MONITORING THE TOHOKU EARTHQUAKE ON 11, MARCH 2011 BY USING GPS TECHNOLOGY

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ABSTRACT

The earthquake in northern Honshu, Japan with a magnitude of 9.0 affected a very large area. When the earthquake occurred, some surrounding IGS permanent stations were continuously recording GPS data. We processed these data to calculate precisely their displacements. They reveal that the nearest station was moved approximately 2.4m. Amazingly some stations in South Korea, which are about 1350km from the epicenter, were still affected and shifted around 2cm in the East direction.

1. INTRODUCTION

The Earthquake occurred at around 3 pm (05:46:24 UTC) on 11, March 2011 in northern Honshu, Japan with a magnitude of 9.0. This magnitude places the earthquake as the fourth largest in the world since 1900 and the largest in Japan since modern instrumental recordings began 130 years ago. The earthquake centre was about 373km from Tokyo (figure 1). According to the U.S. Geological Survey (USGS) [1], the bed rock in the area where Japan is situated was moving which is why it shifted some eight feet equivalent to 2.4 meters.

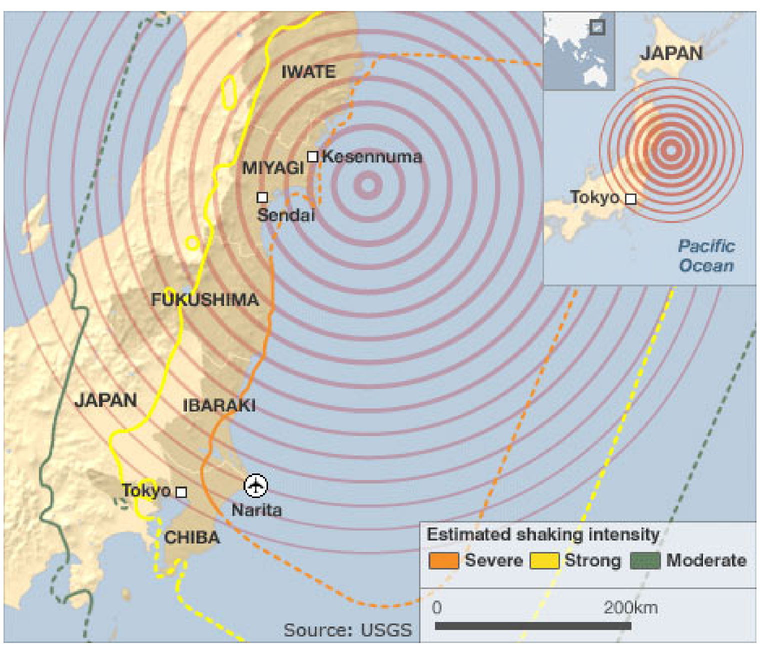

Figure 1. The earthquake location

We collected some GPS data from 9 IGS stations around the epicenter for two days 10-11, March 2011. These stations are listed in table 1 and figure 2.

Table 1. IGS permanent stations in the survey

N0	Station	Distance from epicenter (km)
1	MIZU	134
2	TSKB	361
3	TSK2	361
4	MTKA	430
5	USUD	467
6	AIRA	1323
7	DAEJ	1361
8	SUWN	1371
9	SHAO	2125

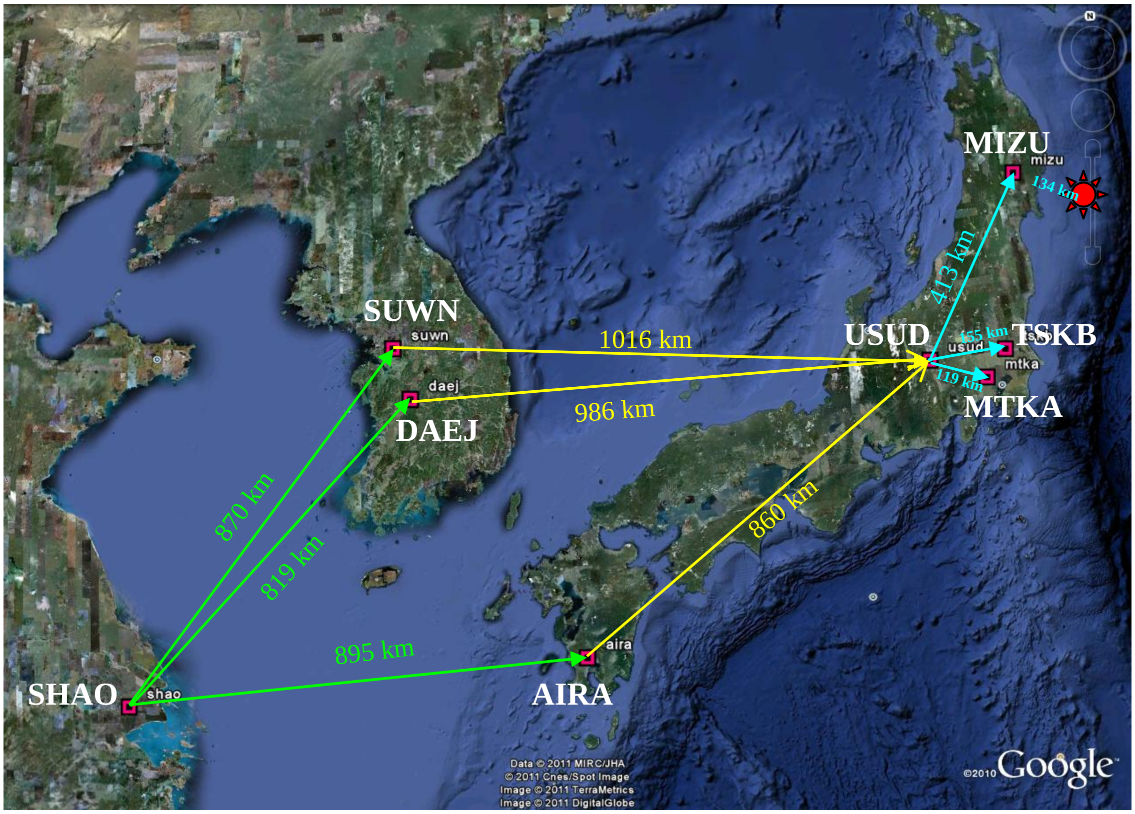

Figure 2. IGS stations near the epicenter

In table 1, TSKB and TSK2 are only 36m apart and station SHAO is located in China (>2000km from the epicenter) therefore it was almost unaffected by the earthquake.

2. METHOD OF DETERMINING IGS STATION DISPLACEMENT

GPS receivers set up at the IGS stations are high quality dual frequency receivers with choke-ring antenna. Some receivers are equipped with external atomic oscillators which provide high quality pseudo-range measurements. The receivers record data with an interval of 30 seconds and work continuously except during special events such as disaster, maintenance, firmware update, etc. The recorded data are stored daily in accessible databases. Users can freely download them via the internet.

Processing the GPS data every epoch gives us precise coordinates of stations over time. If an earthquake occurs and shifts the station, we can obtain the displacement by comparing its coordinates before and after the time of the earthquake.

It is necessary to know how accurate the GPS processed coordinates are because this will determine the minimum detectable displacement. To obtain the highest accuracy in GPS processing from mm to cm, one uses static point precise positioning (PPP) or static relative positioning methods. Some previous researches prefer to use PPP to avoid difficulties for long baselines [7, 8]. However, PPP is still less accurate than the relative method when resolving successfully ambiguity parameters. In this research we choose the static relative positioning method for our GPS processing.

Eckl et al. [4] used GPS data with 4-24 hour sessions and baseline lengths between 26 and 300km. With a 24 hour session, the standard error for the relative position in the North-South direction is 1.5 ÷ 2.4 mm; in the East-West direction is 1.4 ÷ 2.6mm and vertically is 5.6 ÷ 9.3mm when using IGS ephemerides. HÄKLI et al. [5] used commercial GPS software with default parameters, covering observing sessions between 10 minutes and 24 hours and baselines between 0.6 km and 1069 km. The root mean square (RMS) accuracy of 3-D geodetic GPS for broadcast orbits (solid line) and precise orbits (dashed line) are given in figure 3. With a 24 hour session and using precise ephemerides, an accuracy can be obtained of 1 cm for 350km baselines and 2cm for 1000km baselines.

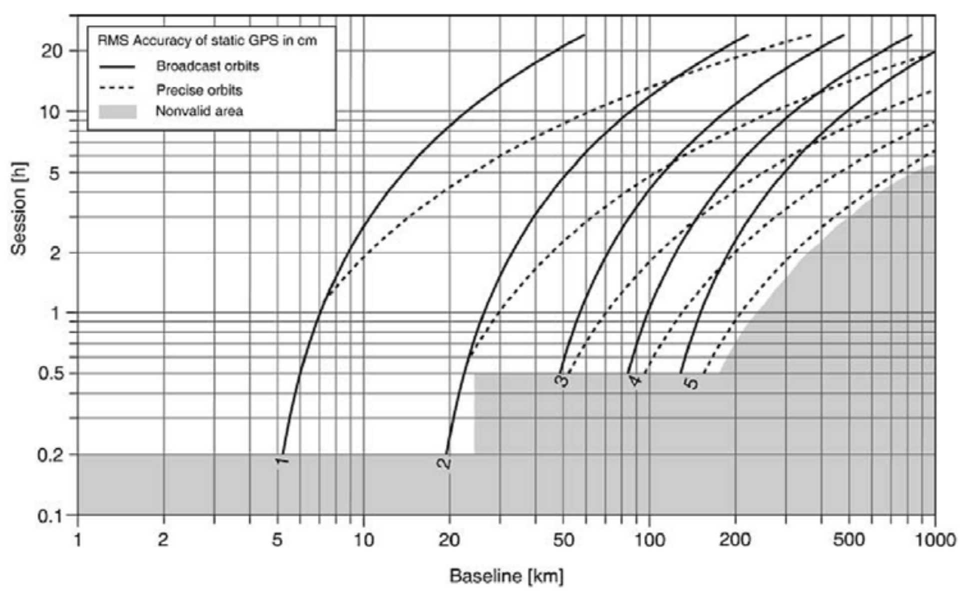

Figure 3. Static GPS results for individual baseline solutions (accept from [5])

In summary, for GPS baselines ranging from 100 to 1000km, we can obtain an accuracy of 3-6mm in the horizontal and 10-20mm in the vertical component. With such accuracy we can detect the minimum displacement of 1-1.5cm in the horizontal and 3-5cm in the vertical component of a baseline. For our purpose, we designed a GPS network as in figure 2. This network includes 11 baselines ranging from 119 – 1016km as shown in table 2.

Table 2. Lengths of processed baselines

Baselines	Length (km)
SHAO-SUWN	870
SHAO-DAEJ	819
SHAO-AIRA	895
SUWN-USUD	1016
DAEJ-USUD	986
AIRA-USUD	860
USUD-MTKA	119
USUD-TSKB	155
USUD-TSK2	155
USUD-MIZU	413
MTKA-MIZU	408

To achieve the desired accuracy, we have to process GPS carrier phase measurements. The greatest challenge is how to resolve successfully ambiguity for some long baselines (800-1000 km). Commercial software packages only process baselines shorter than 50km. Therefore we used GUST software, the acronym describing the adopted processing philosophy which is "GPS processing Using Sequential static Techniques". The double differenced carrier phase observations can be processed *continuously* without limiting the length of the observation session and without breaking the continuity of the session. As a result this approach has more advantages in cycle slip detection and repair as well as ambiguity resolution and hence the accuracy of the parameter estimates can be improved, especially for long baselines. In addition, GUST can process many consecutive data days and is capable of re-initializing the estimated coordinates at any epoch [5]. The following are some options which can be set in the processing of single baselines:

- Using IGS precise ephemerides
- Using L3 carrier phase measurements
- Setting elevation cut off angle as 5°
- Estimating one tropospheric zenith delay every 2.5 hours with Niell mapping function
- Applying IGS antenna model and solid Earth model
- For each baseline, processing separately 24h data before and after the earthquake.

The processing results of all the single baselines are presented in section 3.

3. SINGLE BASELINE PROCESSING RESULTS

3.1 Baselines SHAO-SUWN, SHAO-DAEJ and SHAO-AIRA

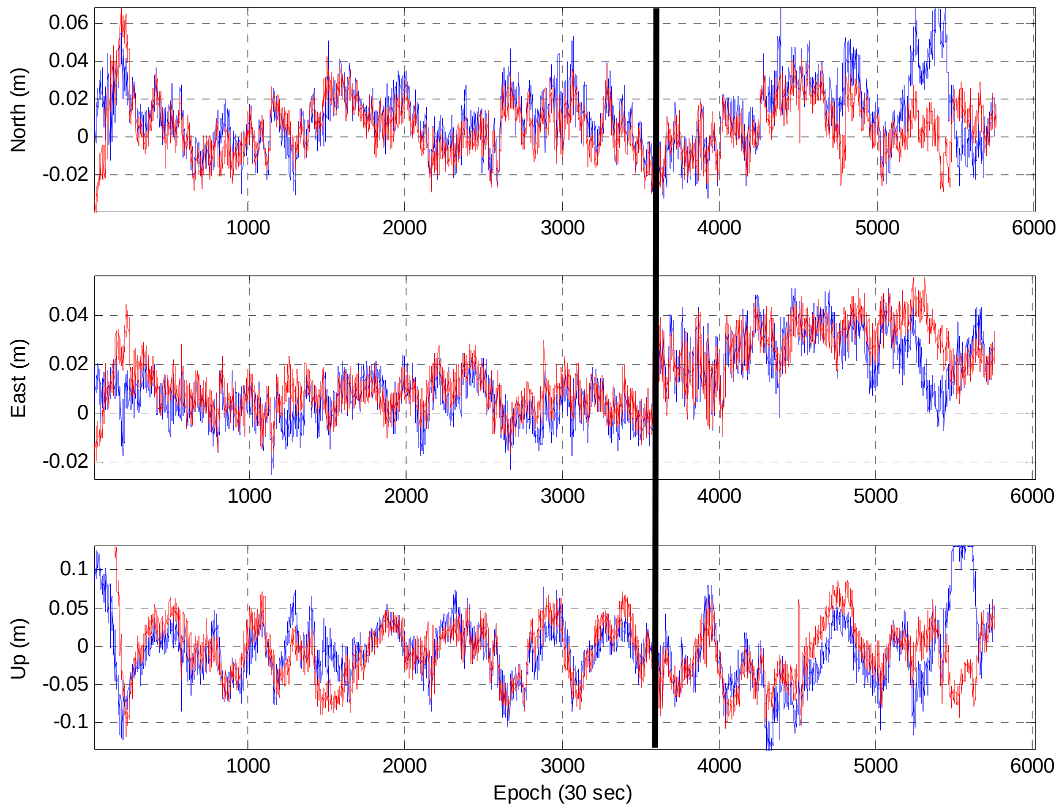

Figure 4. Baseline SHAO-SUWN (blue) and SHAO-DAEJ (red)

Figure 4 shows the North, East and Vertical components of baselines SHAO-SUWN (blue) and SHAO-DAEJ (red) at each epoch of 30 seconds. These results represent the two days 10-11/03/2011, where the earthquake started from epoch 3583 and lasted for about 5 minutes. We can see clearly that SUWN and DAEJ are shifted in the East component about 2cm.

Table 3. Baseline displacements

Baselines	North (m)	East (m)	Up (m)
SHAO-SUWN	-0.002	+0.019	-0.012
SHAO-DAEJ	-0.001	+0.018	-0.035
SHAO-AIRA	-0.000	+0.016	-0.029

Table 3 gives us the displacements of baselines SHAO-SUWN, SHAO-DAEJ and SHAO-AIRA due to the earthquake. If we suppose that SHAO was not affected, these displacements are caused by stations SUWN, DAEJ and AIRA.

3.2 Baselines SUWN-USUD, DAEJ-USUD and AIRA-USUD

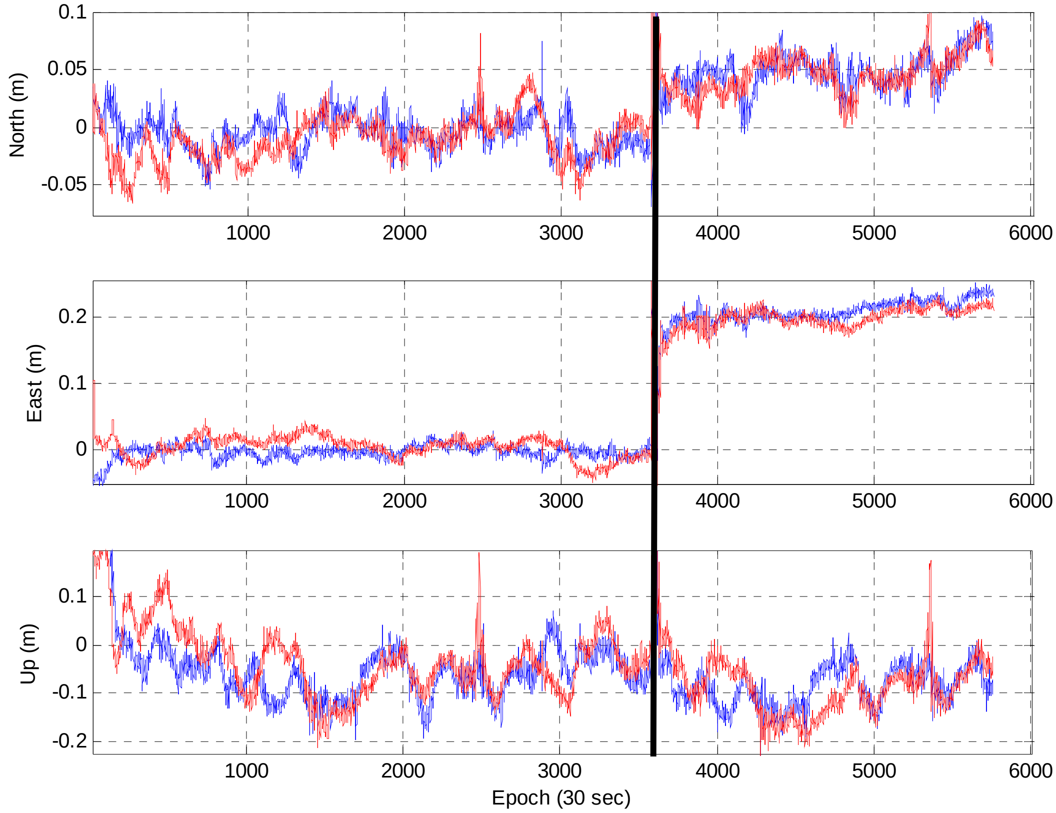

Figure 5. Baselines AIRA-USUD (red) and DAEJ-USUD (blue)

To determine precisely the displacement of station USUD, we processed 3 baselines from stations SUWN, DAEJ, AIRA and compared them with each other. Figure 5 shows that the changes of components of baselines AIRA-USUD and DAEJ-USUD are almost the same. From the baseline displacement in table 4, we can calculate the displacements of station USUD in table 5. The weighted mean value of the displacement from 3 values has a RMS of 1cm.

Table 4. Baseline displacements

Baselines	North (m)	East (m)	Up (m)
SUWN-USUD	+0.049	+0.189	-0.074
DAEJ-USUD	+0.051	+0.195	-0.058
AIRA-USUD	+0.042	+0.202	-0.061

Table 5. Displacements of station USUD

Computed from	North (m)	East (m)	Up (m)	Weight
SUWN	+0.047	+0.208	-0.086	1/1016
DAEJ	+0.050	+0.213	-0.093	1/986
AIRA	+0.042	+0.218	-0.090	1/860
Weighted mean	+0.046	+0.213	-0.090	

3.3 Baselines USU-MTKA, USUD-TSKB and USUD-TSKB2

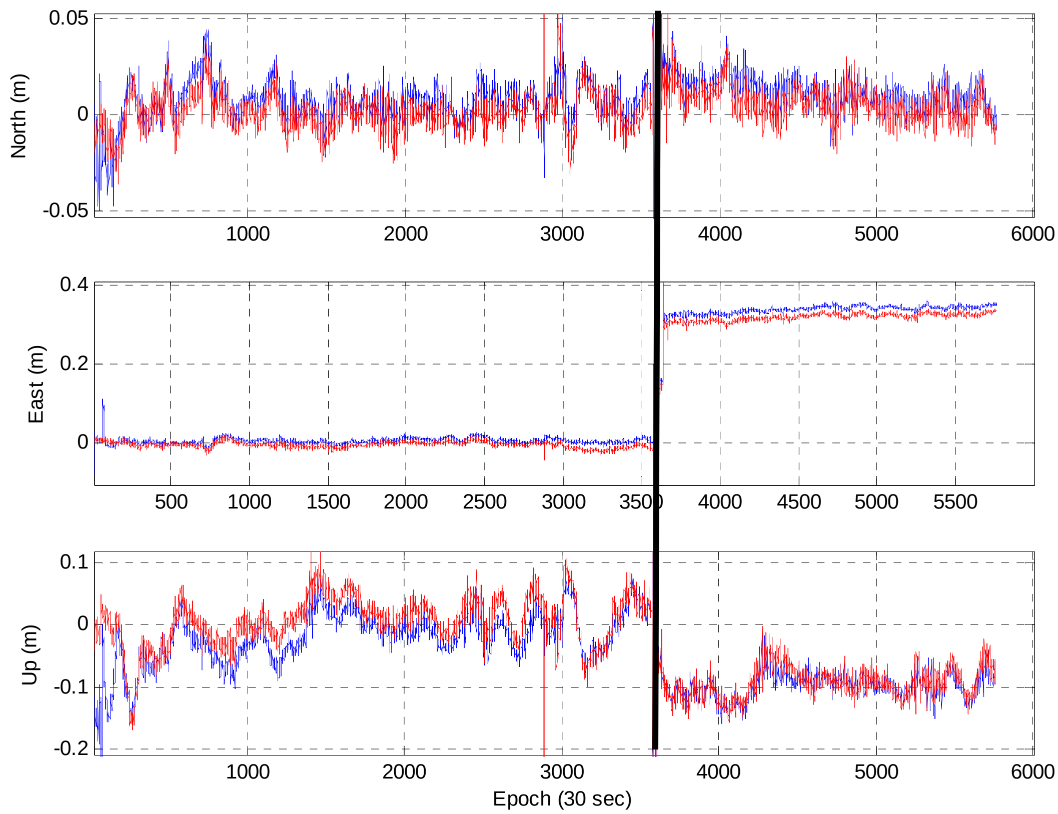

Figure 6a. Baselines USUD-TSKB (blue) and USUD-TSK2 (red)

Considering USUD as a base station and using baseline displacements in table 6, we calculate displacements of stations MTKA, TSKB and TSK2 given in table 7. Stations TSKB and MTKA are very close to each other therefore their displacements are quite similar.

Table 6. Baseline displacements

Baselines	North (m)	East (m)	Up (m)
USUD-MTKA	+0.008	+0.019	-0.024
USUD-TSKB	-0.010	+0.330	-0.152
USUD-TSK2	-0.004	+0.330	-0.156

Table 7. Displacements of stations computed from USUD

Station	North (m)	East (m)	Up (m)
MTKA	+0.054	+0.232	-0.114
TSKB	+0.036	+0.543	-0.242
TSK2	+0.042	+0.543	-0.246

Looking more carefully at the baseline displacements, we will see that the movement was a bit complicated as shown in figure 6b. Station TSKB was shifted twice. The first jump occurred at epoch 3577 and the second 28 minutes later. Between the two events, the station was shaken for a couple of epochs.

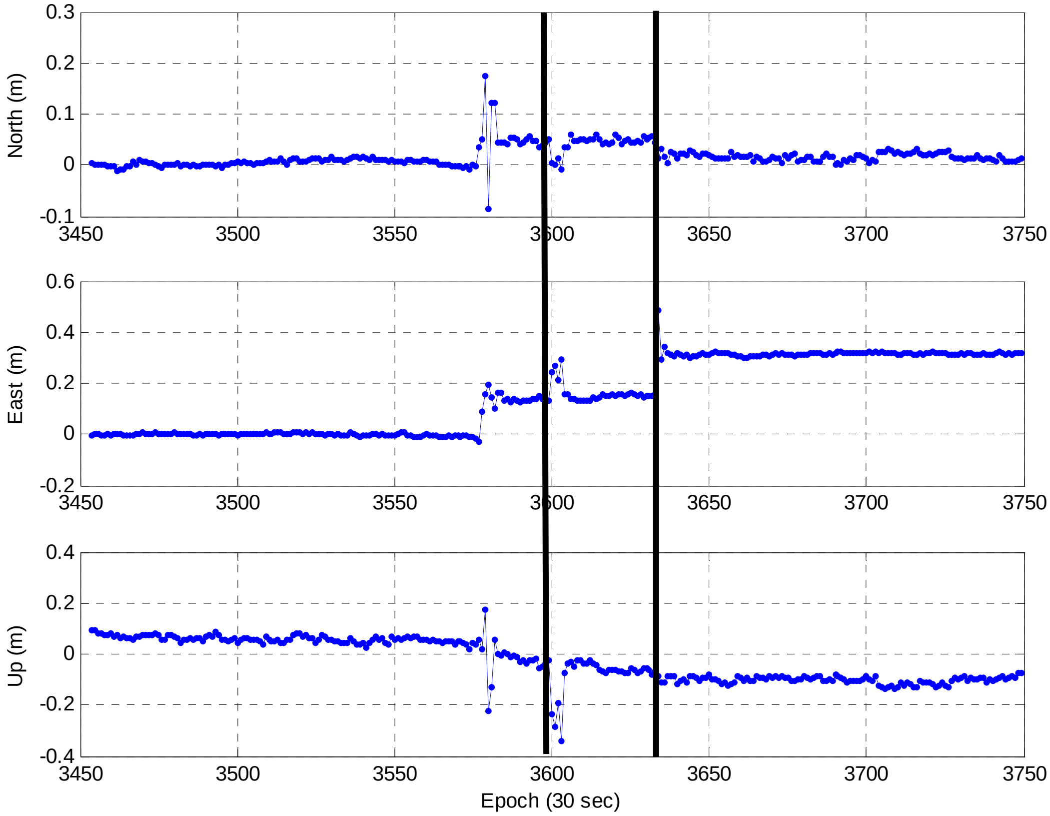

Figure 6b. Baseline USUD-TSKB

3.4 Baselines USUD-MIZU and MTKA-MIZU

Station MIZU is closest to the epicenter. Therefore it was affected the most. Its coordinates started to change at epoch 3575, i.e. 3.5 minutes sooner than stations AIRA, DAEJ and SUWN. Its displacements are computed from stations MTKA and USUD with an accuracy of 5mm in North/East and 2cm in the Vertical component. After the earthquake, this station worked only for a further 7 minutes then stopped due to the tsunami.

Table 8. Displacements of baselines

Baseline	North (m)	East (m)	Up (m)
USUD-MIZU	-1.170	+1.899	-0.126
MTKA-MIZU	-1.182	+1.913	-0.059

Table 9. Displacements of station MIZU

Computed from	North (m)	East (m)	Up (m)	Weight
USUD	-1.124	+2.112	-0.216	1/413
MTKA	-1.128	+2.145	-0.173	1/408
Weighted mean	-1.126	+2.128	-0.194	

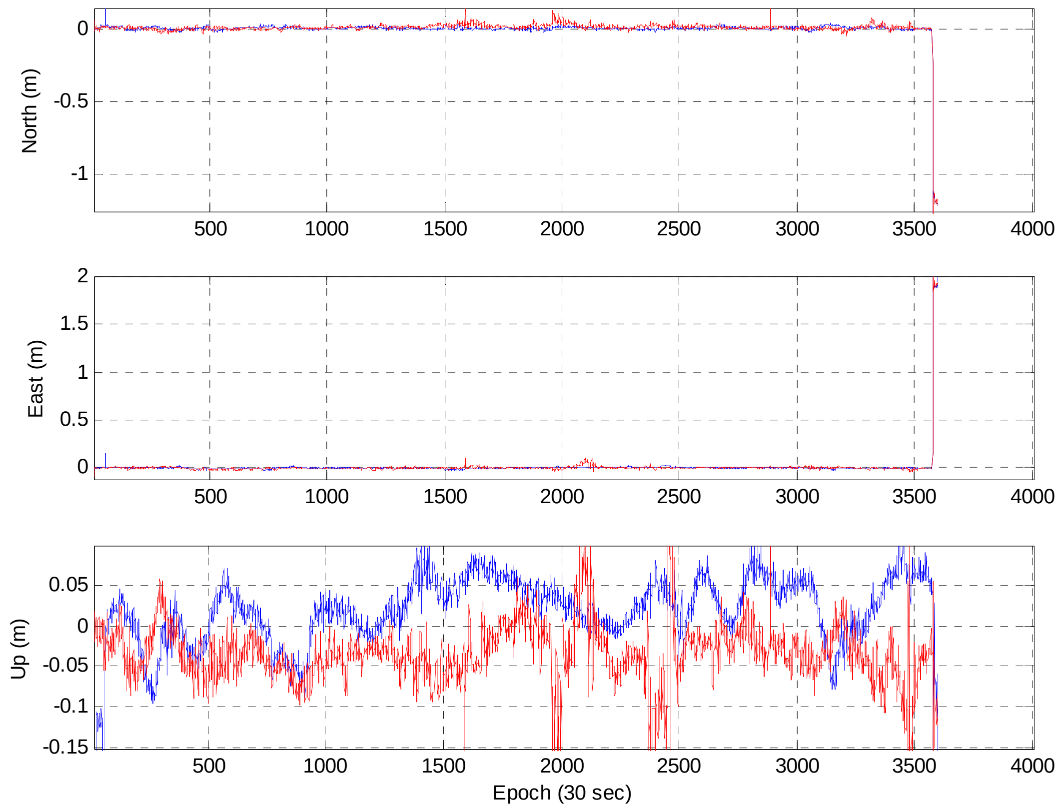

Figure 7. Baselines USUD-MIZU (blue) and MTKA-MIZU (red)

4. SUMMARY AND CONCLUSION

To monitor the affect of the earthquake with magnitude of 9.0 on 11, March 2011 in northern Honshu, Japan, we collected and processed GPS data at 9 IGS stations around the epicenter. The IGS station displacements are calculated precisely with an accuracy of 2cm in the horizontal and 6cm in the vertical component. These displacements are summarized in table 10 and figure 8.

Table 10. Summary

Station	North (m)	East (m)	Vertical (m)	S (m)
SUWN	-0.002	+0.019	-0.012	0.019
DAEJ	-0.001	+0.018	-0.035	0.018
AIRA	-0.000	+0.016	-0.029	0.016
USUD	+0.046	+0.213	-0.090	0.228
MTKA	+0.054	+0.232	-0.114	0.249
TSKB	+0.036	+0.543	-0.242	0.555
TSK2	+0.042	+0.543	-0.246	0.555
MIZU	-1.126	+2.128	-0.194	2.407

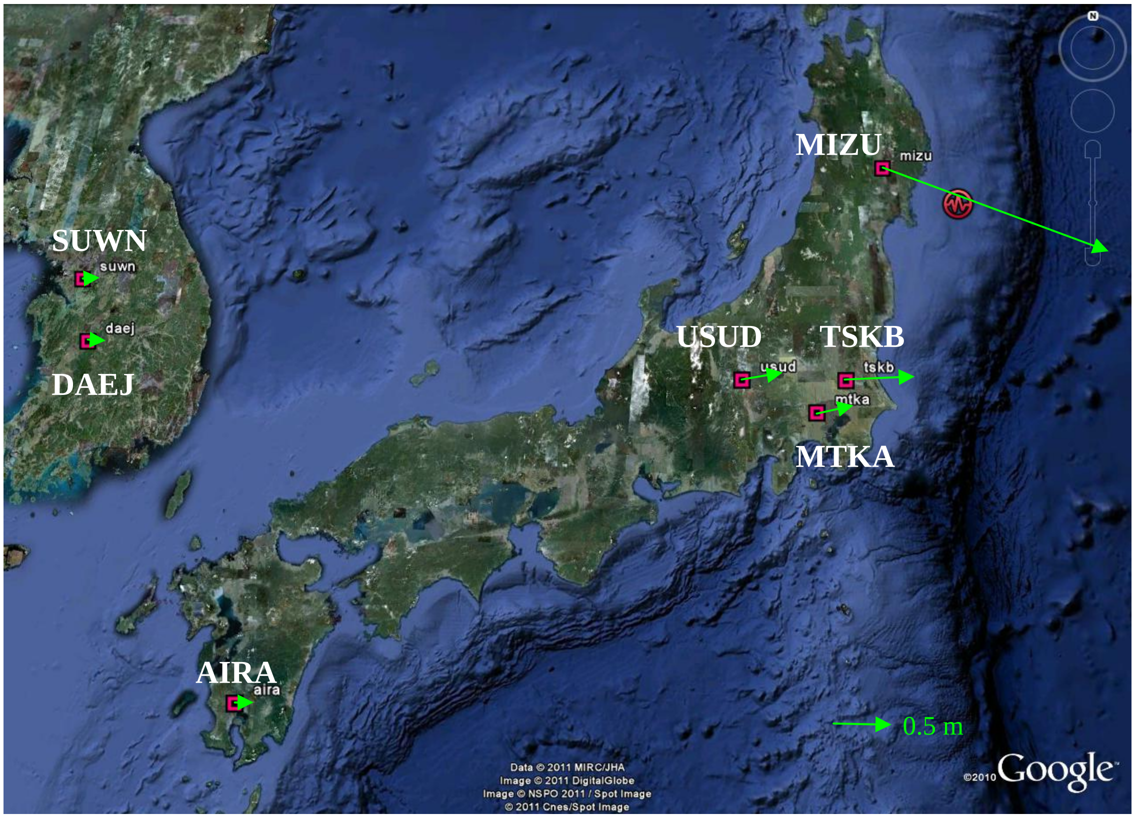

Figure 8. IGS station displacements

Figure 8 shows that the earthquake affected a very large area. Its intensity decreased with distance from the epicenter. Station MIZU, closest to the epicenter, jumped South-Eastward by up to 2.4m. It is quite surprising that stations SUWN, DAEJ and AIRA located greater than 1320km from the epicenter were still affected. They were shifted Eastward by an amount of 2cm. The shock propagation rate is approximately 6.4 km/s from the epicenter (twice larger than [8]).

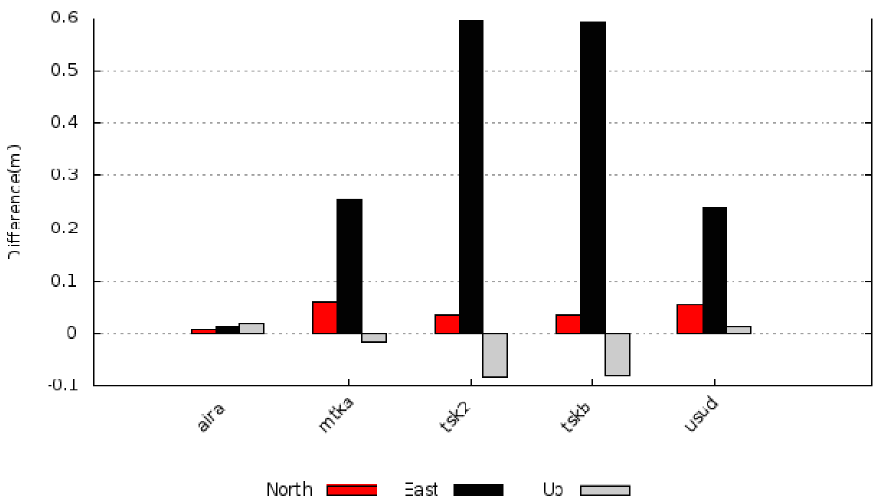

Figure 9. IGS station displacements due to Tohoku earthquake (accept from [7])

Our results are similar to Álvaro's research [7]. He processed one data day from some IGS stations by using PPP with magicGNSS software. His results are summarized in figure 9. Using the same PPP method, Dash [8] used Bernese GPS Software to provide equivalent results. Figure 10 illustrates one of Dash's results for station USUD.

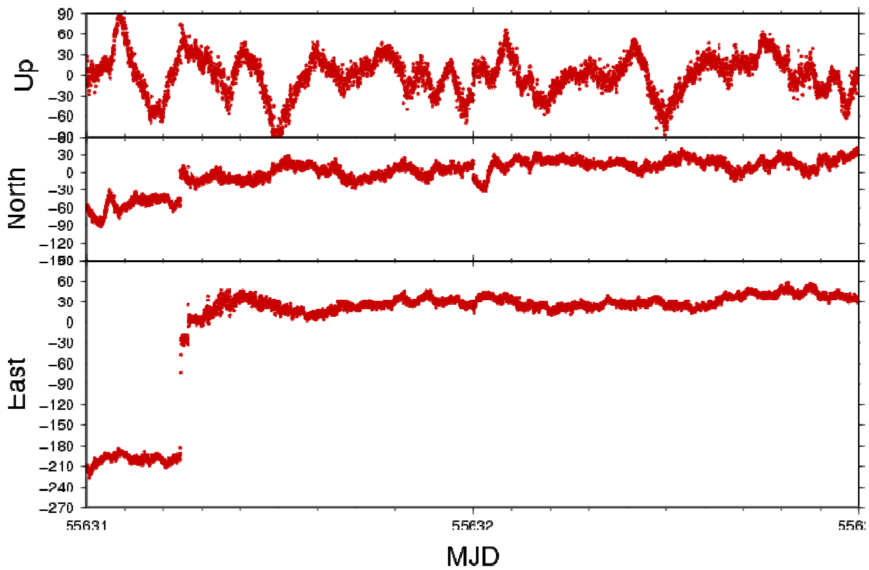

Figure 10. Station USUD displacements due to Tohoku earthquake (accept from [8])

In conclusion, GPS technology has proven its advantages for monitoring ground movements due to earthquake such as accuracy, large area coverage, availability, short-term or long-term displacement tracking.

5. REFERENCES

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