Real-time capability of GEONET system and its application to crust monitoring

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Abstract

The GPS Earth Observation Network system (GEONET) has been playing an important role in monitoring the crustal deformation of Japan. Since its start of operation, the requirements for accuracy and timeliness have become higher and higher. On the other hand, recent broadband communication infrastructure has had capability to realize real-time crust monitoring and to aid the development of a location-based service. In early 2003, the Geographical Survey Institute (GSI) upgraded the GEONET system to meet new requirements. The number of stations became 1200 in total by March, 2003. The antennas were unified to the choke ring antennas of Dorne Margolin T-type and the receivers were replaced with new ones that are capable of real-time observation and data transfer. The new system uses IP-connection through IP-VPN (Internet Protocol Virtual Private Network) for data transfer, which is provided by communication companies. The Data Processing System, which manages the observation data and analyses in GEONET, has 7 units. GEONET carries out three kinds of routine analyses and an analysis of RTK-type for emergencies. The new system has shown its capability for real-time crust monitoring, for example, the precise and rapid detection of coseismic (and post-seismic) motion caused by 2003 Tokachi-Oki earthquake.

1. Introduction

GSI's GPS observation and its importance have increased during the past decade. The first observation system started as a Continuous Strain Monitoring System with GPS by GSI (COSMOS-G2), with 110 GPS stations in the southern Kanto and Tokai area, installed in 1993 (Sagiya et al., 1995). In 1994, an extra 100 stations, which formed the GPS Regional Array for Precise Surveying/Physical Earth Science (GRAPES), were installed to cover the whole of Japan (Miyazaki et al., 1996). The two separate systems, COSMOS-G2 and GRAPES, were integrated in 1995 and an additional 400 stations were established. The operation of the integrated network, named GEONET, started in March, 1996 (Miyazaki et al., 1998). Since then, GEONET has grown occasionally by adding stations to strengthen the observation network.

GEONET has been utilized for manifold purposes: GSI's GPS network was originally designed to monitor long-term crustal movements. After that, GRAPES showed its ability to detect coseismic displacements caused by earthquakes like the Kobe earthquake (January 15, 1995, M7.2). GEONET was also able to detect volcanic activities like the eruption of Mt. Usu (March 29, 2000). The Revised Survey Act, which enables surveyor to use GPS data for public surveys, was enforced on April 1, 2002 (Matsumura et al., 2004) and GEONET stations became usable as reference points for public surveys. GEONET can record not only crustal movements but also incidental phenomena in nature that contribute to different areas of research such as meteorology, ionospheric research and so on as well as geodesy. Both the potential of the system and the demand for the system have been mutually increasing.

While the requirements for accuracy and timeliness of GEONET had become higher and higher since the start of its operation, the hardware of the data management system was almost the same as it had been, which seemed to find it hard either to manage heavier amounts of data or to meet the increasing demand for the system. On the other hand, the recent broadband communication infrastructure has enabled us to transfer data in real time, which may be GEONET's breakthrough for real-time crust monitoring and aid to the development of location-based services.

In response to this background, GSI upgraded the GEONET system and added real-time capability to meet the requirements in early 2003 (Geodetic Observation Center, 2004). The upgrade aims to renew almost all of the hardware and data management schemes, e.g., observation instruments, communicating methods, data processing systems, and analysis settings.

In this paper, we introduce the new GEONET system and its potential for crust monitoring.

2. Requirements for the new system

Before reforming the system, we must consider what function in the old system should be improved as well as what function should be newly added. We particularly took the following requirements into account:

1) The system must provide analysis results as fast as possible, especially when natural hazards happen. Moreover the results should be as precise as possible. Both requirements can't be met at the same time in general, since these two conditions have a trade-off relationship. Therefore we need to find optimal halfway conditions by viewing tolerable delay and expected precision.
2) The system should be able to pick up GPS signals as frequently, for example, as 1 Hz, and should transfer the data in real-time. The real-time data should be usable for both real-time (or semi-real-time) crust monitoring and civil location-based services.
3) The data format inside the system must be standardized so that GEONET can handle different types of receivers. To meet this requirement, streaming data should be converted from a receiver-dependent format to a RTCM (ver.2.2) format and the archiving data format should be the RINEX format.
4) To clarify each kind of hardware and its function, the data processing system should be divided into independent units per each function.

3. Reinforcement of the observation network

253 new stations were added to the preexisting 947 stations, and the number of the stations became 1200 in total by March, 2003 (Fig. 1). The new stations include Mt. Fuji, the highest point in Japan, and the Minamitorishima Island (Marcus Island) located at the eastern end of the Japanese territory, the only island of Japan on the Pacific plate. As of April 1, 2005 the total number of stations is 1229.

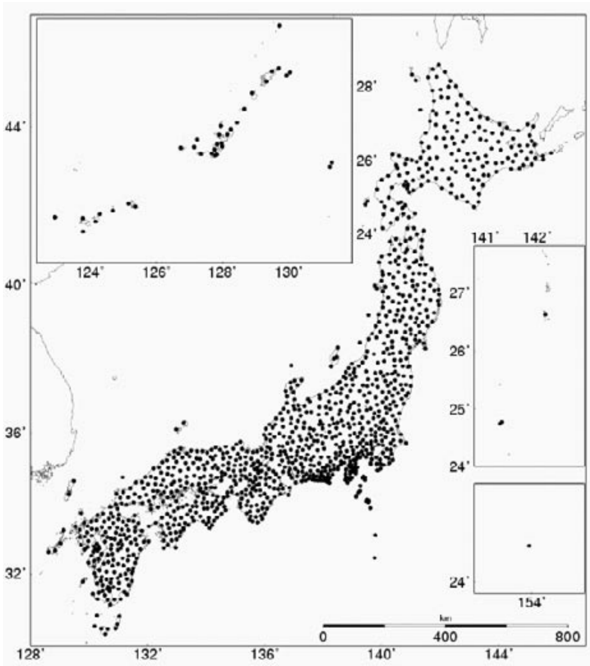

Fig. 1 Geographical distributions of GEONET stations.

The monuments of GEONET are roughly classified into four types of shape reflecting the augmentation steps; the first, Type93, were built in 1993, Type94 in 1994, and from the following year Type95 was introduced. Abe et al. (1999) reported that sunbeams can cause a diurnal tilt of the pillar which has an amplitude of about 5mm and affects the daily solution by about 3mm. The newest, Type02, established in 2002, are characterized by a doubled stainless steel pillar in a simple shape, which reduces the effect of the tilt by the thermal ductility of the pillar.

The antenna types were unified to the choke ring antennas of Dorne Margolin T-type to reduce the dispersion in analyses caused by both multipath and different antenna phase center variations. For this purpose, the old antennas of preexisting stations were replaced by the same ones as the new stations. The old receivers were also replaced with new ones that are capable of 1-Hz sampling and real-time data transfer. The receiver setting of elevation cutoff angle was changed from 15 degrees to 5 degrees. All stations are operational 24 hours a day and transfer observation data with 1 Hz sampling, except for 12 stations which are not provided with a broadband connection. Simultaneously, the receivers stock backup data into memories every

30 seconds. The backup data are available for about 3 weeks and can be downloaded by the data processing system in GSI. Receivers are equipped with batteries in case of power outage of at least 6 hours.

4. Data transmission

The observed data of all stations are transferred to the data processing system at the data center of GSI in Tsukuba city. Fig. 2 shows a schematic diagram of the data flow of GEONET. Most of the sites, where broadband lines are available, have an IP connection through IP-VPN (Internet Protocol Virtual Private Network). IP-VPN is a communication network provided by communication companies, and realizes IP connection to sites with closing the communication within limited users ("virtually private") for high security. The raw data observed in 1 Hz are transferred in real time to the Data Processing System.

The 1 Hz real-time data are also provided to commercial users of the positioning service through a non-profit organization which charges a cost. The Japan Association of Surveyors (JAS) takes on this task of the portal of the real-time data provision, and four positioning service companies have a contract with JAS as of April 2005.

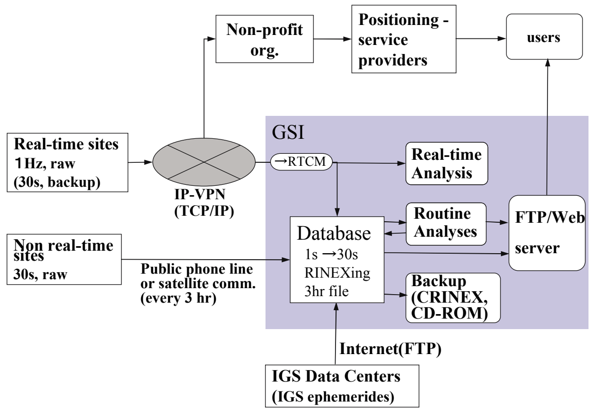

Fig. 2 Schematic diagram of the data flow of the new GEONET system.

The 12 stations that don't have real-time connection send the stored data to the Data Processing System every 3 hours.

The observation data in GSI are archived as 3-hour RINEX files with a 30-second sampling interval and uploaded to a FTP/Web server. The 1 Hz data are not archived permanently but discarded a few weeks after the observation, except for the case of special experiments or seismic/volcanic events of interest. Observation data in RINEX format and the solutions of Final Analysis from the most recent April to the present can be downloaded via a web service or an ftp service.

5. Structure of the data processing system

Data Processing System is physically divided into 7 units. These units intercommunicate through a 1000BASE private LAN.

5.1 Real-time Communication Operating Unit

The Real-time Communication Operating Unit controls the communication between the GPS-based Control Stations and the Data Processing System. The unit, which consists of 14 machines, stores 1 Hz raw data and converts them into RINEX format decimated to a 30-second sampling rate every 1 hour. This unit responds to requests from the Real-time Analysis Unit, converts the raw streaming data into RTCM format, and pours them to the Real-time Analysis Unit in real time.

5.2 Non-real-time Communication Operating Unit

The Non-real-time Communication Operating Unit controls the non-real-time communication between the GPS-based Control Stations and the Data Processing System. The unit downloads the data of the GPS-based Control Stations, which don't have real-time connection, every 3 hours. The data files are uploaded to a temporary directory of the Administration System after the conversion of raw data into RINEX format.

5.3 Administration System

The Administration System manages all schedule and database of GEONET. The schedule includes download of the data in the Non-real-time Communication Operating Unit, start of analysis in the Routine Analysis Unit, checking of temporary directories and so on. The database keeps all information related to GEONET, for example station information, RINEX holdings, analysis results, health status of the system etc.

The unit also controls the receiver of every GPS-based Control Station through Real-time or Non-real-time Communication Operating Units.

5.4 Data Storage Server

The Data Storage Server holds 30-second RINEX data created in the Real-time Communication Operating Unit and the Non-real-time Communication Operating Unit. Three 1-hour data files are concatenated into one 3-hour data file every 3 hours. This server is equipped with a CD-RW drive to back up the data files.

5.5 Routine Analysis Unit

The Routine Analysis Unit processes 3 types of routine analyses. These are 1) Quick Analysis, 2) Rapid Analysis, and 3) Final Analysis. The unit can also perform special analyses using the data for arbitrary hours on demand.

5.6 Real-time Analysis Unit

The Data Processing System has a Real-time Analysis Unit for emergency analysis. Now GEONET handles 2 real-time analysis programs; RTnet (GPS Solutions Inc.) and 3D Tracker (Condor Inc.).

5.7 Display Unit

The Display Unit visualizes and provides the results for users to monitor crustal deformations. There are 4 components: Display part for Routine Analyses, Display part for Real-time Analysis, Crust Monitoring Web Server, and Crust Monitoring Plot Editor with Data Plotter. Two display parts obtain analysis results to make time-series graphs and illustrate vector fields. The Crust Monitoring Web Server rearranges the results and provides users visible information on recent crust motion through the internet. The Crust Monitoring Plot Editor with Data Plotter supports editing graphs.

6. Enhancement of analyses

Three kinds of routine analyses (Table 1) are carried out using the data from 30-second sampling. Quick Analysis is carried out in near real-time, every 3 hours with a 6-hour data window. Rapid and Final Analyses produce daily solutions with 24 hours of data and much more precisely than Quick Analysis. The IGS ultra rapid products are used in the Quick and Rapid Analyses. Final Analysis is carried out about two weeks later with the IGS final products. The same software package (BERNESE version 4.2; Hugentobler et al., 2001) is used with the same model settings for these three analyses so that the solutions can be compared without significant biases. Most of the settings are the same as the former system (Hatanaka et al., 2003) except that the whole network is fixed by single stations at Tsukuba with ITRF 2000 coordinates.

Table 1 list of routine analyses

Type	Sess.	Freq.	eph.
Quick (Q2)	6hr	every 3 hr	IGU
Rapid (R2)	24hr	daily	IGU
Final (F2)	24hr	weekly	IGS

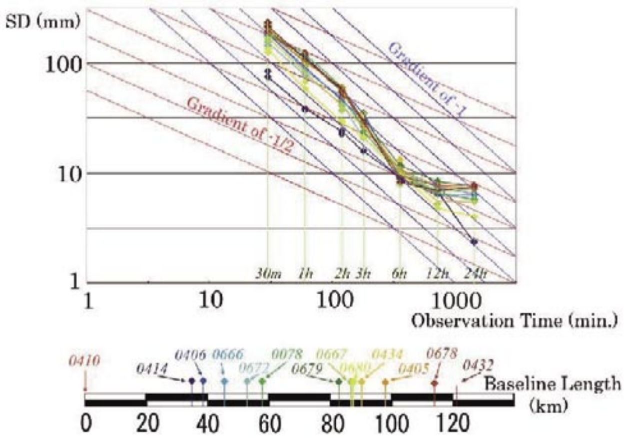

Fig. 3 Trade-off curves between the standard deviation and session duration taken from the test analysis of 13 baselines.

The session length of 6 hours for the quick analysis was chosen by checking the baseline repeatability for various baseline lengths and session durations. There is a trade-off relationship between temporal resolution and precision. As shown in Fig. 3, the shorter the baseline is, the worse the repeatability is. It is also shown in the trade-off curve that increase of standard deviation by shortening of session is less severe in the range of session duration of less than 6 hours.

Similar results are also obtained by Eckl et al. (2001).

Temporal resolution higher than 3 hours is necessary in an emergency situation. In such a case, GEONET can carry out a special analysis of the RTK type by using the 1 Hz real-time data of dual frequency for up to fifty selected stations as well as routine analysis. The RTnet software (GPS Solutions Inc.) is used for this analysis, and the 3D tracker (Condor Inc.) supports and checks its results by post-processing analysis.

7. Example of a new GEONET application to the 2003 Tokachi-Oki earthquake

Fig. 4 shows an example of a time series of baseline components taken from the quick solutions obtained by the new system (Hatanaka et al., 2004). The coseismic crustal deformation of the 2003 Tokachi-oki earthquake (September 26, 2003, M8.0) is clearly seen as steps of several tens of centimeters followed by a post-seismic movement of more than 10cm. The coordinates run off at the session just after the steps and this may be an error caused by the huge movements of the sites in the middle of the session, which is not modeled in the analysis.

Fig. 5 shows an example of kinematic solutions of 1 Hz data for another baseline obtained by RTnet in post-processing mode. Seismic waves (difference between two sites) are clearly observed as well as the permanent deformation although a smoothing condition is imposed slightly to stabilize the solutions. This result is consistent with that from 3D tracker (Fig. 6).

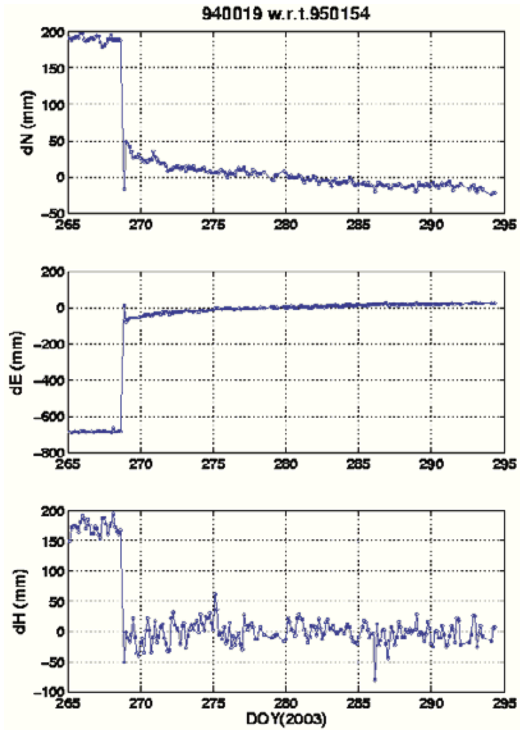

Fig. 4 Time series of three components of a sample baseline vector (950153-940019) of quick solutions for the 2003 Tokachi-oki earthquake.

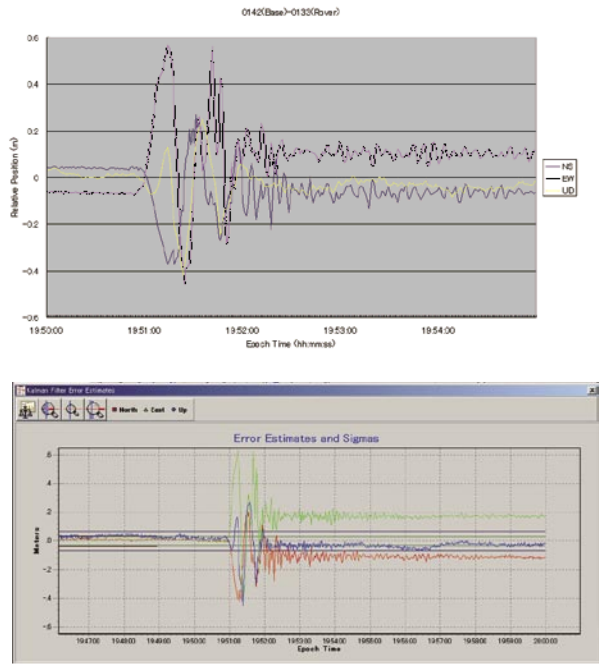

Fig. 5 Example of time series of baseline solutions obtained by the analysis of 1 Hz data with the RTnet software (top) and 3D Tracker software (bottom) for the 2003 Tokachi-Oki earthquake. The analysis was done in a post-processing mode and results over five minutes are shown.

Table 2 shows the difference in coseismic displacements estimated by various analyses. As for the estimation from real-time analyses, the averages of 15-second results 5 minutes after the earthquake are compared with those 1 minute before the event. For estimation from routine analyses, both 1-day results and 15-day averages of the results just before and after the earthquake are taken. The displacements estimated by real-time analyses have a small offset from the averaged results from Routine Analysis of about 4 cm. Because the time series around the earthquake shown in Fig. 4 implies long-lasting post-seismic slips for the same direction of the coseismic motion, the difference may reflect post-seismic effects in the 15 days after the earthquake.

Although the accuracy of kinematic solutions is, in general, worse than that of static solutions, this example demonstrates that the RTK analysis is still useful for detecting large crustal movement.

Table 2 Comparison among coseismic displacements estimated by two real-time analyses and final analysis. The baseline is same as Fig. 5 (Tomakomai-Biratori).

	Coseismic displacement(cm)			Difference from the results from F2 analysis (cm)		
	NS	EW	UD	NS	EW	UD
RTnet	-10.54	+16.32	-5.55	+4.49	-1.42	+1.27
3D Tracker	-11.11	+16.79	-5.11	+3.91	-0.95	+1.70
F2 (1day)	-13.03	+17.31	-5.22	+1.99	-0.43	+1.60
F2 (15-day average)	-15.02	+17.74	-6.81	0	0	0

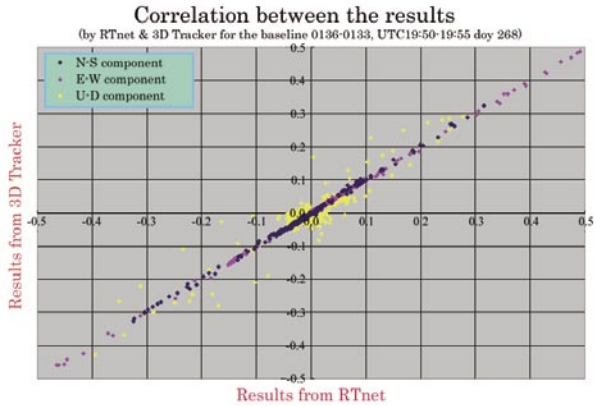

Fig. 6 Correlation between solutions from RTnet and 3D Tracker.

8. Summary

By upgrading the system, GEONET has had real-time capability in both observation and analysis. The observed 1 Hz data are also provided to commercial users in real time who are expected to utilize the data for various kinds of location-based services. Quick Analysis and real-time analysis are newly added into GEONET analyses so that the new system makes it possible to provide the information on crustal deformation timely which is important to take measures to cope with seismic and volcanic events.

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