Twenty-Year Successful Operation of GEONET

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Abstract

The Geospatial Information Authority of Japan (GSI) started installing permanent Global Positioning System (GPS) stations in 1994. The initial number was 210, which increased to 610 in 1996 and 1,200 in 2003. As of April 1, 2017, a total of 1,318 Continuously Operating Reference Stations (CORS) had been installed by the GSI. The receiving and analysis systems were upgraded in 2010 to expand the function to receive other Global Navigation Satellite System (GNSS) signals. This network is now called GEONET (GNSS Earth Observation NETwork system), and is one of the largest CORS networks in the world. It is not only a tool for precise surveying, detection of crustal deformation, and research on earthquakes and volcanoes, but is also an infrastructure for precise positioning of automated vehicles, weather forecasting, and more. We report on the history of GEONET and the results obtained during its 20 years of successful operation.

1. Introduction

The Global Navigation Satellite System (GNSS) has become a necessary infrastructure for daily life. One of its components, the Global Positioning System (GPS) developed and maintained by the United States (US), is the most popular, and navigation devices that have a positioning function by GPS are used worldwide, such as in automobile navigation systems and smartphones.

GNSS can be employed for not only navigation but also surveying. The Geospatial Information Authority of Japan (GSI) has performed GPS surveying since 1987. After confirming the availability of GPS surveying on triangulation points, the GSI installed the first permanent GPS stations in April 1994 for the purpose of establishing a new control point network and monitoring crustal deformation in Japan. In 1994, a total of 210 GPS stations were installed, and this number increased to 610 in 1996 and to 1,200 in 2003, completing a dense network of GPS stations at 20-km intervals, covering the Japanese area. This network acquired the name GEONET (GPS Earth Observation NETwork system) in 1995. A photo of a typical GEONET station and a distribution map of GEONET stations are shown in Photo 1 and Figure 1, respectively.

One of the main purposes of GEONET operation is monitoring crustal deformations in Japan. Small crustal deformations associated with plate motions have

Photo 1 GEONET station

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usually been monitored by analyzing the daily data from GEONET stations, and large co- and post-seismic deformations were detected when large earthquakes occurred. In addition, a slow slip event (SSE) along plate boundaries without emitting the usual seismic waves was first detected by GEONET. Moreover, GEONET contributed to prediction of volcanic eruptions by detecting the crustal deformation associated with the movement of magma under volcanoes.

At the same time, GEONET is the framework of the Japanese geodetic reference frame, and the obtained data has been used to revise the geodetic results of the control points (e.g. Geodetic Coordinates 2000). After the amendment of the Survey Act in 2001, the Japanese geodetic system was aligned with the global geodetic system, and since then the GEONET stations have been available for direct usage as reference points for GPS/GNSS surveys, thus making public surveying more efficient. In addition, the distribution of real-time data streams from GEONET stations has created have made it possible to an environment for performing precise surveys in real time with centimeter-level accuracy by the public and private sectors.

Initially, GEONET stations received only GPS signals. However, with the launch of the first satellite of the Japanese Quasi-Zenith Satellite System (QZSS) in 2010 as a turning point, receiving and analysis systems were upgraded to be able to receive other GNSS signals. In 2013, all GEONET stations started receiving the signals from Russia's GLONASS and Japan's QZSS. GEONET now means GNSS Earth Observation NETwork system. The larger number of satellites available for observations makes real-time positioning more stable and allows GEONET data to be used for automating construction machinery (ICT construction; i-Construction). In 2016, the signals from Galileo by the European Union (EU) started being received by GEONET stations.

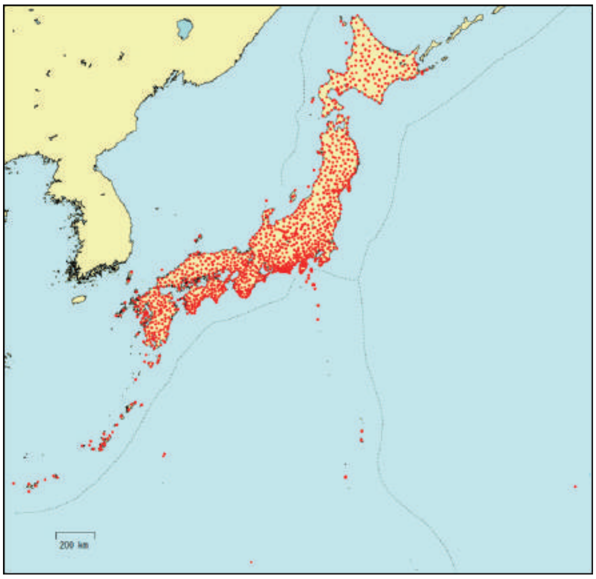

Figure 1 Distribution map of GEONET stations

The largest co-seismic horizontal deformation was detected by GEONET when the 2011 Great East Japan Earthquake occurred. Unfortunately, because real-time analysis was not yet available, the analysis results were not used for an early warning of the huge tsunami. Therefore, a real-time analysis system for rapid detection of crustal deformations accompanied by large earthquakes was developed to estimate the magnitude of earthquakes. At present, nationwide crustal deformations can be continuously monitored by GEONET in real time with spatial resolution of approximately 20 km.

Since GEONET was established in 1996, it has continued operating for over twenty years, and is now an essential infrastructure for precise surveying, detection of crustal deformation, research on earthquakes and volcanoes, automation of vehicles and construction machinery, weather forecasting, and more.

There are other Continuously Operating Reference Stations (CORSs) similar to those of GEONET that were installed by the GSI for other purposes, and the total number of GEONET and the GSI's CORSs was 1,318 as of April 1, 2017.

This paper describes the history and achievements of GEONET.

2. History

Geodetic GPS receivers were introduced in Japan in 1987. Important events that occurred during these past thirty years are described in the following subsections. A detailed chronology of the history is given in the Appendix.

The history of GEONET can be briefly divided into three periods:

1) 1987–1995: Preparation for GEONET
2) 1996–2009: Establishment of GEONET for GPS
3) 2010–2016: Upgrade for GNSS and real-time analysis

Figure 2 is an overview of the evolution of GEONET.

2.1 Preparation for GEONET

2.1.1 Introduction of GPS to Japan and start of continuous GPS observation

After the US introduced GPS in the early 1980s, a relative positioning technique with GPS signals was developed to achieve precise relative positioning with centimeter-level accuracy in the US. The GSI also started performing trial observations by relative positioning in 1987 to apply GPS to precise surveying in Japan. As a result, a precision of a few centimeters for a 10-km baseline, all-weather availability, lack of need for direct visibility between observation points, three-dimensional coordinates determination, efficient operation, and so on were confirmed, and GPS surveys were employed for basic surveying instead of electro-optical distance meters (EDM). On the other hand, routine measurement on the control points has been carried out as a method to detect crustal deformations, and the technique was later replaced with continuous GPS measurement, which started in active volcanic areas east of the Izu Peninsula and Mt. Unzen in 1990. In addition, GPS satellite tracking stations were installed in 1991 near the GSI's Very Long Baseline Interferometry (VLBI) stations in order to determine the precise ephemerides of GPS satellites for higher precision of GPS surveys. This was the first example of the GSI's GPS CORS. It should be noted that the task of determining the precise ephemerides subsequently became an international activity as part of the International GNSS Service (IGS) components.

2.1.2 Plan to establish GPS-based control points and initial CORS network

Construction of GPS progressed smoothly and 24 satellites were deployed in 1993 as planned. In the same year, a plan to construct GPS CORSs in Japan as a new framework for the national control point system was proposed. This was the start of the concept of 'GPS-based control points.' The proposed plan was highly evaluated as an effective tool for the detection of crustal deformations accompanied by earthquakes and volcanic activity in Japan, and the budget for the plan was approved in 1993. In April 1994, a CORS network covering the central part of Japan, i.e. Kanto and Tokai areas with 110 stations, was installed, which was named the Continuous Strain Monitoring System with GPS by GSI (COSMOS-G2),

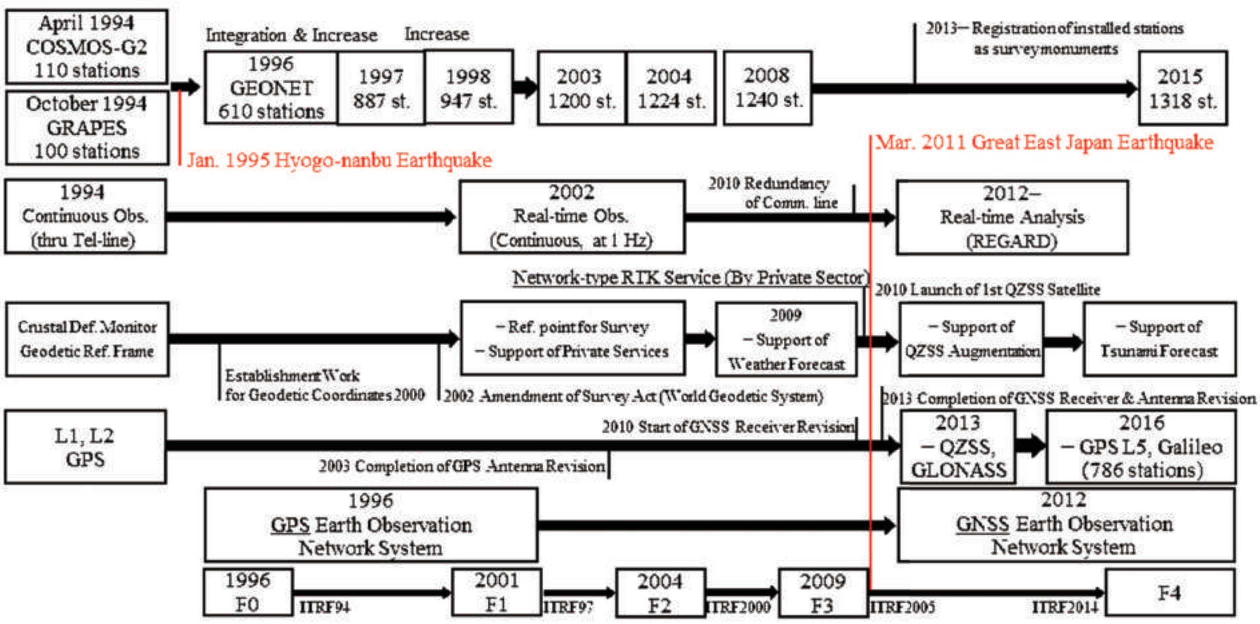

Figure 2 Overview of the evolution of GEONET

and another CORS network covering other Japanese areas with 100 stations was installed in October 1994, which was named GPS Regional Array for PrEcise Surveying (GRAPES). The exterior structure of the two types of stations was slightly different, but the interior configuration was the same. A GPS antenna was installed at the top of the 5-m stable stainless pillar, and a receiver and communications device was equipped in the pillar at each station. The pillars themselves have been used without replacement up to now. All data received at all stations was automatically transferred to the GSI through telecommunications lines (e.g. ISDN). Two analysis systems, however, were independently operated for each CORS network.

2.1.3 Results of initial phase

Installation of the two CORS networks was completed before the large earthquakes, i.e. Hokkaido Toho-oki Earthquake in 1994, Sanriku Haruka-oki Earthquake in 1994, and Hyogo-Nanbu Earthquake in 1995, and the spatial distribution of crustal deformations was detected within a few days after each earthquake by comparing the differences of the obtained coordinates before and after the earthquake (Tsuji et al., 1995; Hashimoto et al., 1996). The co-seismic displacement detected by GPS gave us different information from a seismometer to estimate the fault motions that caused the earthquakes. In addition, post-seismic displacement was first detected at the Sanriku Haruka-oki Earthquake in 1994 (Heki et al., 1997). These remarkable results in the initial phase showed the effectiveness of GPS CORS in the field of earthquake research and led to the remarkable progress of GEONET thereafter. The two networks were integrated in GEONET in 1996, which means that surveying and crustal deformation measurement are two sides of the same coin in Japan.

2.2 Birth of GEONET and its establishment

2.2.1 Birth of GEONET and increase of stations

After the Hyogo-Nanbu Earthquake in 1995, a supplementary budget was approved to increase the number of GEONET stations by 400, and GEONET operation started in April 1996 with 610 stations. The Headquarters for Earthquake Research Promotion determined that GEONET should be one of the basic research and observation networks related to earthquakes and that its stations should be uniformly distributed at intervals of 20–25 km. The number of GEONET stations gradually increased to 887 in 1997, 947 in 1998, 1,200 in 2003, and 1,240 in 2008, the highest number in the world.

At the same time as the installation of additional stations, improvements were made to the receiving system. The pillar height of each station was standardized at 5 m except for a few stations (e.g. Mt. Fuji, Marcus Island, Okinotorishima), but the pillar itself was modified in 2002 to a double-tube structure to prevent it from moving due to heating by the sun. All antennas were replaced in 2003 with a choke ring type that mitigates multipath effects.

2.2.2 Detection of crustal deformations accompanied by earthquakes and volcanic activity

Crustal deformations accompanied by large earthquakes were detected by GEONET, such as the Tottori-Seibu Earthquake in 2000, Geiyo in 2001, Tokachi-oki in 2003, Chuetsu in 2004, Fukuoka in 2005, Noto in 2007, Chuetsu-oki in 2007, and Iwate-Miyagi in 2008. Post-seismic deformations were also detected after the Tokachi-oki and Iwate-Miyagi earthquakes. Furthermore, a slow slip event that occurred along plate boundaries without emitting seismic waves was first detected in 1996 by GEONET at the Boso Peninsula (Chiba Prefecture), and the same phenomenon was detected at the Bungo Channel (between Kyushu and Shikoku islands) in 1997 and the Tokai area in 2001. Moreover, nationwide secular crustal deformations associated with plate motions around Japan were also clarified through the accumulation of many years of GEONET data.

Concurrently, GEONET stations were also deployed to monitor crustal deformations associated with volcanic activity. As a result, before the eruption of Mt. Usu (Hokkaido) in 2000, volcanic inflation associated with the accumulation of magma under the volcano was detected, which was important information for deciding to evacuate residents. In this case, not only the values of coordinates obtained per day with 24-hour data but also that of coordinates per three hours with six-hour data were employed to obtain higher time resolution. In addition, the GSI also developed the Remote GNSS Monitoring System (REGMOS) with the functions of a solar panel and a satellite mobile phone for installation in volcanic areas where neither electric power nor telephone lines were available. The first installation of REGMOS was at Mt. Iwate (Iwate Prefecture) in 1998 (Hirai, 2000).

2.2.3 Introduction of terrestrial reference frame and usage of GEONET for basic and public surveying

Before the amendment of the Survey Act in 2001, the reference for the coordinates (longitude and latitude) was the old Japanese geodetic system, which was different from that for GPS surveying (WGS84). To facilitate the use of GPS surveys, the Japanese geodetic reference system was revised in 2001 based on the International Terrestrial Reference Frame (ITRF) established and maintained by the International Earth Rotation and Reference Systems Service (IERS). At that time, GEONET played an important role in the construction of the nationwide framework for the new Japanese geodetic reference system (Geodetic Coordinates 2000), which was the origin of the ITRF position of the Kashima VLBI antenna.

Since the amended Survey Act became effective in April 2002, GEONET stations have been available for direct use for control point surveying for public surveying. The format of the data to be open to the public had already been switched to RINEX (Receiver INdependent EXchange format) in 1999 for compatibility between several data formats depending on the receiver manufacturers. Surveyors working for the control point surveying of the public surveys install the GPS antenna and receiver only on the new control point to be determined and download the data from the GEONET stations near the new control point to determine its coordinates by analyzing the data of the GEONET stations and the new control point together. In this case, the coordinates of the new control point can be determined more easily than before because the GEONET stations are generally used as fixed (reference) points. However, the height determined by GPS surveying is the ellipsoidal height, which is different from the orthometric height and requires a geoid model for the conversion. In 2003, the GSI published the 'GSIGEO2000' geoid model covering the main islands of Japan. This model made it easy to obtain the orthometric height by GPS surveying with the precision of a few centimeters (Kuroishi et al., 2002).

2.2.4 Implementation of real-time positioning system using GEONET data

To reinforce the ability to monitor crustal deformations by GEONET, a new acquisition system was implemented to collect real-time data obtained in 1 Hz (per second) from GEONET stations through a special communications network for data transfer, which was called IP-VPN (Internet Protocol Virtual Private Network). Since this real-time data allowed us to perform real-time positioning with the precision of a few centimeters, distribution of the real-time data streams from GEONET stations started in 2002. The number of stations that supplied real-time data streams was initially 200, which increased to 931 in 2003, and 1,200 in 2004. By using the real-time data streams from GEONET stations, network-type Real Time Kinematic (RTK) GPS positioning techniques called VRS (Virtual Reference Station) and FKP (Flächen Korrektur Parameter) are now employed nationwide. The real-time data streams are distributed to private companies for location-based services through a non-commercial data distribution agency. The cost of maintaining the data distribution is shared by private companies without using public budget. Both the VRS and FKP techniques can now be used for more efficient public surveying. However, the application of these techniques to real-time positioning with GPS alone did not have sufficient precision, and thus additional satellite constellations were necessary for the realization of GNSS.

2.2.5 Improvement of the precision of daily coordinates

The coordinates of GEONET stations are published as official survey results that can be used for public surveying. In addition, the daily coordinates are also obtained and published by analyzing the daily data from GEONET stations. Both values are based on the same reference frame (ITRF), but the epoch that represents the point in time for the reference is different. In the case of the survey results, the epoch is determined as a time in the past. On the other hand, in the case of the daily coordinates, the epoch is the present time and the values of the coordinates change from day to day according to crustal deformations. The daily analysis has been performed with the Bernese analysis software using the final orbits of the GPS satellites produced by the IGS.

The first analysis strategy was called F0, and its reference was based on ITRF94. Improvements were made several times (Hatanaka, 2006). In 2001, the second analysis strategy, F1, started based on ITRF97 employing the newest models of ocean tide loading and phase center variation (PCV) depending on the type of antenna basement. The third analysis strategy, F2, started in 2004 and was based on ITRF2000, in which antenna dependency was not necessary because the antenna type was unified with the choke ring. Since the IGS final orbits were published more than two weeks after the observation, a rapid analysis called R2 was performed by using IGS Rapid orbits that were published two days after the observation, and a quick analysis called Q2 by using IGS Ultra-Rapid orbits in the interval of three hours with six-hour data. Finally, the fourth analysis strategy F3 started in 2009 employing the estimated atmospheric delay gradient, an absolute PCV model, ITRF2005 as a new reference frame, and the new fixed (reference) point. F3 is considered to be the most complete as a GPS analysis strategy (Hatanaka et al., 2005; Nakagawa et al., 2009).

2.2.6 Application to weather forecasting

Water vapor in the atmosphere causes errors in GPS measurement and thus the amount of precipitable water vapor (PWV) is estimated in GPS analysis to improve the precision of GPS measurement. However, better PWV estimation is useful for weather forecasting (Shoji et al., 2009). GPS meteorology started in the 1990s as an interdisciplinary study of geodesy and meteorology, and since 2009 the PWV estimation obtained by using GEONET data has been applied to numerical weather forecasting by the Japan Meteorological Agency (JMA), resulting in more precise weather forecasting (Shoji, 2015).

2.2.7 Development of semi-dynamic datum

In the case of public surveying and mapping, the epoch should be fixed at a time in the past in order to maintain consistency of all survey results and maps that are produced. The present positions of the control points, however, move according to linear crustal deformations associated with plate motions and gradually become more different from the values listed as the survey results. To correct this difference, semi-dynamic datum correction was introduced and its model, which was produced by using F3 results from GEONET analysis, was first published in April 2009. This model has been applied for public surveying (Tanaka et al., 2006; Hiyama et al., 2010). In this method, the positions (coordinates) of the survey results whose epoch is a time in the past are converted to the positions at the time when the public surveying was performed, and the GPS analysis and related calculations are done. Then, the obtained positions are again converted to the time in the past that is defined as the fixed epoch to maintain the consistency of the survey results. This method is available nationwide since GEONET stations are being distributed uniformly throughout Japan.

As described above, the contribution of GEONET has widely spread to real-time location-based services and weather forecasting as well as public surveying, monitoring of crustal deformations, and research on earthquakes and volcanoes. GEONET became a social infrastructure in 2009.

2.3 Upgrade for GNSS and real-time analysis

2.3.1 Upgrade for multi-GNSS

Since the start of GEONET in 1996, the ‘G’ in GEONET meant ‘GPS’ for a long time. However, other positioning satellite systems, such as GLONASS by Russia, QZSS by Japan, and Galileo by the EU, were developed and realized in parallel with GPS modernization. These satellite systems are generically named GNSS (Global Navigation Satellite System). It was then decided that GEONET would be upgraded gradually to receive not only GPS signals but also multi-GNSS signals in view of the 2010 launch of Michibiki as the first quasi-zenith satellite, the progress of GPS modernization, and the public use of GEONET data for multi-GNSS. In 2010, the replacement of aged GPS receivers started with those of GNSS. In 2012, GEONET was renamed GNSS Earth Observation NETwork system. In 2013, all GEONET stations started to receive the signals of QZSS and GLONASS, and it became possible to distribute the received data including GPS, QZSS and GLONASS to contribute to reconstruction after the Great East Japan Earthquake. The increase in the number of satellite constellations by receiving not only GPS but also GLONASS signals allowed more stable use of the network-type RTK positioning techniques in restricted environments for sky coverage such as urban and mountain areas and produced good results for the expansion of i-Construction (Tsuji et al., 2013). In 2016, 786 GEONET stations started receiving L5 signals from Galileo by the EU and modernized GPS, and all stations will receive L5 signals by 2019. In addition, a centimeter-level augmentation service in real time through QZSS, which is called CLAS, is planned by Quasi-Zenith Satellite System Services Inc. In the case of CLAS, errors in GNSS positioning will be reduced by applying correction information produced from GEONET data.

2.3.2 Japanese geodetic datum 2011

When the 2011 Great East Japan Earthquake struck, large crustal deformations in wide areas of eastern Japan from the Tohoku to Koshin regions (such as Yamanashi Prefecture) were detected by GEONET, for example, approximately 5.3 m to the east-southeast and subsidence of approximately 1.2 m at Oshika (Miyagi Prefecture) which was near the epicenter, and GEONET data helped clarify the generation mechanism of the earthquake (Nishimura et al., 2011; Suito et al., 2011). In addition, the subsidence information for areas along the Pacific coast, which was detected by GEONET, was referred to for issuing warnings of high waves. This is a typical example of GEONET's contribution to disaster risk reduction.

In the case of this earthquake, the post-seismic deformations continued for such a long time that it was very difficult to determine when and how the survey results of GEONET stations should be revised. May 31, 2011 was the publication date of the revised survey results for which the epoch was May 24, 2011 when the post-seismic deformations were within the range that could be calculated by the method of semi-dynamic datum correction (Hiyama et al., 2011). In this case, the position of the Tsukuba VLBI antenna on ITRF2008 was used as the reference to revise the survey results of the GEONET stations. The revised survey results including other triangular control points are now called Japanese Geodetic Coordinates 2011. Because the survey results were not revised for the Hokkaido and western Japan regions, they are the same as those of Geodetic Coordinates 2000, but all survey results in all Japanese areas are called Japanese Geodetic Coordinates 2011. This means that there are two epochs: January 1, 1997 for western Japan and Hokkaido, and May 24, 2011 for eastern Japan.

2.3.3 Continuous analysis in real time for contribution to tsunami early warning

When the 2011 Great East Japan Earthquake occurred, continuous analysis in real time was not performed, so the large crustal deformations were not detected until approximately 5 hours after the earthquake. In fact, the tsunami height estimated by seismometers was smaller than the actual height since the seismometers were not able to correctly detect the magnitude of the very large earthquake because of saturation. On the other hand, GEONET can detect large displacement with no limit and contribute to tsunami forecasting by providing a more accurate estimation of the magnitude of a large earthquake (Ohta et al., 2013). This change of approach focuses on speed rather than precision of results. To achieve this idea, the Real-time GEONET Analysis system for Rapid Deformation monitoring (REGARD) was developed through joint research with Tohoku University and the Meteorological Research Institute, and its trial operation started in 2016 (Kawamoto et al., 2015). The system does not yet contribute to tsunami forecasting, but continuous monitoring of nationwide crustal deformations by GEONET has been active and it detected the crustal deformations accompanied by the Kumamoto Earthquake in 2016 (Kawamoto et al., 2016a, b).

2.3.4 Resilience of GEONET system

GEONET is a tool for surveying, positioning, and detection of crustal deformations in real time, so the operation of GEONET continues without interruption as much as possible. In 2010, additional communications lines with mobile phones were installed, and worked well as backup lines when the 2011 Great East Japan Earthquake occurred. Other equipment was also modified to maintain redundancy or electric power with backup batteries.

As described above, GEONET has evolved over twenty years to perform various tasks and is now a GNSS CORS network for monitoring Japanese areas in real time.

3. Results of 20 years of operation of GEONET

What are the outcomes from GEONET? The results and achievements of GEONET are summarized below.

3.1 Contribution to research on earthquakes and volcanic eruptions by monitoring nationwide crustal deformations with centimeter-level precision

Figures 3-6 show the horizontal displacement of each GEONET station for every half year over the past twenty years. The spatial distribution of the deformations and its change accompanied by four plate motions around Japan, earthquakes, and volcanic activity are clearly detected. These are the most remarkable results of twenty years of GEONET operation and show what it means to live in Japan where the crustal deformations are complicated and earthquakes and volcanic eruptions occur frequently. A movie of the deformation by GEONET is available on the GSI's website (http://www.gsi.go.jp/kanshi/index.html#5-2).

3.1.1 Crustal deformations associated with earthquakes and volcanic activity

The information obtained by GEONET on crustal deformations accompanied by earthquakes and volcanic activity is promptly provided to JMA, the Earthquake Research Committee, the Coordinating Committee for Earthquake Prediction, the Coordinating Committee for Volcanic Eruption Prediction, and others, and is used to reduce disaster risk as well as evaluate the mechanism of earthquakes and volcanic activity. Since the distribution of the crustal deformation information is related to the position of the earthquake source fault and the situation of the damage and provides information on the chain occurrence of large earthquakes and aftershocks, it can be used for reducing disaster risk (Sagiya, 2009). In the case of the eruption of Mt. Usu in 2000, the volcanic inflation and deflation associated with magma activity under the volcano were detected, which provided important information for deciding to evacuate residents. After the 2011 Great East Japan Earthquake, information about land subsidence in the coastal area was also used to warn of the high tide.

The largest horizontal displacement detected by GEONET was 5.40 m at M-Oshika as a co-seismic deformation of the 2011 Great East Japan Earthquake, and the largest vertical displacement was an uplift of 2.08 m at Kurikoma-2, which was located on the fault of the Iwate-Miyagi Earthquake in 2008 (Kimura and Miyahara, 2013).

3.1.2 Discovery of post-seismic deformations and slow slip events

A time series of GEONET daily solutions contains many geophysical signals that are not only co-seismic deformations, but also post-seismic linear crustal deformations associated with plate motions, slow slip events, and so on (Nishimura, 2009). GEONET's contributions in this field are the discovery of the Niigata-Kobe Tectonic Zone (Sagiya et al., 2000) and a slow slip event at the plate boundary (Sagiya, 2004; Sagiya, 2009; Nishimura et al., 2013). In addition, the post-seismic deformation of the 2011 Great East Japan Earthquake still continues with a large displacement velocity, and is considered to be the key to solving the gap between geodetic and geological deformations (Nishimura, 2012).

3.1.3 Detection of crustal deformation in real time

REGARD is now in operation, analyzing the GEONET data in real time and immediately estimating the fault models of large earthquakes based on the distribution of crustal deformations accompanied by large earthquakes (Kawamoto et al., 2017). REGARD is expected to contribute to the estimation of tsunami caused by large earthquakes and will be useful for monitoring earthquakes and volcanic activity. Furthermore, REGARD demonstrated its capability for large inland earthquakes by providing a reliable finite fault model for the 2016 Kumamoto Earthquake (Kawamoto et al., 2016a, b). Note that REGARD uses the open-source software GSILIB (Furuya et al., 2013) produced by modifying the GNSS analysis software RTKLIB developed by the Tokyo University of Marine Science and Technology (Takasu, 2011), which was one of the outputs from the general technical development project in 2011-2014 towards the realization of multi-GNSS surveying in Japan (Tsuji et al., 2015).

3.2 Maintenance of geodetic reference system aligned with world geodetic system

3.2.1 Maintenance of Japanese geodetic reference system

GEONET was essential for revising the Japanese geodetic system, i.e. establishing the Geodetic Coordinates 2000 (see 2.2.3). In addition, the revision of Japanese geodetic results after large earthquakes can be done more efficiently (see 2.3.2). Furthermore, semi-dynamic datum correction parameters to cancel out the influence of crustal deformations for surveying are produced by using the daily coordinates of GEONET stations (see 2.2.7).

3.2.2 Promotion of public surveying

Data obtained by GEONET stations and their survey results are employed as position references based on the Survey Act for public surveying using GNSS to improve accuracy and efficiency of the surveys. In the category of public surveying, GEONET data and survey results are employed for control point surveying, aerial photogrammetry and airborne laser scanning, and surveys using a mobile mapping system (MMS). The size of the public surveying market was approximately ten billion yen in 2013 (Shimoyama, 2016).

With the availability of GEONET data, it is not necessary for users to perform GNSS surveys on the reference points, so the survey procedure is easier and simpler. Compared with control point surveys using all stations, it is possible to reduce the surveying procedures by 20–30% by using control point surveying with GNSS. A new surveying method that employs GEONET data GNSS leveling by a Smart Survey Project (SSP) procedure recently became available, and is expected to make leveling surveys more efficient (Technical Management Division, Planning Department, Geospatial Information Authority of Japan, 2013; Goto et al., 2013).

3.2.3 Contribution to international observations

Since the campaign for GPS trial observations in 1992, the GSI has participated in IGS activities as a member of IGS components (Tracking Stations, Governing Board, Central Bureau, Data Centers, Analysis Centers, and so on) for determining the orbits of GNSS satellites by international cooperation and so on. At present, the GSI provides GNSS data from stations in Tsukuba, Shintotsukawa, Aira, Chichijima, Marcus Island, and Syowa on Antarctica (in real time except Marcus Island). IGS precise orbit information (ephemeris) determined by using GNSS data obtained all over the world is important for calculating GEONET daily solutions. On the other hand, the compact RINEX format (commonly called ‘Hatanaka format’), which has the unique characteristic of high compressibility, was provided to the IGS by the GSI to efficiently store the data obtained by IGS stations (Hatanaka, 1996, 2008).

3.3 Contribution to expansion of positioning field for ICT construction by promoting real-time precise positioning

3.3.1 Creation of network-type RTK service by the private sector

The real-time data streams from GEONET stations are distributed to private companies for location-based services. These companies offer users network-type RTK-GNSS services that provide precise positioning with an accuracy of a few centimeters, enabling real-time determination of precise coordinates for surveying and mapping in the field of i-Construction and automated agricultural machinery. In Japan, three companies presently offer the network-type RTK service. A function of the network-type RTK is already built into the new models of some construction machinery. In Hokkaido, the network-type RTK is increasingly being used to automate agricultural tractors. Some companies also provide the correction parameters for QZSS as well as those for GPS and GLONASS.

3.3.2 Support for augmentation service by QZSS

In the case of CLAS by QZSS, GEONET real-time data streams are necessary to correct error sources with spatial dependency such as tropospheric delays due to the dense distribution of GEONET stations throughout Japan (see 2.3.1). At present, the CLAS provider receives the GEONET real-time data streams from the data distribution agency.

3.4 Contribution to weather forecasting and geoscience

3.4.1 Improvement of weather forecasting

Since October 2009, JMA has applied the PWV values obtained by using GEONET data to numerical weather forecasting, resulting in more accurate forecasts (see 2.2.6).

3.4.2 Mapping of ionosphere above Japanese areas

By using the dual-frequency data of GNSS L1 and L2, two-dimensional monitoring of the ionosphere above Japan is possible, and GEONET data is employed for research on the ionosphere (Saito et al., 2002; Seemala et al., 2014). In addition, ionospheric disturbances triggered by rocket launches are also detected (Ozaki and Heki, 2010). After the 2011 Great East Japan Earthquake, an extremely huge ionospheric disturbance was detected (Rolland et al., 2011). Some researchers insist that a disturbance was detected before the 2011 Great East Japan Earthquake, but this is still under discussion (Heki and Enomoto, 2014; Iwata and Umeno, 2016).

3.4.3 Human resource development for geoscience

The GEONET data and the obtained results have been released on the GSI's website without delay since the start of GEONET operation and are widely used by researchers in geoscience and related study fields. As a result, GEONET has contributed to the progress of geoscience and development of geoscience researchers.

3.5 Other contributions

3.5.1 Education

Many GEONET stations were installed in the schoolyards of primary and junior high schools due to the need for open skies and continuous operation. 'Delivery lecture' projects have been conducted at the schools where GEONET stations are installed since 2016. As of March 2017, twenty-one delivery lectures were conducted and approximately 1,300 students learned about the role of GEONET stations.

3.5.2 Technical cooperation with developing countries

In response to the growing interest in GNSS observations in developing countries, courses on GNSS CORS in the GSI have been provided for relevant personnel as official lectures of the Japan International Cooperation Agency since 2015 (Nakagawa et al., 2014). About ten trainees attend the lectures every year.

4. Summary

Twenty years have passed since the start of GEONET operation, which has evolved into a continuously running infrastructure that is widely used in society for such applications as precise surveying, detection of crustal deformation, research on earthquakes and volcanic activity, automation of vehicles and construction machinery, weather forecasting, and more. GEONET is now the largest CORS network in the world that is operated by an organization, and its spatial distribution is the densest in the world. In Japan, geospatial information of the highest level in the world is now available by using this advanced infrastructure.

Earth observation technologies such as satellite remote sensing from space have remarkably improved, but the feature of the CORS network to continuously monitor the movement of a specific site is unique, and GEONET will be revealing Japan's complicated crustal deformations in closer cooperation with Interferometric Synthetic Aperture Radar (InSAR) observations that can detect two-dimensional crustal deformation. The stability of GEONET operation in Japan has made it possible to provide several types of location-based services in real time, as well as network-type RTK, CLAS through

QZSS, and more.

The roles of GEONET are summarized as follows:

1) Reference for surveying in Japan
2) Detection of crustal deformation
3) Realization of semi-dynamic datum. Due to the accumulation of displacements caused by crustal deformation, the difference in coordinates between present and past epochs becomes larger.
4) Supply of obtained data that is available for improvement of satellite positioning (e.g. network-type RTK, CLAS through QZSS)

The necessity of GEONET will not diminish as long as GNSS is available for use. GEONET has been in operation for two decades, and the GSI will try to improve the GEONET analysis system and maintain the high quality of GEONET data and its services.

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October 1997 (0.5 years passed)

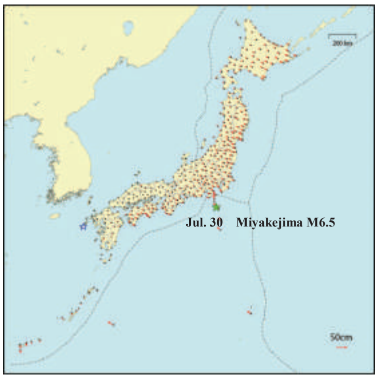
April 1998 (1.0 year passed)

October 1998 (1.5 years passed)

April 1999 (2.0 years passed)

October 1999 (2.5 years passed)

April 2000 (3.0 years passed)



October 2000 (3.5years passed)

April 2001 (4.0years passed)

October 2001 (4.5 years passed)

April 2002 (5.0 years passed)

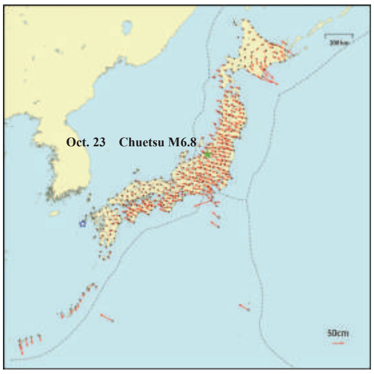
October 2002 (5.5 years passed)

April 2003 (6.0 years passed)

Figure 3 Crustal deformations in Japan for every half years from April 1997 (from October 1997 to April 2003)

April 2004 (7.0 years passed)

October 2004 (7.5 years passed)

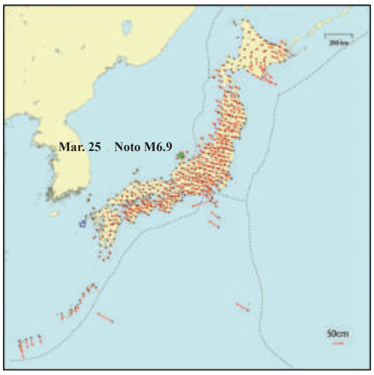


April 2005 (8.0 years passed)

October 2005 (8.5 years passed)

April 2006 (9.0 years passed)

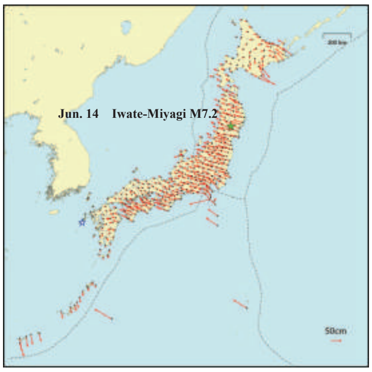
October 2006 (9.5 years passed)



April 2007 (10.0 years passed)

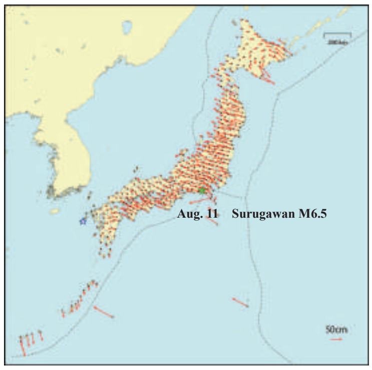
October 2007 (10.5 years passed)

April 2008 (11.0 years passed)



October 2008 (11.5 years passed)

April 2009 (12.0 years passed)



October 2009 (12.5 years passed)

Figure 4 Crustal deformations in Japan for every half years from April 1997 (from April 2004 to October 2009)

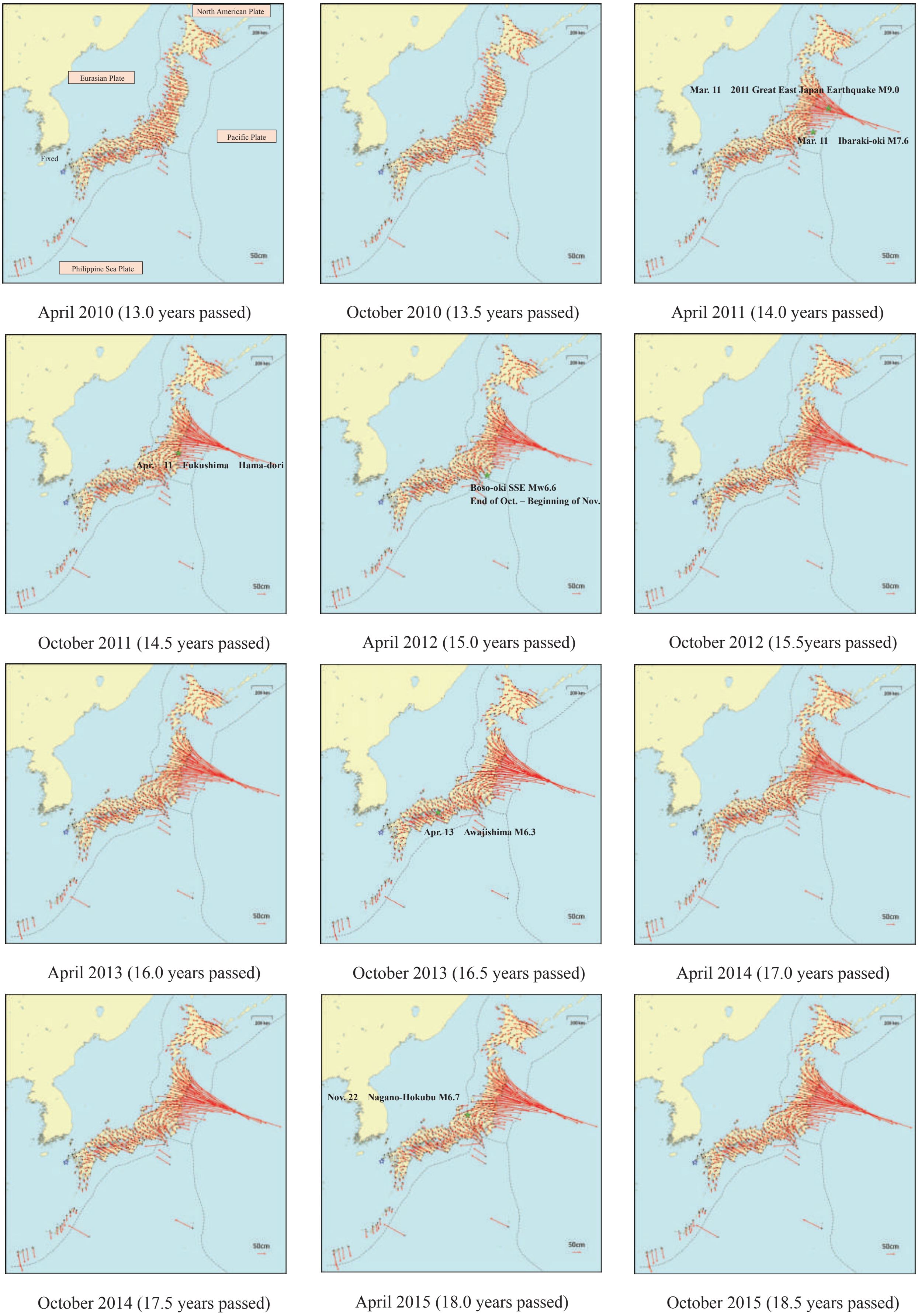
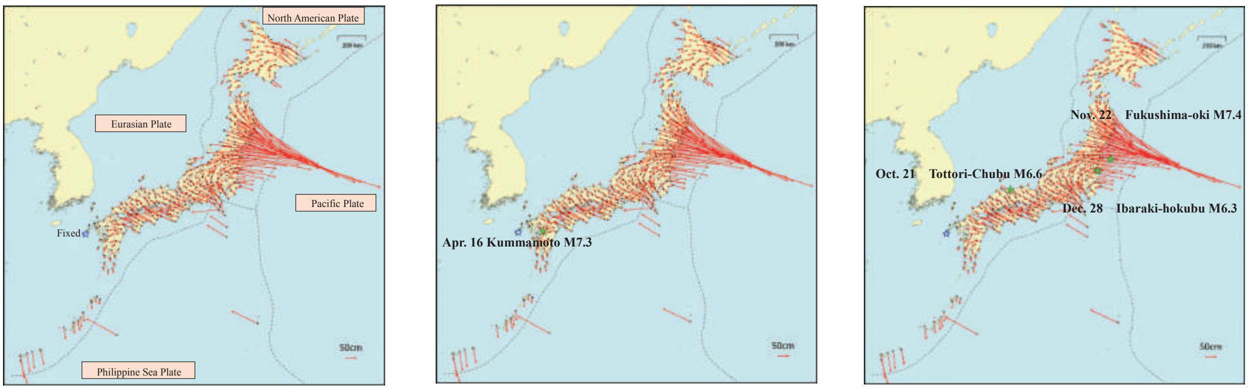


Figure 5 Crustal deformations in Japan for every half years from April 1997 (from April 2010 to October 2015)



April 2016 (19.0 years passed) October 2016 (19.5 years passed) April 2017 (20.0 years passed)

Figure 6 Crustal deformations in Japan for every half years from April 1997 (from April 2016 to April 2017)

Horizontal displacements detected by GEONET stations are shown as arrows. The fixed point ☆ is 'Fukue' in Kyushu. A scale bar described in the lower right is 50 cm. Daily solutions (F3) are used. According to the epoch of Geodetic Coordinates 2000 (April 1st, 1997), the reference period was determined as April 1997. The epicenter of the major earthquakes are shown as the mark ★ .

Appendix. **A detailed chronology of the history of GEONET (1987–2016). Items highlighted in yellow are also mentioned in the text. Items in bold type are important events; items in red type are crustal deformations and those in blue type are academic or international events.**

Year	Month/Day	Event
1987	Feb 10 – Mar 4	Installation of six ground markers (metal type) for GPS trial observation around GSI
	In Mar	**Introduction of the first GPS receiver for surveying (Macrometer II) in Japan**
	May 21	Report on the results of GPS trial observation at the Geodetic Society of Japan
	Oct 17–27	Long baseline observation by GPS (Tsukuba, Kanozan, Chichijima, Miyazaki)
	Nov 11	Report on the results of GPS trial observation at the Geodetic Society of Japan
1988	In Feb	Trial observation of 100-km baselines (Tsukuba, Dodairasan, Kanozan) and in Izu-oshima
	Mar 7–11	Comparison of baselines observed by GPS and VLBI (Tsukuba-Kashima)
	In Apr	**Introduction of GPS receivers (Mini-Mac 2816, Trimble 4000SX)**
	May–Sep	Trial observation by installing GPS baselines around Tsukuba
	May 18	Report on the precision of GPS relative positioning at the Geodetic Society of Japan
	Jun 27 – Jul 1	**GPS observation for deformation surveying at three points around Suruga Bay**
	Oct 18–20	Report on the precision of GPS relative positioning in Japan, GSI's field for trial, and GSI's plan for crustal deformation observation by GPS at the Geodetic Society of Japan
	Nov–Dec	Comparison of GPS (4 points) and EDM (14 baselines) observations for deformation surveying in the southern Kanto region
	Nov 21 – Dec 19	GPS experimental observation through the cooperation of Japan and Korea
1989	Feb–Mar	GPS trial observation around Suruga Bay and in the Tokyo area
	In Apr	Observation for the GPS baseline installation site
	Jun–Aug	Trial observations for precise geodetic surveying of second-order control points (Nagoya) and repeatability of baselines (Tokyo area)
	Jul 25 – Aug 3	GPS observation for submarine eruption off the east coast of the Izu Peninsula on July 13
		GPS trial observation for precise deformation surveying around Suruga Bay and Sagami Bay
	In Oct	Observation for analysis of GPS satellite orbit (Shintotsukawa, Miyazaki, Kanoya, Chichijima)
	Oct 28 – Nov 1	**GPS surveying at Okinotorishima by installing first- and third-order triangulation points.** Calculation of longitude and latitude using VLBI points (Chichijima, Miyazaki, Tsukuba) as fixed points
1990	In Feb	**Start of observation by GPS CORS at three sites east of the Izu Peninsula**
	Feb 28 – Mar 10	GPS trial observation for precise geodetic surveying of first-order control points (standard network)
	Jun 13–22	Trial observations by installing GPS observation points at Chiba and Ichikawa cities
	Jul 9–27	Confirmation of availability of determination of local geoid model produced by GPS and leveling method around Nagoya
	Oct 2–25	Precise geodetic surveying of second-order control points by GPS in Muroran region (14 points)
	Nov 2 – Dec 1	GPS emergency observation for monitoring of volcanic eruption at Unzendake (11 points); volcanic activity continued until 1995
	From Nov	**Start of GPS continuous observation at Unzendake by installing three ground markers for emergency research of eruption of Unzendake**
		Investigation of installation of GPS CORS at Suruga Bay (east of the Izu Peninsula)
1991	Feb 18 – Mar 19	Precise geodetic surveying of first-order control points by GPS in Kazusa region (20 points)
	In Mar	**Installation of GPS tracking stations (Shintotsukawa, Tsukuba, Kanoya, Chichijima)**
	In Apr	Introduction of GPS receiver (Trimble 4000SST) for precise geodetic surveying of first-order control points
		Determination of draft procedure for precise geodetic surveying of first- and second-order control points using GPS
	From Jul	Implementation of precise deformation surveying using GPS
	Nov 6–30	Implementation of first-order control point surveying using GPS at observation concentration area in Tokai region (8 points); excessive limitations due to precision degradation of SA (selective availability)

Year	Month/Day	Event
1992		Trial observation of GPS receivers (Trimble 4000SST, 4000SSE) at GPS baseline site
	Jun 23	Start of trial observation for International GPS Service for Geodynamics (IGS) (to Sep. 23), with the participation of GSI
	Sep–Dec	Implementation of volcanic deformation surveying using GPS at Unzendake and two other sites
	Dec 7–11	Trial observation of GPS receiver (Leica system 200) to establish a continuously operating GPS network
1993	In Mar	Determination of draft operating manual for public surveying using GPS
	In Mar	**Summary of 'New Framework for Control Points;' first usage of the term 'GPS-based control points' for GPS CORS**
		Approval of supplementary budget for installation of GPS-based control points (GPS CORSs)
	Jul 16–22	Emergency observation by GPS for Hokkaido Nansei-oki Earthquake (M7.8)
		Start of establishment of COSMOS-G2 in the southern Kanto and Tokai regions
	Dec 8	**Declaration of GPS initial operational capability (24 Block I & II satellites)**
1994	Jan 1	**Establishment of International GPS Service for Geodynamics (IGS). Start of data transfer from Tsukuba station (TSKB)**
	In Apr	Start of establishment of GRAPES
	Apr 1	**Start of operation of COSMOS-G2 (110 stations in the southern Kanto and Tokai regions)**
	Apr 1	Determination of draft operating specifications for precise geodetic surveying of advanced control points. Instead of precise geodetic surveying of first-order control points, start of precise geodetic surveying of advanced control points using GPS-based control points as fixed points
	Jun 1	Determination of 5th basic survey plan; 640 GPS-based control points (GPS CORSs) planned
	Oct 1	**Start of operation of GRAPES (100 stations in other areas of southern Kanto and Tokai)**
	Oct 4	**Detection of crustal deformation accompanied by Hokkaido Toho-oki Earthquake (M8.2)**
	Dec 28	**Detection of crustal deformation accompanied by Sanriku Haruka-oki Earthquake (7.6); post-seismic deformation also detected**
1995	Jan 7	Detection of crustal deformation accompanied by Iwate-oki Earthquake (M7.2)
	Jan 17	**Detection of crustal deformation accompanied by Hyogo-Nanbu Earthquake (M7.3)**
	Jan 27	Installation of three additional GPS CORS around Kobe City
	Feb 21	Awarding by IGS Board for GSI's contribution to establishing IGS
	Feb 28	Approval of second supplementary budget in 1994 for installation of GPS continuous observation points
	Apr 27	Declaration of GPS full operation capability (24 Block II satellites)
	Jun 15	Installation of mobile-type GPS CORS around Kobe City (increase by 15 to 20)
	Jun 21	Start of GPS continuous observation in northern Niigata prefecture (4 points)
	Aug 14–18	Lecture on GIPSY at GSI (Tsukuba) in cooperation with JPL
	Oct 6	Detection of crustal deformation accompanied by earthquake swarms off the east coast of the Izu Peninsula
	In Nov	Revision of the operating specifications for public surveying determined by the Ministry of Construction
	Nov 2	Installation of GPS CORS in Kikaijima and Amami Oshima
1996	Mar 14	Establishment of Tokai observation station
	Mar 19	**Increase of GPS CORSs by 400 to 610**
	Apr 1	**Start of GEONET (GPS Earth Observation NETwork system) by integrating COSMOS-G2 and GRAPES**
	Apr 1	Start of operation of IGS Associate Analysis Center for regional network
	In May	**First detection of slow slip event on the Boso Peninsula**
	May 11	**Establishment of Geodetic Observation Center in GSI conducting GEONET operation**
	Jul 17–19	GPS Symposium held at GSI
	Aug 7–8	Discussion about GPS in Japan and the US
	Aug 11	Detection of crustal deformation accompanied by Akita-Miyagi Earthquake (M6.1)

Year	Month/Day	Event
1996	Oct 15	Detection of crustal deformation accompanied by earthquake swarms east of the Izu Peninsula
	Oct 18	Detection of crustal deformation accompanied by Tanegashima-Kinkai Earthquake (M6.4)
	Oct 19	Detection of crustal deformation accompanied by Hyuganada Earthquake (M6.9)
	Dec 3	Detection of crustal deformation accompanied by Hyuganada Earthquake (M6.7)
1997		Detection of slow slip event around the Bungo Channel
	In Mar	**Increase of GEONET stations by 277 to 887**
	Mar 1	RTK experiment using GEONET stations in cooperation with the Ministry of Posts and Telecommunications
	Mar 3	Detection of crustal deformation accompanied by earthquake swarms east of the Izu Peninsula
	Mar 15	Installation of GPS CORS at Christmas Island in the South Pacific region
	Mar 26	Detection of crustal deformation accompanied by Kagoshima-Hokuseibu Earthquake (M6.6)
	Apr 1	Start of ‘GPS Meteorology’ research project (to 2001)
	In May	Public release of ‘Outline of crustal deformation detected by GPS’ (based on data from approximately 900 stations)
	May 13	Detection of crustal deformation accompanied by the Kagoshima-Hokuseibu Earthquake (M6.4)
	Jun 10	Information on crustal deformation obtained by GPS continuous observation posted on website (updated every month)
	Jun 25	Detection of crustal deformation accompanied by the Yamaguchi-Chubu Earthquake (M6.6)
	Aug 29	**Planning of distribution of GEONET stations with spacing of 20–25 km by the Headquarters for Earthquake Research Promotion**
	Nov 29	Installation of GPS CORS at Tonga in the South Pacific region
	Dec 19	Completion of Space Geodetic Laboratory (1st floor: seismic base isolation)
1998	Feb 13	Start of usage of Space Geodetic Laboratory (including the Geodetic Observation Center, GEONET Center, and so on)
	Feb 25 – Mar 7	Installation of three GPS CORSs at Rarotonga Island in the South Pacific region
	In Mar	**Increase of GEONET stations by 60 to 947**
	In Mar	**Report on ‘New position reference Geodetic Coordinates 2000’**
	Apr 22–28	Detection of crustal deformation accompanied by earthquake swarms east of the Izu Peninsula
	In May	Installation of temporary CORS around Mt. Iwate according to volcanic activity
	May 29	Workshop on technical research for RTK-GPS
	Aug 21	**Installation of REGMOS on the side of Mt. Iwate**
	Sep 3	Detection of crustal deformation accompanied by the Iwate-Nairiku-Hokubu Earthquake (M6.2)
	Oct 3	Installation of REGMOS on the ridgeline of Mt. Iwate by using a helicopter
	Oct 11–14	Participation in IGS Workshop held in the US; visit to UNAVCO for GPS meteorology
	Nov 9–12	Second lecture on GIPSY at GSI (Tsukuba) in cooperation with JPL
1999	Feb 7–20	Installation of GPS CORS at Tarawa in the South Pacific region
	Mar 2	Installation of GPS CORS at Midway Atoll in the South Pacific region
	Mar 26	**Installation of 25 precise height observation stations around Omaezaki**
	In Mar	Transfer of 41 GPS CORSs from the Science and Technology Agency
	May 29	Start of continuous height variation observation around Omaezaki
	In Jun	Registration of Syowa IGS station on Antarctica
	In Aug	Start of public release of GEONET data (RINEX format, 30-s sampling) via the Internet
	Oct 18	International Symposium on GPS held in Tsukuba
	Dec 1	Revision of the 5th Long-Term Plan for Basic Surveying; plan for 1,200 GEONET stations
2000	Jan 1	Trouble with GEONET caused by Year 2000 problem (one-day delay of public release of data)
	Mar 31	**Detection of crustal deformation two days before Mt. Usu eruption; emergency analysis every three hours**

Year	Month/Day	Event
2000	Apr 8	Installation of GPS CORS at Mangareva Island in the South Pacific region
	May 2	End of SA of GPS by the US
	Jun 26	Detection of crustal deformation accompanied by volcanic activity at Miyakejima and earthquakes around Miyakejima, Niijima and Kozushima
	Jul 19	Determination of operating manual for public surveying using RTK-GPS
	Aug 17–22	Installation of two GPS continuous observation systems around Mt. Bandai
	Sep 8	Installation of five continuous crustal deformation observation facilities using GPS on the Itoigawa-Shizuoka Tectonic Line
	Oct 6	Detection of crustal deformation accompanied by Tottori-Seibu Earthquake (M7.3)
	Nov 9	Open experiment for actual proof of availability of real-time positioning with centimeter-level precision based on GEONET
2001	In Jan	Introduction of new analysis strategy for GEONET (F1)
	Jan 6	Reorganization of central government ministries: GSI under the Ministry of Land, Infrastructure, Transport and Tourism
	Feb 5	Participation in Japan-US GPS Plenary Meeting
	Mar	Publication of ITRF2000 by IERS
	Mar 7	Installation of mobile-type GPS CORS at the north side of Mt. Fuji
	Mar 24	Detection of crustal deformation accompanied by Geiyo Earthquake (M6.7)
	In Jun	Detection of crustal deformation accompanied by volcanic activity at Mt. Hakone
	Jun 14	Publication of crustal height variation for 100 years in Japan
	Jun 15	Workshop on RTK-GPS positioning by VRS and so on
	In Jul	Detection of slow slip event in the Tokai region
	In Oct	Detection of crustal deformation accompanied by volcanic activity at Izu-Oshima
	In Nov	**Establishment of Promotion Council of Real Time Positioning using GPS-based Control Stations**
	Dec 18	Detection of crustal deformation accompanied by Yonagunijima-Kinkai Earthquake (M7.3)
2002	Jan 7	Public release of coordinates transformation software 'TKY2JGD'
	In Mar	Revision of the operating specifications for public surveying determined by the Ministry of Land, Infrastructure, Transport and Tourism
	Mar 31	Detection of crustal deformation accompanied by an earthquake near Taiwan (M7.0)
	Apr 1	**Enforcement of the amended Survey Act (world geodetic system); GEONET data available for public surveying**
	Apr 1	Start of public release of daily coordinates of GEONET stations (F1)
	In May	Detection of crustal deformation accompanied by earthquake swarms east of the Izu Peninsula
	May 27	**Start of public release of real-time data streams from 200 GEONET stations located in large cities**
	Sep 12	**Installation of GEONET station at the top of Mt. Fuji**
	In Oct	Detection of slow slip event on the Boso Peninsula
	Nov 3	**Detection of crustal deformation accompanied by Miyagiken-oki Earthquake (M6.1); post-seismic deformation also detected**
	Dec 10	**Installation of GEONET station on Marcus Island**
	Dec 11	GEONET Symposium held in Shinjuku
2003	Jan 14–16	International Workshop on GPS Meteorology held in Tsukuba
	In Mar	**Increase of GEONET stations by 253 to 1,200** (including Mt. Fuji and Marcus Island) **Start of continuous communications line (IP-VPN) except on isolated islands** **Unification of antenna type with choke ring. Remodeling of part of the GEONET stations to a double-tube type structure.**
	In May	Detection of crustal deformation accompanied by earthquake swarms east of the Izu Peninsula
	May 26	Detection of crustal deformation accompanied by Miyagi-oki Earthquake (M7.1)
	May 28	Tsuboi Prize of the Geodetic Society of Japan (Group Prize) awarded to GEONET group

Year	Month/Day	Event
2003	Jun 2	**Start of public release of real-time data streams from 645 stations located nationwide**
	Jul 26	Detection of crustal deformation accompanied by Miyagi-Hokubu Earthquake (M6.4)
	Sep 26	**Detection of crustal deformation accompanied by Tokachi-oki Earthquake (M8.0); post-seismic deformation also detected**
	Oct 8	Detection of crustal deformation accompanied by Kushiro-oki Earthquake (M6.4)
	Oct 27	**Start of public release of real-time data streams from 931 stations located nationwide**
	Oct 29	Detection of slow slip event around the Bungo Channel
	Oct 31	Detection of crustal deformation accompanied by Fukushima-oki Earthquake (M6.8)
	Dec 10	GEONET Symposium held in Shinjuku
2004	In Mar	**Increase of GEONET stations by 24 to 1,224 in the Tonankai and Nankai regions**
	Mar 1–5	Participation in IGS workshop held in Switzerland
	Mar 29	Public release of daily coordinates of GEONET stations (F2) using analysis strategy F2
		Establishment of relative phase center variation model for combination of antenna and basement
	Jul 1	Revision of the survey results for the orthometric height of 947 existing GEONET stations; public release of survey results for 253 new GEONET stations
	Jul 1	**Increase of GEONET stations providing real-time data stream to 1,180**
	Jul 2	Determination of draft operating manual for public surveying using network-type RTK-GPS
	Sep 5	Detection of crustal deformation accompanied by Mie Nanto-oki Earthquake (M7.4)
	Sep 24	Decrease of GEONET stations providing real-time data streams to 1,178
	Oct 23	**Detection of crustal deformation accompanied by Chuetsu Earthquake (M6.8)**
	Nov 1	Installation of two REGMOSs at Mt. Asama
	Nov 19	Revision of the survey results from four GEONET stations according to the Chuetsu Earthquake
	Nov 29	Detection of crustal deformation accompanied by Kushiro-oki Earthquake (M7.1)
	Nov 30	GEONET Symposium held in Osaka
	Dec 6	Detection of crustal deformation accompanied by Kushiro-oki Earthquake (M6.9)
	Dec 14	Detection of crustal deformation accompanied by Rumoi-Nanbu Earthquake (M6.1)
2005	In Mar	**Increase of GEONET stations by 5 to 1,229 in the Tonankai and Nankai regions**
	Mar 20	**Detection of crustal deformation accompanied by Fukuoka Seiho-oki Earthquake (M7.0)**
	Apr 1	Revision of the survey results for control points according to the 2003 Tokachi-oki Earthquake (including 59 GEONET stations)
	Apr 18	Revision of the survey results from three GEONET stations according to the Fukuoka Seiho-oki Earthquake
	Jun 6	Increase of GEONET stations providing real-time data streams to 1,181
	Jun 8	Determination of draft operating manual for public surveying using network-type RTK-GPS
	Jun 25	**Installation of GEONET station at Okinotorishima (1,230 GEONET stations in total)**
	Aug 1	Determination of draft operating manual for production of Digital Elevation Model (DEM) using airborne laser scanning
	Aug 16	Detection of crustal deformation accompanied by Miyagi-oki Earthquake (M7.2)
	Sep 26	Launch of GPS satellite emitting L2C signals for civil purposes (Block IIR-M). Start of modernization of GPS.
	Nov 8	GEONET Symposium held in Sapporo
	Dec 15	Increase of GEONET stations providing real-time data streams to 1,188
2006	Feb 2	Registration of four GPS stations (Chichijima, Shintotsukawa-A, Aira, Tsukuba-2A) and one GEONET station (Marcus Island) as IGS stations
	Aug	Start of project for developing next-term analysis strategy F3
	Sep 1	Determination of draft operating manual for public surveying using digital aerial photogrammetry
	Nov 5	Alteration of reference frame of F3 to ITRF2005 (from IGb00 to IGS05)

Year	Month/Day	Event
2006		Establishment of absolute phase center variation model for combination of antenna and basement
	Nov 15	GEONET Symposium held in Hiroshima
2007	Jan 15	Increase of GEONET stations providing real-time data streams to 1,218
	Mar 25	**Detection of crustal deformation accompanied by Noto Peninsula Earthquake (M6.9)**
	Apr 23	Revision of the survey results from five GEONET stations according to the Noto Peninsula Earthquake
	Jul 16	**Detection of crustal deformation accompanied by Chuetsu-oki Earthquake (M6.8)**
	Jul 17	Decrease of GEONET stations providing real-time data streams to 1,215
	Aug 17	Revision of the survey results from six GEONET stations according to the Chuetsu-oki Earthquake
	Oct 31	Public release of survey results for orthometric height of 452 attached markers of GEONET stations as a second-order benchmark
2008	In Mar	**Increase of GEONET stations by 10 to 1,240.** Modification of analysis system for redundancy and so on
	Mar 31	Revision of all parts of the rules for the operating specifications for public surveying
	Jun 14	**Detection of crustal deformation accompanied by Iwate-Miyagi Earthquake (M7.2); post-seismic deformation also detected**
	Aug 4	Revision of the survey results from 21 GEONET stations according to the Iwate-Miyagi Earthquake
	Sep 11	**Detection of crustal deformation accompanied by Tokachi-oki Earthquake (M7.1)**
	Nov 4	Increase of GEONET stations providing real-time data streams to 1,217
2009	Feb 2	Eruption of Mt. Asama; detection of baseline expansion accompanied by volcanic activity from six months before the eruption
	Apr 1	**Public release of daily coordinates of GEONET stations (F3) using analysis strategy F3**
	Jun 1	Revision of the survey results from GEONET station on Ioto Island
	Aug 11	**Detection of crustal deformation accompanied by Suruga-Wan Earthquake (M6.5)**
	Oct 28	**Start of usage of precipitable water vapor value obtained from GEONET data by the Japan Meteorological Agency for weather forecasting (MesoScale model)**
2010	Jan 1	**Introduction of 'semi-dynamic datum correction' for basic surveying and part of public surveying (first class control points surveying using only GEONET stations as fixed points)**
	Jan 13–14	Participation in the 7th Japan-US GPS Plenary Meeting held in Washington, DC
	Jan 25–26	Participation in the 1st Asia Oceania Regional Workshop on GNSS held in Thailand
	Feb 27	Detection of crustal deformation accompanied by Okinawahonto-Kinkai Earthquake (M7.2)
	In Mar	**Duplication of communications lines with mobile phone packet switching at approximately 1,100 GEONET stations** Unification of real-time data format to BINEX **Replacement of 450 GPS receivers with GNSS receivers at GEONET stations**
	Mar 2	Registration of GPS tracking station Chichijima-A as an IGS station
	Mar 5	Detection of slow slip event around the Bungo Channel
	Apr 1	Increase of GEONET stations providing real-time data streams to 1,221
	May 18	Start of launch of GPS satellites emitting L5 signals for civil purposes (Block IIF)
	Sep 11	**Launch of the 'Michibiki,' the first satellite of the Quasi-Zenith Satellite System**
	Sep 21–24	Participation in the GNSS2010 Workshop held by the Institute of Navigation (ION) in the US
	Oct 18–22	Participation in the 5th Meeting of the International Committee on Global Navigation Satellite Systems held in Italy
	Nov 1–3	Participation in the 2nd Asia Oceania Regional Workshop on GNSS held in Australia
	Dec 22	Detection of crustal deformation accompanied by Chichijima-Kinkai Earthquake (M7.8)
2011	Jan 13–14	Participation in the 8th Japan-US GPS Plenary Meeting held in Tokyo
	Jan 26	Eruption of Mt. Kirishima (Shinmoedake); detection of slight baseline expansion accompanied by volcanic activity from 8 months before the eruption; baseline contraction after eruption
	Mar 9	Detection of crustal deformation accompanied by Sanriku-oki Earthquake (7.3)

Year	Month/Day	Event
2011	Mar 11	**Detection of crustal deformation in wide area from the Hokkaido to Kinki regions accompanied by the 2011 Great East Japan Earthquake (9.0); post-seismic deformation also detected**
	Mar 12	Detection of crustal deformation accompanied by Nagano-Hokubu Earthquake (M6.7)
	Mar 15	Detection of crustal deformation accompanied by Shizuoka-Tobu Earthquake (M6.4)
	Mar 19	Public release of information on crustal deformation accompanied by the 2011 Great East Japan Earthquake (horizontal: approximately 5.3 m, vertical: approximately 1.2 m subsidence)
	Mar 19	Detection of crustal deformation accompanied by Ibaraki-Hokubu Earthquake (M6.1)
	Mar 23	Detection of crustal deformation accompanied by Fukushima Hama-Dori Earthquake (M6.0)
	Mar 31	Partial revision of the rules for the operating specifications for public surveying
	Apr 1	Increase of GEONET stations providing real-time data streams to 1,223
	Apr 7	Detection of crustal deformation accompanied by Miyagi-oki Earthquake (M7.0)
	Apr 11	**Detection of crustal deformation accompanied by Fukushima Hama-Dori Earthquake (M7.0)**
	Apr 12	Detection of crustal deformation accompanied by Nagano-Hokubu Earthquake (M5.6)
	May 31	**Revision of the survey results from 438 GEONET stations located in eastern Japan according to the 2011 Great East Japan Earthquake. 'Geodetic Coordinates 2011'**
	Jun 10	Installation of GNSS mobile continuous observation system 'M-Minamisoma' in place of destroyed 'S-Minamisoma'
	Jun 23	Detection of crustal deformation accompanied by Iwate-oki Earthquake (M6.9)
	Jun 27	Public release of crustal deformation correction parameter (semi-dynamic datum correction) for fiscal year 2011; continuous public release every year
	Jun 30	Detection of crustal deformation accompanied by Nagano-Chubu Earthquake (M5.4)
	Jul 15	Start of research and development project on the smart use of multi-GNSS signals for more efficient surveying and precise positioning essential in the management of national lands (to 2015)
	In Sep	Trial public release of real-time data streams from twelve GEONET stations in the Kinki and Kanto regions for actual-proof experiments of GNSS
	Sep 5–9	Participation in the 6th Meeting of the International Committee on Global Navigation Satellite Systems held in Tokyo
	Sep 22	Public release of information on crustal deformation accompanied by the 2011 Great East Japan Earthquake obtained by using 1 Hz data from GEONET stations
	Sep 29	Detection of crustal deformation accompanied by Fukushima Hama-Dori Earthquake (M5.4)
	Oct 5	Detection of crustal deformation accompanied by Toyama-Tobu Earthquake (M5.4)
	Oct 31	Detection of slow slip event off the Boso Peninsula
	Nov 1–3	Participation in the 3rd Asia Oceania Regional Workshop on GNSS held in South Korea
	Nov 8	Installation of GNSS mobile continuous observation system at Otsuchi Twon
	Nov 21	Approval of the third supplementary budget in 2011 for replacement of GEONET receivers and so on
	Dec 8	Return of full operation of GLONASS (24 satellites) after an interval of 15 years
2012	Jan 18–19	Participation in the 9th Japan-US GPS Plenary Meeting held in Washington, DC
	Mar 8	Removal of 'M-Minamisoma' according to the start of operation of 'S-Minamisoma-A'
	Mar 14	Detection of crustal deformation accompanied by Chiba Toho-oki Earthquake (M6.1)
	Apr 1	**Revision of 'GEONET' from GPS Earth Observation NETwork system to GNSS Earth Observation NETwork system.** Decrease of GEONET stations providing real-time data streams to 1,221
	Apr 1	Transfer of authority of GPS CORSs installed in Java and Sumatra by JST-JICA project (ended in 2011) to local organization in Indonesia
	Apr 6	**Start of trial operation of REGARD**
	Apr 19	Recovery of GEONET station 'Odaka' in Minamisoma City
	Apr 27	Detection of uplift exceeding 15 cm for two days at Ioto Island
	Jul 13	**Start of public release of QZSS and GLONASS data obtained from 187 GEONET stations in the Tohoku region and so on**

Year	Month/Day	Event
2012	Sep 1	Start of joint research with Tohoku University on the contribution of tsunami forecasting
	Sep 20–22	GNSS observation at Maehodakadake in the Hida Mountains
	Oct 31	Increase of GEONET stations providing real-time data streams to 1,223
	Dec 7	Confirmation of absence of crustal deformation accompanied by Sanriku-oki Earthquake (7.3) using REGARD
	Dec 8–10	Participation in the 4th Asia Oceania Regional Workshop on GNSS held in Malaysia
2013	Feb 25	Detection of crustal deformation accompanied by Tochigi-Hokubu Earthquake (M6.3)
	In Mar	**Completion of replacement of antennas and receivers with GNSS type at all GEONET stations**
	In Mar	Public release of survey results from 30 GPS continuous observation stations installed for research purposes
	Mar 8	New opening of special page for crustal deformations for two years after the 2011 Great East Japan Earthquake
	Mar 26	Structural remodeling to the double-tube type for twelve GEONET stations that constitute the backbone in baseline analysis
	Mar 29	Partial revision of the rules for the operating specifications for public surveying
	Apr 13	**Detection of crustal deformation accompanied by Awajishima Earthquake (M6.3)**
	Apr 17	Detection of crustal deformation accompanied by Miyakejima-Kinkai Earthquake (M6.2)
	Apr 26	Determination of operating manuals for orthometric height surveying using GNSS and control point surveying using only GEONET stations as fixed points; revision of the geoid model
	May 10	**Start of public release of QZSS and GLONASS data obtained from all GEONET stations**
	Jul 1	Revision of the survey results for the orthometric height of GEONET stations in the Chugoku, Shikoku and Kyushu regions
	Jul 24–25	Participation in the 10th Japan-US GPS Plenary Meeting held in Tokyo
	Nov 10–14	Participation in the 8th Meeting of the International Committee on Global Navigation Satellite Systems held in United Arab Emirates
	Nov 14	Public release of multi-GNSS analysis software ‘GSILIB prototype’
	Dec 1–3	Participation in the 5th Asia Oceania Regional Workshop on GNSS held in Vietnam
2014	Jan 2	Detection of slow slip event off the Boso Peninsula
	Jan 27–29	Participation in the 2014 International Technical Meeting of the Institute of Navigation in the US
	Apr 1	Revision of the survey results for the orthometric height of GEONET stations in the Hokkaido, Tohoku, Kanto, Hokuriku, Chubu, Kinki, and Okinawa regions Revision of the operating manual for public surveying
	Jun 9	Revision of the GEONET data public release page
	Jun 20	Public release of the survey results from 39 GPS continuous observation stations installed in tide stations and so on. Including these stations, there are **approximately 1,300 GEONET stations**
	Jul 8	Detection of crustal deformation accompanied by Iburi-Chutobu Earthquake (M5.6)
	Jul 23–29	Detection of crustal deformation accompanied by earthquakes near Izu-Oshima
	Sep 26	Designation of the Japan Association of Surveyors as the distribution agency for GEONET real-time data streams
	Sep 27	Eruption of Mt. Ontake; public release of the detection of crustal deformation within two days after the eruption
	Sep 30	Seismic base isolation of the server room on the third floor of the Space Geodetic Laboratory
	Oct 9–11	Participation in the 6th Asia Oceania Regional Workshop on GNSS held in Thailand
	Oct 16–17	Participation in the Seminar on GNSS Geodetic Network held in Myanmar
	Nov 9–14	Participation in the 9th Meeting of the International Committee on Global Navigation Satellite Systems held in Czech Republic
	Nov 22	Detection of crustal deformation accompanied by Nagano-Hokubu Earthquake (M6.7)

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2015	Jan 8	Public release of multi-GNSS analysis software ‘GSILIB’
	Feb 17	Detection of crustal deformation accompanied by Sanriku-oki Earthquake (M6.9)
	Feb 26	United Nations resolution on Global Geodetic Reference Frame for Sustainable Development adopted by the UN General Assembly
	May 1	Partial revision of the operating manual for orthometric height surveying using GNSS
	May 8	Installation of REGMOS at Owakudani on Mt. Hakone Detection of crustal deformation accompanied by volcanic activity at Mt. Hakone
	May 13	Detection of crustal deformation accompanied by Miyagi-oki Earthquake (M6.8)
	May 13	Public release of information on crustal deformation accompanied by volcanic activity around Mt. Hakone
	May 18	Start of public release of daily coordinates by rapid analysis (R3)
	May 29	Determination of draft operating manual for multi-GNSS surveying
	Jun 12	Installation of REGMOS at Kuchinoerabujima (to 2016)
	Aug 19	Estimation of source of crustal deformation accompanied by volcanic activity at Mt. Sakurajima
	Sep 14	Detection of crustal deformation accompanied by volcanic eruption at Mt. Aso
	Sep 30	Reinforcement of power supply and basement of 67 GEONET stations around volcanoes
	Nov 1–5	Participation in the 10th Meeting of the International Committee on Global Navigation Satellite Systems held in the US
	Nov 24	Start of ‘delivery lecture’ project for schools where GEONET stations are installed
	In Dec	Detection of slow slip event around the Kii Channel (from mid-2014 to Oct. 2016)
	Dec 7–9	Participation in the 7th Multi-GNSS Asia Conference held in Brunei Darussalam
2016	Jan 14	Detection of crustal deformation accompanied by Uraga-oki Earthquake (M6.7)
	Apr	Detection of slow slip event around the Bungo Channel (from Dec. 2015 to Dec. 2016)
	Apr 1	**Start of public release of new data from 786 GEONET stations including GPS L5 signals and Galileo signals**
	Apr 14	Detection of crustal deformation accompanied by Kumamoto Earthquake (M6.3)
	Apr 16	**Detection of crustal deformation accompanied by Kumamoto Earthquake (M7.3); post-seismic deformation also detected**
	Apr 18	Detection of crustal deformation accompanied by Kumamoto-Aso Earthquake (M5.8)
	Apr 29	Detection of crustal deformation accompanied by Oitaken-Chubu Earthquake (M4.5)
	May 19, Jun 16	Revision of the survey results from GEONET stations according to the Kumamoto Earthquake (37 stations and 1 station, respectively)
	Sep 30	Public release of the survey results from 9 precise height observation stations around Omaezaki
	Oct 21	Detection of crustal deformation accompanied by Tottori-Chubu Earthquake (M6.6)
	Oct 31	Installation of solar panels at 33 GEONET stations around volcanoes
	Nov 7–11	Participation in the 11th Meeting of the International Committee on Global Navigation Satellite Systems held in Russia
	Nov 14–16	Participation in the 8th Multi-GNSS Asia Conference held in the Philippines
	Nov 22	Detection of crustal deformation accompanied by Fukushima-oki Earthquake (M7.4)
	Nov 24	Revision of the survey results from GEONET stations according to the Tottori-Chubu Earthquake
	Nov 24	Start of public release of QZSS and Galileo data obtained at 34 GEONET stations installed in tide stations and so on Start of public release of GNSS data in RINEX ver.3.02 format
	Dec 15	Declaration of initial service by 18 Galileo satellites by the EU committee
	Dec 28	Detection of crustal deformation accompanied by Ibaraki-Hokubu Earthquake (M6.3)
2017	In Mar	Replacement of aged leading-in poles at approximately 540 GEONET stations