td>Soam</td>
<td>-21.086</td>
<td>-135.798</td>
<td>0.108 ± 0.003</td>
<td>6.35</td>
<td>0.4</td>
<td>5</td>
</tr>
</tbody>
</table>

Plate abbreviations are given in Table 1. \( \omega \) is positive for anti-clockwise rotation. \( \sigma_{maj} \) and \( \sigma_{min} \) are the major and minor axes of the pole error ellipse, with the azimuth of the major axis given CCW from East. \( \chi^2 \) values, given for estimates performed in this study, refer to the sum of squared weighted residuals, normalized by the degrees of freedom. N is the number of stations used to estimate block rotation parameters.
Global Plate motion obtained by GPS
Time series analysis
Modeling Position Time Series

- Site motion is modeled at each site in each direction (north, east, up) as:

\[ y(t_j) = a + bt_j + csin(2\pi t_j) + dcos(2\pi t_j) + esin(4\pi t_j) + fcos(4\pi t_j) + \sum_j g_j H(t_j - T_j) + \nu_j \]

- The weighted least squares solution for the model parameters is:

\[ x = [a \ b \ c \ d \ e \ f \ g]^T \]
\[ y = Ax + \nu \]
\[ \hat{x} = (A^T C^{-1}_v A)^{-1} A^T C^{-1}_v y \]
\[ C_w = \chi^2 (A^T C^{-1}_v A)^{-1} \]

- The observation covariance matrix is constructed with a white noise + colored (power law) noise model, with noise amplitudes determined for each site by maximum likelihood estimation:

\[ C_v = a_w^2 I + b_k^2 J_k \]
Global solutions are dominated by spatially correlated and latitude dependent flicker noise. Magnitudes of white noise and flicker noise components are a good indicator of site problems.
Comparison of 2 solutions for LHAS U

Solution in the regional RF

Solution in the global RF
Time series of U component at LHAS:

- **blue**: obs. in regional RF
- **pink**: fitted result
- **yellow**: residuals
3. Results from GNSS observations in China

Crustal deformations of 4 earthquakes:

- The Wenchuan earthquake of M8.0
- The Tohoku earthquake of M9.0 in Japan
- The Lushan earthquake of M7.0
- The Minxian earthquake of M6.6
Crustal movements related to the Wenchuan earthquake of M8.0 on May 12, 2015 in China obtained from GPS observations

— Evidence for the existence of crustal movements precursory to great earthquakes
Major and great earthquakes in and around China from 2001 to 2015:

- 2001.11.14 Kunlun Mnt. M8.1
- 2004.12.26 Indonesia M9.3
- 2008.05.12 Wenchuan Eq. M8.0
- 2011.03.11 East Japan Eq. M9.0
- 2013.04.20 Lushan Eq. M7.0
Anomalies before the Wenchuan earthquake detected by GPS observations
(1) Results from the regional stations: long-term and medium-term anomalies in horizontal and vertical displacements.
(2) Result from continuous observations: short-term and imminent anomalies
(3) Single epoch solution for data of 30s sampling rate before the earthquake – possible imminent anomalies
(4) Imminent anomalies in TEC of the ionosphere detected by GPS observations
Results from the regional stations:
Number of stations: 1000 before 2009, 2000 since 2009

GPS data processing software: GAMIT/GLOBK, being used at data center, CMONOC.

Methods and software for analysis (used even before the Wenchuan earthquake): Displacements in the regional reference frames, strains, trend surface mapping and statistical analysis.

Preliminary result of displacements and strains was obtained on May 25, 2008, after the result of the observation data processing was available. At the end of 2010 the vertical displacement data were reanalyzed.

Results: horizontal displacements and strains, vertical displacements
Horizontal displacement from 1999 to 2001
Horizontal displacement from 1999 to 2004

Coseismic and post seismic displacements of the M8.1 Kunlun Mnt. Eq.

Wenchuan Eq.
Horizontal displacement from 1999 to 2007

Wenchuan Eq.

Coseismic and post seismic displacements of the M8.1 kunlun Mnt. Eq.
Horizontal displacement from 2004 to 2007

Wenchuan Eq.
Strain accumulations in the regional network before the Wenchuan earthquake


Conclusion: The anomalies were quite significant and developed gradually in an expanding area. The amplitudes of the anomalies increased gradually, anomalies in $\gamma_1$ were the most significant.

The following slides show the mapping of the discrete data and trend surface mapping.
Strain accumulations in the regional network before the Wenchuan earthquake

Result at discrete points—Direct and faithful presentation of the original results of estimation

Trend surface mapping—Presentation of the smoothed results through trend surface mapping

Trend surface mapping with GMT can produce Delicate and fine figures.

Comparison of the 2 presentations shows that the trend surface mapping can reliably show the results of anomalies at discrete points with better and clearer visual effect.

Note: Estimated coseismic strains of the Kunlun Mnt. Eq. were deleted in the analysis and mapping, the deleted data are small in number because there are only a small number of GPS stations around the Eq.. In the displacement maps coseismic displacements of this Eq. are not deleted.
The Wenchuan earthquake occurred in the region with dense GPS stations. The red rectangle indicates the area with anomalies.
Note on data processing:
The methods of analyzing the data were tried in early 2008.
The result of GPS observation data processed earlier was available on May 23, 2008. The map in the next slide was obtained on May 25, 2008.
Further studies were carried out and showed further evidences of the existence and development of the anomalies.
Strain accumulation of $\gamma_1$ from 1999 to 2007

Area with anomalies

Wenchuan Eq.

Local magnification of the previous slide
Strain accumulation of $\gamma_1$ from 1999 to 2001
Strain accumulation of $\gamma_1$ from 1999 to 2001
Strain accumulation of $\gamma_1$ from 1999 to 2004
Strain accumulation of $\gamma_1$ from 1999 to 2004
Strain accumulation of $\gamma_1$ from 1999 to 2007
Strain accumulation of $\gamma_1$ from 2001 to 2007

Area with anomalies
Vertical displacements from 1999 to 2007
Vertical displacements from 1999 to 2001 (-100mm < u < 100mm)

Stations of large subsidence
Vertical displacements from 1999 to 2004 (-100mm < u < 100mm)
Vertical displacements from 1999 to 2007 (-100mm < u < 100mm)

Stations of large subsidence
Results at fiducial stations of continuous GPS observations

Horizontal displacement time series in the regional reference frame have been used in monthly data review at the Institute of Earthquake Science before and after the earthquake.

Software for GPS data processing and results: GAMIT/GLOBK, results from the GPS data center

Methods and software for analysis: (already used before the earthquake):

The results shown in the next few slides are the same as used for a few months in monthly data review before the Wenchuan earthquake.
Characteristics of the preseismic displacements:
Speed up in N component at first, change in the sense of displacements till the earthquake occurrence

Characteristics of the coseismic displacements:
Instantaneous and significant step change, almost simultaneous appearance with the earthquake and at many stations — crustal movements that are widely recognized.

The coseismic displacements are elastic rebound of the preseismic anomalous displacements. They are the clues or evidences for the study on the existence of crustal movements precursory to earthquakes.
Elastic rebound

**Compression**

Release of the elastic spring (like the occurrence of an earthquake)

Displacement

Like the displacement observed by GPS

Initial length

Back to the initial length
Horizontal displacement

From “Earthquake” No.1, Vol.29, 2009
Typical time series with anomalies of simultaneous changes of the same pattern at several stations

From “Earthquake” No.1, Vol.29, 2009
Results until early Dec., 2010 show the step changes, the coseismic displacements, only at the time of the Wenchuan Eq. in a large area.
Step change before the Kunlun Mnt. Eq.

Bold arrows are coseismic displacements. From “Earthquake” No.1, Vol. 29, 2009
Horizontal displacement

From “Earthquake” No.1, Vol. 29, 2009
Results until early Dec., 2010 show the step changes, the coseismic displacements, only at the time of the Wenchuan Eq. in a large area.
Distances of the fiducial stations to the epicenter of the Wenchuan Eq. (km)

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XIAA</td>
<td>631.4</td>
</tr>
<tr>
<td>XNIN</td>
<td>639</td>
</tr>
<tr>
<td>DLHA</td>
<td>898.5</td>
</tr>
<tr>
<td>DXIN</td>
<td>1143.1</td>
</tr>
<tr>
<td>KMIN</td>
<td>664.1</td>
</tr>
<tr>
<td>XIAG</td>
<td>672.2</td>
</tr>
<tr>
<td>LHAS</td>
<td>1189.8</td>
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<tr>
<td>WUSH</td>
<td>2428.5</td>
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<tr>
<td>URUM</td>
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<tr>
<td>TASH</td>
<td>2666.3</td>
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<tr>
<td>GUAN</td>
<td>1308.6</td>
</tr>
<tr>
<td>YONG</td>
<td>1805.7</td>
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<tr>
<td>QION</td>
<td>1472.8</td>
</tr>
<tr>
<td>SELE</td>
<td>2670.5</td>
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<tr>
<td>POL2</td>
<td>2827.2</td>
</tr>
<tr>
<td>KIT3</td>
<td>3384.7</td>
</tr>
</tbody>
</table>

XIAA is the nearest station with anomalies to the Wenchuan Eq.

Red indicates stations with anomalies.

LUZH is the nearest station with anomalies to the Wenchuan Eq.
Epoch specific solutions of 30s: possible imminent anomalies

Double difference solution of the Bernese software in 2009.

LUZH station and other 4 stations PIXI, CHDU, JYAN and NEIJ, YANC is fixed in the solution.

Sampling rate: 30s.

Characteristics of the imminent anomalous change:
Anomalous diurnal changes in 3 components on May 9 at LUZH.
There were imminent anomalous changes in vertical component within an hour before the earthquake.
Stations of continuous GPS observation in Sichuan
Distances from the GPS stations to the epicenter

<table>
<thead>
<tr>
<th>Station</th>
<th>Dist. (km)</th>
<th>Station</th>
<th>Dist. (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIXI</td>
<td>36</td>
<td>LUZH</td>
<td>305</td>
</tr>
<tr>
<td>CHDU</td>
<td>75</td>
<td>YANC</td>
<td>838</td>
</tr>
<tr>
<td>JYAN</td>
<td>129</td>
<td>WUHN</td>
<td>1049</td>
</tr>
<tr>
<td>NEIJ</td>
<td>225</td>
<td>BJFS</td>
<td>1478</td>
</tr>
</tbody>
</table>
Anomaly on May 9 before the Eq.

From "Earthquake Science"
Within an hour before the event, the horizontal displacement was not significant, but there was large vertical displacement of more than 300mm.
Within an hour before the earthquake, vertical displacements were significant at 3 of 4 stations near the epicenter.

Green for PIXI  brown for NEIJ  blue for CHDU  red for JYAN

Earthquake Science
Short term or imminent anomalies in TEC in the ionosphere obtained from GPS observations
Short term or imminent anomalies in TEC in the ionosphere obtained from continuous GPS observations

Stations of continuous GPS observations
Changes in TEC at stations far from the epicenter (by Li Jianyong)
Anomalies in TEC on May 9 at stations near the epicenter (by Li Jianyong)
Anomalies in TEC on May 9 at stations near the epicenter (by Li Jianyong)
There was anomalous displacement at LUZH on the same day.
The global ionosphere map (GIM) of DTEC (subtracted by the 15-day median values) during 04:00UT-10:00UT, May 6-9. The black and gray dots represent the epicenter and the GPS stations used in this paper. The color codes show the difference of the DTEC. The GIM grid points lie between $\pm 87.5^\circ$N and $\pm 180^\circ$E with 2.5$^\circ$ and 5$^\circ$ grid intervals in the latitudinal and longitudinal directions (Li Jianyong).
Crustal movements related to the Tohoku earthquake of M9.0 on March 11, 2011 in Japan obtained from GPS observations

—Added evidence for the existence of crustal movements precursory to great earthquakes
GPS observations in Japan

The densest stations of continuous GPS observations in the world, there are 1239 stations and the distances between the stations are 25-30km.
Coseismic displacements of the East Japan earthquake

GPS station 0550, 98km to the epicenter, moved horizontally for 5.3m, and subsided for 1.2m (Sol. 2).

1 rapid solutions from Geospatial Information Authority of Japan
http://www.gsi.go.jp/ with reference to GPS station （950388）in Japan
Coseismic horizontal displacements at continuous GPS observation stations (obtained in the dislocation reference frame)

In good agreement with the dislocation model.
Comparison of E components for coseismic horizontal displacements obtained in the dislocation reference frame with core stations far from the epicenter (red) and in the global reference frame (blue).
Coseismic horizontal displacements at continuous GPS observation stations (obtained with core stations in eastern part of China)
East components (blue circles) of far field coseismic horizontal displacements of the $M_w$ 9.0 Tohoku earthquake in Japan, observed by GPS and their longitudes. The blue curve is the best fit by the exponential function.
Coseismic strains
Distances from the continuous GPS observation stations to the epicenter of the great Tohoku earthquake, Japan (unit: km)

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
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</thead>
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<tr>
<td>TSKB</td>
<td>314.4</td>
<td>TAIN</td>
<td>2253.8</td>
<td>IRKT</td>
<td>3303.7</td>
<td>LALB</td>
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<td>USUD</td>
<td>435.2</td>
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<td>3531.2</td>
<td>URUM</td>
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<td>SUIY</td>
<td>1202</td>
<td>BJFS</td>
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<td>YSSK</td>
<td>991</td>
<td>TWTF</td>
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<td>DXIN</td>
<td>3574.9</td>
<td>LHAS</td>
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<tr>
<td>DAEJ</td>
<td>1359.8</td>
<td>WUHN</td>
<td>2698.8</td>
<td>QION</td>
<td>3750.6</td>
<td>WUSH</td>
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<td>SUWN</td>
<td>1370</td>
<td>GUAM</td>
<td>2704.1</td>
<td>DLHA</td>
<td>3884.9</td>
<td>SELE</td>
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<td>CHUN</td>
<td>1568.9</td>
<td>XIAM</td>
<td>2746.8</td>
<td>KMIN</td>
<td>3945.3</td>
<td>POL2</td>
</tr>
<tr>
<td>SHAO</td>
<td>2095.3</td>
<td>XIAA</td>
<td>3011.3</td>
<td>KUNM</td>
<td>3945.4</td>
<td>TASH</td>
</tr>
<tr>
<td>JIXN</td>
<td>2162.4</td>
<td>ULAB</td>
<td>3034.2</td>
<td>XIAG</td>
<td>4124.2</td>
<td>KIT3</td>
</tr>
<tr>
<td>HLAR</td>
<td>2197.1</td>
<td>YANC</td>
<td>3043.2</td>
<td>LALX</td>
<td>4182</td>
<td></td>
</tr>
</tbody>
</table>
Coseismic displacements of the Tohoku earthquake of M9.0 in Japan seen from displacement time series obtained at stations of continuous GPS observations

The most reliable crustal movements observed by GPS

Coseismic displacements are in opposite sense to the preseismic anomalous displacements, so they are elastic rebound of these displacements.

Arrows in the time series in the next few slides are coseismic displacements.
Shortly before the Wenchuan earthquake on May 12, 2008, at stations of continuous GPS observations in northeast China and IGS stations in south Korea and Japan, there appeared anomalous westward displacements in E component; the displacements in N component showed rapid northward movements at first, then slow southward movements.

Because core stations of the regional reference frame are in the stable eastern part of Chinese mainland, the anomalous displacements at stations in this part were small. (YANC)
Displacement time series of the E component at GPS stations of YANC, SUIY, TSKB, USUD, MIZU, DAEJ, SUWN, SUIY, HLAR and CHUN.
Wenchuan Eq.

Preseismic Anomalies
Postseismic displacement

Preseismic Anomalies

Wenchuan Eq.
Displacement time series of the N component at GPS stations of YANC, SUIY, TSKB, USUD, YSSK, DAEJ, SUWN, HLAR and CHUN.
TSKB and USUD are exceptional.
Displacement time series of the E component at GPS stations of YANC, XNIN, DLHA, DXIN, XIAA, URUM, TASH, WUSH in northwest China and KIT3, SELE and POL2 in central Asia.
Summary:

Preseismic anomalies in crustal movement were observed in a vast area by GPS before the Tohoku earthquake on Mar. 11, 2011 in Japan and the coseismic horizontal displacements observed in the same area are convincing evidences for the existence of crustal movements precursory to this event.

Dislocation models are important in modeling the coseismic and postseismic displacements and also useful in studying preseismic displacements.

All above-mentioned facts and the studies on the Wenchuan earthquake shows that GPS observations in Japan also observed crustal movements precursory to this event.
Results of the Japanese seismologists

Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan

Shinzaburo Ozawa,¹ Takuya Nishimura,¹ Hiroshi Munekane,¹ Hisashi Suito,¹ Tomokazu Kobayashi,¹ Mikio Tobita,¹ and Tetsuro Imakiire¹

Crustal movements related to the Lushan earthquake of M7.0 on April 20, 2013 in China obtained from GPS observations
Preseismic and coseismic horizontal displacements of the Lushan Eq. in the regional reference frame

(a) Accumulated horizontal displacements before the earthquake from Jul., 2010 to Apr., 2013

(b) Coseismic horizontal displacements

(c) Accumulated horizontal displacements before the earthquake from Jul., 2010 to Apr., 2013 + coseismic horizontal displacement
In comparison to the development of horizontal displacement at other stations in the same area, development of the horizontal displacement at SCTQ shows that the coseismic horizontal displacement was the elastic rebound. It shows that because of the coseismic displacement the station moved back to the position before the anomaly.

The dislocation models are useful in the studies on the coseismic (horizontal) displacements, therefore they are also useful in the studies on the precursory crustal movements.

Other stations near the epicenter show similar preseismic and coseismic changes. (They are not shown here.)
By taking into account of long term displacements at nearby GPS stations, it is reasonable to assume that the green dashed line should be the normal displacement trend at this station and the coseismic horizontal displacement was the elastic rebound.
Attenuation of the coseismic horizontal displacements with the increase of the distances of GPS stations to the epicenter.
Horizontal displacements before and after the earthquakes of M6.6 in Minxian on Jul. 22, 2013

Almost the same as in the case of the Lushan earthquake
Minxian Eq. M6.6  2013-07-22 (34.500, 104.200) in Gansu, China

GPS stations of continuous observations near the epicenter
GSMX   18.2KM   the nearest station to the epicenter
        15.6mm  coseismic horizontal displace
GSLX   68.5km   distance to the epicenter
Minxian M6.6
The area at the epicenter was locked before the quake as shown by the displacement at the GSMX station.

The coseismic displacement at the GSMX station.

Accumulated horizontal displacements after the earthquake.
Time series of horizontal displacements.
Time series of horizontal displacements.
Studies on seismic waves
GPS Measured seismic waves

Data from 2002 Denali earthquake
Studies on postseismic displacements
Postseismic displacement

Preseismic Anomalies

Wenchuan Eq.
Important models in modeling the preseismic, coseismic and postseismic displacements.

Model of global plate motions. Model of elastic rebound explains the occurrences of earthquakes. The dislocation models have given numerical modeling of the coseismic (horizontal) displacements of large earthquakes, and far field coseismic displacements are elastic rebound of the accumulated elastic displacements, therefore dislocation models are also useful in the studies on the precursory crustal movements.
The rock failure test shows that the deformation process before, during and after the earthquake is similar to the process during the test.
4. Conclusions
GNSS is advantageous in monitoring crustal deformation, particularly for earthquake prediction

High precision of 1mm in horizontal component and 3mm in vertical component, relative precision of $10^{-7}$-$10^{-8}$ for baselines of tens to hundreds of km and $10^{-9}$ for the baselines of thousands of km.

Long term stability of the observed results.

Global and regional coverage of observation stations

Rapid and even real time data processing can be realized for short and imminent earthquake predictions.

Rapid and simultaneous solution of 1D vertical and 2D horizontal displacements and all horizontal strain components.

The best observation technique for the detection of the coseismic displacements of large earthquakes, particularly of giant earthquakes of magnitudes over M9.

Dense stations favorable for getting pictures of the spatial developments of anomalous crustal deformations or deformation contaminations.
Observations of high sampling rate can be obtained for detection of short and imminent precursors to earthquakes. Detection of imminent precursory variations in TEC (Total Electron Content) in the ionosphere. Low costs for the establishment of the observation stations and observation operations.

GPS is an advantageous technique for crustal deformation observations at present that can meet different requirements for detecting precursory deformations in space, time and magnitude. Here the magnitude refers to the magnitudes of displacement and strain components, etc..

Earthquake prediction is possible

Seismogeodesy — new horizon of Geodesy.
Acknowledgement:

Data processing results from the First Monitoring Center of CEA and from the Data Center of CMONOC are used and analyzed in this study. And the data were processed with GAMIT/GLOBK.
Thank you for your attention!
References


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