2.1 Introduction

Volcanoes are an awesome display of Nature’s power. In addition, volcanic explosions are often very destructive events having a massive impact on the natural and human environment. In a world of ever-growing population, more and more people live in close proximity to an active volcano. While the volcanic soil is very fertile, volcanoes also pose a significant threat to human life. The disastrous impacts of the eruptions of Tambora, Indonesia in 1815 (92,000 fatalities), Krakatau, Indonesia in 1883 (36,417 fatalities), Mt. Pelée on the Caribbean island of Martinique in 1902 (29,000 fatalities) and, more recently, Nevado del Ruiz, Colombia in 1985 (25,000 fatalities) have emphasised this fact in an impressive and sobering manner (McGuire, 1995). It is therefore necessary to closely monitor volcanoes in order to avoid such catastrophes triggered by an eruption. The successful prediction of the extremely explosive 1991 eruption of Mt. Pinatubo in the Philippines (the second largest eruption in the 20th century) saved many thousands of lives, as 60,000 people had been evacuated on the day prior to the eruption (Newhall & Punongbayan, 1996). However, each volcano is unique and has its own characteristics and behaviour. To really understand a volcano, the researcher has to essentially ‘marry’ the volcano (Abidin, 2000, personal communication). This humorous statement illustrates the need for long-term monitoring to study the varying ‘moods’ of these beautiful, but also hazardous, giants in order to detect as early as possible any deviations from their normal behaviour.

This chapter gives a brief overview of the techniques used for volcano deformation monitoring and then focuses on the utilisation of GPS for this purpose. Different types of permanent GPS networks are described and the UNSW-designed mixed-mode GPS-based volcano deformation monitoring system is introduced.
2.2 Volcano Deformation Monitoring

When and where will the volcano erupt? This is the essential question scientists concerned with volcano monitoring have to answer, as precisely as possible. Several different techniques – such as seismic, microgravitational, geomagnetic, geodetic, chemical, thermal, hydrologic, remote sensing and visual observations – can be applied to study volcanoes (Fig. 2.1).

![Image of volcano monitoring techniques](image_url)

**Fig. 2.1: Volcano monitoring techniques (USGS, 2002a)**

Ground deformation due to volcanic magma intrusion is recognised as an important precursor of eruptive activity at a volcano. Before an eruption occurs, the ground surface generally expands due to the pressure increase within the shallow magma chamber caused by upward magmatic movements below the volcano. The trend is reversed after magma is released from the chamber causing deflation of the flanks of the volcano (Fig. 2.2). Furthermore, the pattern and rate of surface displacements reveal the depth and the rate of pressure increase within the subterranean magma chamber (Dvorak & Dzurisin, 1997), giving important information about the state of the volcano. As ground deformation tends to precede eruptions by periods of hours to months, geodetic monitoring is an effective tool for hazard mitigation. Ground deformation monitoring techniques for volcanic environments have developed from precise spirit levelling to electronic distance measuring (EDM) techniques, and more recently to the use of InSAR, and campaign-style or continuous GPS surveys.
Perhaps the first documented ground deformation associated with a volcanic event was the work reported by Omori (1914). His investigations indicated vertical ground displacements on the Mt. Usu volcano in Japan of up to 2 metres when conducting precise levelling surveys before and after the eruption of 1910. A 100-metre upheaval of the ground surface was also recorded close to the crater at the time of eruption.

Using elastic theory and data from several case studies, Mogi (1958) developed a mathematical model in order to determine the position and depth of a magma source based on ground deformation measurements and their locations. He assumed that the ground deformation is caused by a spherical source (magma chamber) located below a volcano edifice, which exerts hydrostatic pressure upward to the ground surface. Ibid (1958) proposed that the earth’s crust behaves elastically at the time of eruption while, during the long period of deformation after the eruption, the crust behaves as a visco-elastic medium. This simple model has proven to be very effective and is still widely being used today to estimate the location of the magma source.

From the 1960s through to the 1980s, traditional surveying techniques were used for ground deformation monitoring. Generally these networks consisted of spirit levelling runs to detect vertical movements, and triangulation networks in order to determine horizontal displacements.

The introduction of electronic distance measuring (EDM) equipment enabled relatively long distances to be measured quickly and precisely. Suganda (1993) reports a 2m change...
of horizontal distance between points spanning the crater of the notoriously active Mt. Merapi in Indonesia from four campaigns of EDM measurements conducted between 1988 and 1992. At Mt. Unzen (Japan) EDM observations showed that the growing lava dome was expanding at a rate of 70-80cm per hour over a few days preceding the eruptive event of May 24, 1991 (GVN, 1991).

Combining several geodetic techniques further improved ground deformation monitoring. Bonasia & Pingue (1981) report on a system on Mt. Vesuvius in Italy comprising a levelling network, EDM measurements, tilt measurements, and the analysis of apparent zenith distances of the crater bottom from a fixed point located on the crater rim. Blick et al. (1989) describe a network combining angle measurements, EDM measurements and tilt measurements on Mt. Erebus in Antarctica. Even repeated steel tape measurements across cracks in the ground can provide valuable information, as reported by Swanson et al. (1983), who successfully used this technique to record episodes of accelerating growth of the Mount St. Helens lava dome between 1980 and 1982. These measurements, in conjunction with data gathered by other means, led to the prediction of 13 eruptions during this period. A comprehensive review of the various ground deformation monitoring techniques used by the staff of the Cascades Volcano Observatory for the period 1980-1990 can be found in Ewert & Swanson (1992).

With advances in GPS techniques in the 1980s it was quickly realised that GPS is well suited to monitor deformation caused by tectonic motion, ground subsidence and volcanic activity. The GPS techniques will be discussed further in section 2.3.

In recent years, interferometric synthetic aperture radar (InSAR) techniques have increasingly been used to map the topography of volcanoes and detect ground deformation. Using ERS-1 SAR images taken between 1992 and 1993, Briole et al. (1997) detected a deflation “moderate in size and amplitude” associated with the 1986-87 and 1989 lava flows on Mt. Etna, Italy. Around the vent of the New Trident volcano in Alaska, a 7-9cm uplift was observed over a 2-year period by Lu et al. (1997). Other case studies were reported by Rosen et al. (1996), Amelung et al. (2000) and Fujiwara et al. (2000). Due to the large area being covered by a single InSAR image (100km × 100km), its cost-effectiveness and ability to penetrate clouds the use of InSAR is certainly a
beneficial option in complex and inaccessible terrain. However, dense vegetation and snow cover can preclude the use of InSAR as a volcano monitoring tool. Furthermore, these techniques rely on the repeat period of the satellite track (35 days in the case of ERS-1/2), which also influences the coherence of the images. Hence it is not possible to detect short-term deformation. Tobita et al. (2001) proposed a different technique using SAR amplitude images acquired from ascending and descending orbits in order to create a map of three-dimensional displacement vectors. The technique provides wide spatial coverage, delivers 3D displacement components, enables the estimation of displacement velocities and does not depend on coherence. During the 2000 Mt. Usu eruption in Japan, inflation was observed with both vertical and horizontal displacements exceeding 20m. The uplift and north-south spreading velocities were found to reach values of 3.3m/day and 2.7m/day respectively. However, this technique is less precise than InSAR and GPS, and not very sensitive to local deformation. Currently research is being undertaken in order to integrate the use of InSAR and GPS for deformation monitoring applications (e.g. Williams et al., 1998; Ge et al., 2000b; 2001; 2003; Ding et al., 2002).

Deformation monitoring techniques can be classified as being either episodic or continuous (Abidin, 1998). Episodic techniques include angle and distance measurements, levelling, InSAR and repeated GPS surveys. Instrumentation used for continuous monitoring includes tiltmeters, extensimeters, dilatometers and permanent GPS networks.

2.3 Volcano Deformation Monitoring Using GPS

GPS is well suited for monitoring volcanoes (or ground subsidence, landslide prone areas, dams, buildings, etc.) because GPS measurements can provide 3D positions at centimetre-level accuracy, unlike levelling which only produces height, or EDM which only measures distance. In addition, there is no requirement for intervisibility between stations within a GPS network. Measurements can be made independent of weather conditions, 24 hours a day and over relatively long distances. GPS has therefore many advantages over conventional geodetic techniques, considering that most of the world’s volcanoes reach high altitudes and are prone to frequent cloud cover. Furthermore, once a GPS network is installed, no human presence is needed at a potentially dangerous
volcanic locale. By repeatedly measuring the same baseline vector to an accuracy commensurate to (and preferably much higher than) the expected baseline component changes due to deformation, the rate of change in the baseline components can be reliably determined (after several surveys).

Probably the first GPS survey to be carried out in a volcanic area was undertaken in Iceland during 1986 (Foulger et al., 1987). A little later, Sigmundsson et al. (1992) detected ground deformation associated with a fissure eruption at the Hekla volcano in Iceland. Marshall et al. (1997) observed ground inflation caused by dike opening at the Long Valley Caldera, California from five annual GPS campaigns between 1990 and 1994. Ground deformation caused by magma intrusion and lava discharge was detected and reported by Nishi et al. (1999) after a series of GPS campaigns were conducted on Mt. Unzen in Japan over 5 years. The study revealed ground inflation before the lava dome extrusion took place. This was followed by deflation, as the lava dome grew and created pyroclastic flows caused by frequent collapses of the lava dome. The detected ground deformation (inflation and deflation) was successfully explained by a pressure source located about 6km west of the active crater at a depth of 11km, determined using the Mogi model. At the Soufriere Hills volcano, Montserrat, a series of GPS campaigns conducted fortnightly over a period of one year revealed displacements radially symmetrical around the growing lava dome. It was concluded that the centre of pressure causing the observed ground deformation was within the dome itself rather than within a magma chamber at any significant depth beneath the volcano or within a large conduit leading to the surface (Shepherd et al., 1998). The Institute of Technology Bandung conducts regular campaigns on Gunung Guntur and Gunung Papandayan in West Java, Indonesia (Abidin et al., 1998; 2000). Local GPS campaigns are also used to monitor dome growth in conjunction with EDM distance measurements and precise levelling lines on Mt. Etna, Italy (Nunnari & Puglisi, 1994; Puglisi et al., 2001).

Numerous examples of GPS deformation monitoring networks for other applications, such as the monitoring of dams, bridges, tall buildings, etc., can be found in the literature (e.g. Duffy & Whitaker, 1999; Lovse et al., 1995; Stewart & Tsakiri, 2001; Watson & Coleman, 1998).
All of these surveys, however, are conducted in a campaign-style mode, i.e. short measurement surveys separated by long time periods, and therefore give no indication of the rate of ground movement between the campaigns. This might be suitable for quiescent volcanoes, but is certainly not sufficient for volcanoes exhibiting a higher degree of activity. Roberts (2002) summarised the disadvantages inherent in a campaign-style GPS survey approach for deformation monitoring as follows:

- Episodic surveys only provide a snapshot of the phenomenon, and are unlikely to catch an event such as an earthquake as it happens,
- stability of the monuments becomes an issue, as the geodynamic signal can be contaminated by systematic biases such as centring errors of a tripod, movement of marks due to changing local environmental conditions, or theft/vandalism of the marks themselves,
- antenna mixing introduces biases (particularly in the vertical component),
- the cost of planning and executing a GPS campaign can be the largest expense, not the cost of the instruments themselves,
- establishing in-country collaborators, and obtaining permission to work in these countries, is often time-consuming,
- equipment has to be shipped in and out of the country, and cleared in and out of customs,
- in-country observers, often inexperienced, have to be trained as GPS surveyors in intensive courses prior to a survey,
- in-country archiving of the data risks data loss in harsh environments, and
- processing of all of the data is often not completed satisfactorily until months after the data capture survey has been completed.

Most of these disadvantages can be overcome by adopting a continuous GPS deformation monitoring approach. The setting up of a continuous GPS infrastructure is cumbersome, but provides uninterrupted measurements of the displacement of volcano monitoring points. GPS is well suited to operate automatically in a remote environment powered by batteries and solar panels, with the logged data being transmitted to a central computing facility via a radio link.
One of the first continuous GPS networks was established in March 1988 on the Izu Peninsula in central Japan to support earthquake prediction research. Daily observations of this network led to the first GPS measurements of surface deformation as it occurred. Shimada et al. (1990) reported that, “We have, for the first time, used GPS fixed-point measurements to follow the evolution with time of the crustal movements; such measurements provide a continuous uninterrupted record of deformation.” Their results showed that the distance between two benchmarks 10km apart increased by 14.5cm during the seismic activity. This was attributed to the opening of a magma-filled fracture, which indeed fed a new eruption of the Teisha sea-floor volcano located off the coast 10 days later.

Since then several networks of continuously operating GPS receivers have been installed at volcanoes around the world, e.g. at the Long Valley Caldera, California (Dixon et al., 1997), Soufriere Hills volcano, Montserrat (Mattioli et al., 1998), and Kilauea volcano, Hawaii (Owen et al., 2000a; 2000b). Other continuous deformation monitoring applications include tectonic fault lines (Bock et al., 1997; Tsuji et al., 1995) and engineering structures such as tall buildings (Celebi & Sanli, 2002; Ogaja et al., 2001), bridges (Ashkenazi et al., 1997; Wong et al., 2001) and dams (Behr et al., 1998; Whitaker et al., 1998).

On a larger scale, permanent GPS networks can be utilised to detect global or regional tectonic plate motions and to serve as reference stations for geodetic control. Hence GPS networks can be categorised into large scale and small scale networks. Small scale networks can further be subdivided into static, kinematic and ‘low-cost’ networks (Roberts, 2002). These different types of continuous GPS networks are briefly discussed below.

2.3.1 Large Scale Permanent GPS Networks

Large scale permanent GPS networks cannot be used for volcano deformation monitoring. The spacing between receivers is too large and baseline results are normally obtained from 24-hour solutions, providing no information on any sub-diurnal effects. However,
these networks carry out important tasks in a global and national context. Three examples, namely the IGS, GEONET and SCIGN networks, and their roles, are briefly described.

IGS Network
The International GPS Service (IGS) has coordinated the establishment of a global network of about 200 continuously operating dual-frequency GPS receivers (Fig. 2.3). This network is used to realise the International Terrestrial Reference Frame (ITRF), to which all GPS surveys can be connected. In addition, the IGS provides a range of products, such as GPS satellite ephemerides, earth rotation parameters, IGS tracking station coordinates and velocities, and GPS satellite and IGS tracking station clock information (IGS, 2002b). All this information is made available on their website, furthering scientific research, and aiding commercial GPS surveying.

GEONET
Since 1994 Japan’s Geographical Survey Institute (GSI) has operated the GPS Earth Observation Network (GEONET). The main purpose of this GPS array is to continuously monitor crustal deformation in order to study, and hopefully predict, earthquakes and volcanic events, as well as providing the basic geodetic control for Japan (GSI, 2002). It is the world’s most dense permanent GPS network, spanning the entire country and
consisting of almost 1000 GPS sites with an average spacing of about 30km (Miyazaki et al., 1997; 1998). The data collected at each station are transferred to GSI’s data processing centre in Tsukuba via telephone lines. These data are processed with a cluster of workstations to yield the position of each station with an accuracy of a few centimetres or better, in a global reference frame (such as the ITRF). Daily variations of station position are monitored in order to detect any abnormal changes in estimated crustal strain that could indicate an impending earthquake or volcanic eruption. During the 1994 Hokkaido-Toho-Oki earthquake, horizontal displacements of up to 44cm were observed (Tsuji et al., 1995). Unfortunately no precursors were detected during the week preceding the event.

**SCIGN**

The Southern California Integrated GPS Network (SCIGN) was first established in 1990 for the purpose of continuously monitoring crustal deformation in California. Since July 2001 the network has consisted of 250 permanent GPS sites in and around the Los Angeles basin (Hudnut et al., 2001; SCIGN, 2002). Major participants in SCIGN include NASA/JPL, the U.S. Geological Survey (USGS), and the University of California San Diego, operating under the umbrella of the Southern California Earthquake Center (SCEC). GPS data are transmitted to a processing centre via telephone lines, archived and made available to the public via the internet. From 24-hour files of GPS data the coordinates of each receiver are computed to an accuracy of a few millimetres. During the 1992 Landers earthquake a maximum horizontal displacement of 48mm at a distance of 80km from the seismic rupture zone was observed (Bock et al., 1993).

The advantages of continuous GPS networks are manyfold. There is hardly any delay between surveys and coordinate results. No in-field archiving is necessary because the data is downloaded automatically and transferred to a central processing facility. Here, the data can be automatically screened, processed and archived. These networks require reliable power supply, assured communication links, and sophisticated hardware and software.

### 2.3.2 Small Scale Permanent GPS Networks
While large scale GPS networks can be used to detect crustal motion, smaller scale networks are necessary in order to monitor volcanoes or engineering structures such as bridges, dams or high-rise buildings. However, the development of an automatic GPS array for such small scale monitoring is an engineering and software challenge. A network of permanent GPS receivers must be deployed in an often inhospitable environment, in which they must operate reliably on a continuous basis. Power supply in remote locations becomes a big issue, with batteries and solar panels having to be used. The GPS observations must then be telemetered to a central computing facility where data processing occurs with minimum delay. Such local networks can be realised in different ways. Which system design is chosen usually depends on the expected amplitude and frequency of deformation, the terrain, available power sources and budget constraints.

2.3.2.1 Static Small Scale GPS Networks

A local network of continuously operating GPS receivers is well suited to monitor relatively small areas around a volcano. One of the first such networks was established by the U.S. Geological Survey (USGS) on the Augustine volcano, Alaska (Fig. 2.4). Three dual-frequency GPS receivers are used, and the baselines are measured on a weekly basis. The data are transmitted from the two remote stations on the flank and summit of the volcano to a base station for processing (USGS, 2002b).
The USGS also operates 16 continuous GPS sites as part of a ground deformation network to monitor the Kilauea, Mauna Loa and Mauna Kea volcanoes in Hawaii (USGS, 2002c). The network is coordinated by scientists of the Hawaiian Volcano Observatory (HVO), in collaboration with Stanford University. GPS data are sampled every 30 seconds and downloaded once a day to calculate one-day average positions. In addition, more than 100 other sites are surveyed intermittently during GPS campaigns. Figure 2.5 shows part of this network, the sites NUPM and KTPM spanning the east rift zone of Mauna Kilauea, about 6km from the Pu‘u ‘O‘o vent. MLPM is located on the southeastern flank of Mauna Loa, while MKPM is located on the summit of Mauna Kea. During a brief eruptive episode of the Kilauea volcano that began on January 30, 1997, continuously recording GPS receivers measured significant ground deformation near the eruption site. As magma forced its way up into the rift beneath the Napau Crater, the two GPS sites located on either site of the east rift moved apart by 36cm during the activity, and continued to move apart at a slower rate after the activity stopped on January 31 (Fig. 2.6). The results clearly showed that the relatively small eruption was associated with a much larger volume of magma that intruded into the rift zone and remained below ground.
The eruption on Kilauea was preceded by 8 hours of rapid deflation of Kilauea’s summit (Owen et al., 2000b).

A dense, continuous GPS network of about 20 sites was established to monitor ground deformation at the Iwate volcano in Japan. GPS data are collected at a sampling rate of
60 seconds and transferred to the computing facility at Tohoku University via phone line, cellular phone or radio link, depending on the site location. The data are analysed using the GAMIT software (King & Bock, 1995) and precise ephemerides to produce daily solutions. During a period of unrest in 1998, significant deformation of about 3-4cm horizontally and a 2cm uplift were observed (Miura et al., 2000). The horizontal displacements showed a radial pattern pointing outward from the western flank of the volcano and displacement rates increased especially in the east-west components. It was estimated that the source of deformation was initially dike intrusion caused by a tensile fault located 5km west of the summit at a depth of 3km. During the course of activity it then changed its nature to an isotropic pressure source according to the Mogi model, and migrated approximately 6km further westward. Displacements due to an M6.1 earthquake that occurred on September 3, 1998, about 10km southwest of the summit were also detected. A fault model of the earthquake was determined based on GPS data and showed good agreement with the results from seismological studies (Ibid, 2000). After the earthquake the volcano deformation ceased.

Recently a software package called Eolo has been developed in Italy, which permits the automatic management of data from a GPS deformation monitoring network (Amore et al., 2002). The software combines the treatment of raw data, their storage in a database, the calculation of the main strain parameters, and the visualisation of the results. Eolo takes into account a lot of the problems associated with the management of a deformation monitoring network. Missing data due to technical difficulties is dealt with, the constant operation of a reference station is not required, and the software is capable of contacting the supervisor by sending emails or SMS messages over the mobile telephone network whenever any anomaly in the analysed data is detected. The desired parameters, such as height variation, distance variation, dilatation and shear, can be visualised in several panels for easy interpretation. Eolo is in use on the island of Stromboli, Italy where a network of four continuous GPS receivers monitors the volcano by observing a 3-hour session daily.

A small scale deformation monitoring network implies a higher density of GPS stations, and therefore better resolution of the deformation pattern. However, these systems use expensive, dual-frequency GPS receivers, and this high expense can severely restrict the
number of GPS stations that can be deployed. Usually daily baseline solutions are determined, although it is possible to process shorter sessions if the frequency of data transfer from the remote stations to the computing facility, and the processing software package that is used, allow this. At the Kilauea volcano, efforts have been made to upgrade the continuous GPS network, so that instead of the routinely generated 24-hour solutions, 15-minute position estimates can be computed in near real-time, based on a random walk parameterisation of ground displacement. Using this approach, smaller inflation events that had amplitudes as low as 1 cm, with periods ranging from 6 hours to 2 days, were observed (Larson et al., 2001).

2.3.2.2 Kinematic Small Scale GPS Networks

The Real-Time Kinematic (RTK) GPS surveying technique typically requires two dual-frequency GPS receivers, connected by a radio data link. Carrier phase measurements are simultaneously observed at the reference or ‘base’ station and the (user) ‘rover’ station. The base station generates RTK messages and transmits these to the rover receiver. Using these corrections, the rover can determine its position to centimetre accuracy in real-time, making this an excellent option for some deformation monitoring applications. Several GPS manufacturers have developed RTK products, which can be used for deformation monitoring.

One such system was modified to specifically meet the requirements of a volcano deformation monitoring application, and has been deployed at the Rabaul volcano in Papua New Guinea (Lowry & MacLeod, 1997). It works essentially as a reverse RTK system by computing the position solutions at the rover and then transmitting these results back to the base for archiving. While this approach delivers real-time positions of the monitoring stations, the requirements for hardware, software, field computer and telemetry components are relatively high, making the equipment comparatively expensive. The volume of data transmission between the base and rover is doubled, which either limits the number of GPS sites in the network, or the sampling rate between epochs, as only one station at a time can transmit its data to the base.
Another example of a RTK system where the base station receives the computed positions of its roving receivers is the Furuno landslide monitoring system (Kondo & Cannon, 1995). It utilises 8-channel GPS receivers capable of outputting raw C/A code and carrier phase at a 0.5Hz data rate, and has been designed to facilitate up to 10 rover stations. The receivers communicate via a cable connection, which is also used to supply the system with power. This, however, limits the baseline lengths to a maximum of 1200m (typically only 800m) between any two receivers in the network. All data are collected at a central PC, where baseline vectors are determined in real-time with typical accuracies of 2cm. Due to the cable connection between GPS receivers, amongst other things, this system is unsuitable for volcano monitoring.

Kato et al. (2000) report on tests of a newly developed RTK system to detect tsunamis before they reach the coast. This system utilises dual-buoys consisting of a support-buoy and a sensor-buoy, both equipped with GPS antennas. The support-buoy is designed to move with the wind-waves and is equipped with two GPS receivers, a number of batteries, a wind generator and solar panels for power supply, and a communication device. It is anchored by tri-directional sinkers in order not to float away or rotate. The sensor-buoy is a spar-type buoy designed to be resistant to wind-wave motion and is connected to the support-buoy by the antenna cable and loosely tied to the supporting ropes to restrict its motions as little as possible. A reference station located on the shore complements the system. GPS data are processed in RTK mode onboard the support-buoy and the resulting positions are transmitted to the base station via a radio link. At the base facility the positions of the GPS sensors, which have an accuracy of a few centimetres, are monitored and archived. A test performed over nine days revealed that the buoy system successfully tracks the change of the sea-surface. Frequency analysis of the data after adding a real tsunami record to the observed RTK data suggests that the system is capable of detecting a tsunami. At present, however, no corrections for ionospheric or tropospheric effects can be applied, restricting the baseline lengths to about 10km. In order to detect tsunamis early enough to initiate warning procedures, the ‘tsunami-meter’ will have to be installed further from the coast.

An interesting, unique experiment was recently carried out in Japan, where earthquakes were simulated by controlled blasting of explosives (Turner, 2002). RTK GPS
observations were used to study the effects on ground deformation, pipelines and bridge structures. In this RTK system raw code and carrier phase data are collected at a 10-20Hz sampling rate and transmitted via a radio link, from two base stations and up to ten rover stations, to a single computer that processes the data. Both single- and dual-frequency GPS receivers were tested in a laboratory environment and were found to deliver horizontal accuracies at the centimetre-level. The field tests in Japan demonstrated the versatility and robustness of the GPS monitoring package under severe weather conditions. Deployment of this system is planned on two landslide sites and two bridges in California.

Researchers in Germany developed the GPS-based Online Control and Alarm (GOCA) system, a software infrastructure that is designed to receive GPS baseline solutions from any combination of single- or dual-frequency GPS systems (K·lber et al., 2000). It can be set up as an early warning system to monitor engineering structures, landslide activity, earthquakes or volcanoes. Data from the base station is transmitted to the rover stations, where the baseline processing takes place. The estimated baseline vectors, along with their covariances and other information, are then transferred to the GOCA centre via radio modems. Here, a network adjustment is performed in order to detect any movements between observation epochs. The system is designed to handle both permanently and intermittently occupied rover stations, offering a high degree of flexibility. GOCA was successfully used to detect movements caused by filling and emptying the lock Uelzen I in Germany (Borchers & Heer, 2002). The lock, which is part of the Elbe-Seiten-Canal, has a length of 185m and overcomes a height difference of 23m. During operation (filling and emptying the lock) the walls of the lock expanded in the range of 25mm to both sides, and a typical operation period of one hour was clearly estimated by time series analysis.

A real-time monitoring software package, called 3-D Tracker, was developed by Condor Earth Technologies Inc. (Condor, 2000). It can process data from single- or dual-frequency GPS receivers, or a combination of both. Instead of raw GPS data from reference station(s) and rover station(s) being processed at the rover(s), all data are processed at a centralised station. After a period of initialisation, Kalman-filtered epoch-by-epoch solutions are provided by processing both double-differenced and triple-differenced data. The manufacturers claim mm-accuracy for this system.
RTK systems can provide real-time coordinates of rover stations at the computing facility and are certainly an attractive option for a range of deformation monitoring applications. However, such systems are comparatively expensive. On a volcano, most of the time deformational signals cannot be characterised as ‘kinematic’, except under extreme conditions just before an eruption. Since only positions are received and stored by the base facility, raw GPS data is not archived for the processing of longer observation sessions. This, however, may be very useful in order to analyse long-term displacements and to check the RTK solution in quiescent periods.

2.3.2.3 Low-Cost GPS Networks

The monitoring systems mentioned above are very costly because they require the use of high-quality, dual-frequency instrumentation. This is a significant constraint, especially as most of the world’s active volcanoes are located in less developed countries, which cannot fund such systems for monitoring all potentially hazardous volcanoes. In recent years, however, low-cost options have been developed. Based on original equipment manufacturer (OEM) board sets, single-frequency GPS receivers are available at a fraction of the cost of standard dual-frequency receivers. They can be integrated into custom-built systems that output code and/or carrier phase measurements for baseline determination.

The lower cost of such systems means that it is possible to deploy a denser network, which in turn makes it feasible to map deformation on a finer scale. Such systems can fulfil all requirements needed for a deformation monitoring system, such as suitability for remote locations, power supply in the form of batteries and solar panels, transmission of data via radio links, and computerised control of data management and communications software. In addition, the lack of peripheral components to the GPS receiver and computer (e.g. displays, screens and hard disks) significantly reduces the power usage of the system. Hence, the size of the battery bank and the solar panels can be reduced, resulting in further cost savings.

The GPS volcano deformation monitoring system developed by the University NAVSTAR Consortium (UNAVCO) is an example of such a system. As described by
Meertens (1999), single-frequency GPS receivers continuously transmit carrier phase and pseudorange observations through a Time Delay Multiple Access (TDMA) radio data modem network to a central computing facility. Instead of sending logged data files, these ‘intelligent’ radios send GPS data epochs continuously according to pre-defined time slots. The data (collected at a 10-second sampling rate) can be processed at hourly or shorter intervals in order to provide station deformation estimates. The UNAVCO system was deployed at the Long Valley Caldera, California, in 1998 and on the Popocatepetl volcano near Mexico City in April 1999. The latter network comprises five remote stations located on the flanks of the volcano, including one just 300m below the summit (Fig. 2.7).

Another low-cost, single-frequency system has been developed at The University of New South Wales (UNSW) and will be described in greater detail in the next section.

The commercially available Movement Monitoring System (MMS) has been developed by the University of Applied Sciences of Southern Switzerland and GEODEV (GEODEV, 2002). This system consists of a network of single-frequency GPS receivers which are connected to a base station via either a cable, cellular modem or a radio link. The system follows a repetitive sequence of measurement, communication and post-processing. Observation sessions are typically 15-30 minutes in length, and processing takes place at
the base facility where the GPS data are also archived. The baseline results can be visualised using tables or graphs in relative or cumulative terms, and the software can automatically initiate the distribution of warning or alarm messages (e.g. via email or mobile phone) if the deformation exceeds a certain pre-set limit. The horizontal precision achievable for baselines up to 10km is claimed to be 7mm ± 1.5⋅(baseline length in km) (Knecht & Manetti, 2001). Although designed for monitoring buildings, dams, bridges and landslide sites, this system can also be utilised in a volcano environment.

Low-cost systems are more appropriate for developing countries like Indonesia. The use of custom-designed software means access to the source code for algorithm improvement. Due to the use of only one frequency, however, the ionospheric bias cannot be accounted for. In general, a single-frequency, carrier phase-tracking system is appropriate for small-scale continuous GPS networks if the baseline lengths are not longer than about 10 kilometres (a scale usually adopted for volcano deformation monitoring systems). This ‘rule-of-thumb’ implies that the differential ionospheric delay between the two receivers is assumed to be essentially zero, and therefore does not impact on the baseline result. Orbit bias over such short distances can also be ignored (Rizos, 1997). However, as outlined in section 2.5 and chapter 4, these assumptions do not always hold true, and a sparse outer network of dual-frequency receivers may be required to ensure high accuracy.

### 2.4 A Continuous Low-Cost GPS-Based Volcano Deformation Monitoring System in Indonesia

The Indonesian archipelago is home to 129 active volcanoes and 271 eruption points as a consequence of interactions and collisions among several continental plates, including the Australian plate (Abidin & Tjetjep, 1996). 20 million Indonesians, approximately 10% of the total population, live in areas under threat from volcanic eruptions.

A small scale, low-cost, continuous GPS volcano deformation monitoring system was designed by UNSW in collaboration with the Institute of Technology Bandung (ITB) and the Volcanological Survey of Indonesia (VSI). The general specifications of this system are (Roberts, 2002):
Volcano Deformation Monitoring with GPS

Chapter 2

- Suitable for short baselines,
- remote stations powered by batteries and solar panels,
- remote stations designed for harsh environments,
- L1 OEM GPS boards controlled by PC or micro-controller,
- radio modems modular in design to allow for different range transmissions in different environments,
- in-house baseline processing software,
- centimetre accuracy from post-processed static baselines,
- designed for volcano monitoring in equatorial regions,
- suitable for operation in developing countries, and
- as inexpensive as possible.

The system has been deployed on Gunung Papandayan, which is located about 60km south-southeast of Bandung in West Java, Indonesia (Fig. 2.8). Papandayan is a complex stratovolcano with four large summit craters and a maximum elevation of 2665m above sea level. A very violent eruption occurred on August 11-12, 1772, resulting in the collapse of the summit portion of the mountain, which was ejected over 250km² surrounding the area, and the creation of the present horseshoe-shaped crater. A subsequent debris avalanche destroyed 40 villages, killing 2951 people (Kusumadinata, 1979; Kimberly et al., 1998). Although it later developed into a tourist destination, the volcano continued to be an eruptive threat with heightened activity observed in the 1920s, and several explosions of mud occurring until 1993 (VSI, 2002a). This was underlined recently with the spectacular November 11-20, 2002 eruption that dramatically changed the topography inside the old crater complex (see Appendix).
Rizos et al. (2000) describe the four-station network of single-frequency GPS receivers installed on Gunung Papandayan. The network array consists of one base station situated at the VSI observatory and three ‘slave’ stations (Bukit Maung, Nangklak and Kawah) located approximately 8km away in the zone of deformation around the crater of the volcano (Fig. 2.9). Each station comprises five components: (1) GPS/PC module, (2) radio modem sub-system, (3) monument, (4) GPS antenna, and (5) power supply. These components are briefly described below.
GPS/PC Module

GPS/PC modules integrate a 12-channel, single-frequency, Canadian Marconi Company (CMC) Allstar GPS receiver board with an 8086 PC board, which controls data decoding, file management and communications. The slave station computers do not have a screen, keyboard or hard disk (memory storage is restricted to the RAM only), resulting in a significantly reduced power usage. At the base station a 133MHz Pentium computer board is utilised, as it collects data from all slave stations (and its own receiver), and runs the baseline processing software. GPS data is collected at a data rate of 15 seconds and logged hourly at all stations. The GPS/PC modules were custom-built by GPSat Systems Pty. Ltd., Melbourne, Australia.

Radio Modem Sub-System

The base station sequentially polls the three slave stations and downloads their binary data files via a VHF radio link on an hourly basis. Two frequencies (152.375 and 152.475 MHz) are used to transmit and receive data, whereby the ‘transmit’ frequency for the base station corresponds to the ‘receive’ frequency of the slaves, and vice versa. The base station is located at the VSI observatory at the foot of the volcano, about 8km away from the zone of deformation, and has a clear line-of-sight to the summit. VHF radios with directional Yagi antennas at all slave stations and an Omni dipole antenna at the base are used for data telemetry.

Monument

Berntsen 3D monuments (Berntsen, 2002) were emplaced and concreted in position at suitable locations. Issues such as skyview, site stability, line-of-sight for radio communications and avoidance of corrosive gases were important considerations for the location of the monuments. Additionally, the advice of experts from the Volcanological Survey of Indonesia was sought to locate the stations in order to most likely detect any deformation of the volcano. A fibreglass pole, connected to the monument by a screw thread and reinforced by concrete around the base, is used to mount a GPS antenna at all stations.
GPS Antenna
MicroPulse L1 lightweight survey GPS antennas are used at all stations. The U.S. National Geodetic Survey estimated the phase centre variation of these antennas, and the offset model has been incorporated into the GPS baseline processing software. In order to mitigate multipath disturbance, the antenna is mounted on a 1.5m high fibreglass pole. Fibreglass was chosen due to its resistance to the corrosive gases (which are constantly being emitted from the main crater).

Power Supply
At the remote slave stations 12V DC lead acid batteries are used to supply continuous power to the GPS/PC module, GPS antenna and radio modem. Solar panels recharge the batteries during daylight hours, and a solar regulator is used to ensure that the power output from the solar panel array is kept at 12V DC. The base station is powered by AC power backed up by a modified uninterruptable power supply (UPS) to guard against spikes, surges or extended blackouts, which are rather common in rural Indonesia.

Figure 2.10 shows the main hardware components of the slave station equipment: GPS/PC module, radio modem and single-frequency antenna. At the slave stations, the GPS/PC module, radio, solar regulator and battery are housed in a robust plastic drum locked onto a concrete pad to protect the equipment from the environmental elements and theft. Furthermore, PVC tubing surrounding the cables was used in order to give protection from damage by animals. The entire slave station setup is depicted in Figure 2.11, showing GPS antenna, solar panels, radio antenna and the plastic drum containing the remainder of the equipment at Nangklak. At Kawah, in addition, a barbed-wire fence was erected to guard the equipment against vandalism because this area is frequently visited by tourists. The base station setup can be seen in Figure 2.12.
Fig. 2.10: UNSW system equipment: GPS/PC module, radio modem, GPS antenna and cables

Fig. 2.11: Slave station setup on Gunung Papandayan (Nangklak): Solar panels, GPS antenna, plastic drum and radio antenna (left); battery, solar regulator, radio modem and GPS/PC module (right)
Data is collected at a sampling rate of 15 seconds. All software to operate this GPS network has been developed at UNSW to ensure maximum design flexibility. Rudimentary software onboard the GPS/PC module controls the creation of a new data file every hour, which is stored in the RAM at the slave station in the receiver’s binary proprietary format, and the radio transmission of the completed sessions to the base station. The communications software at the base station is more ‘intelligent’ than that at the slave stations. The base station controls the data download via the radio modems by polling each slave station in sequence on an hourly basis, downloading the latest file from its RAM. The binary data received from the slaves is then automatically converted to the Receiver INdependent EXchange (RINEX) format and stored on the hard disk at the base facility. Therefore 24 one-hour files are generated daily for each station, resulting in approximately 12MB of data per day, comprising 192 files. At present baselines are not automatically processed. Data must be manually downloaded from the hard disk at the base station and post-processed. This is a sub-optimal solution and it is intended to remedy this in the near future.

A detailed description of the UNSW-designed system (first installed in 1999), as well as a comprehensive guide for installation, operation and trouble shooting, can be found in Roberts (2002).

The aim was to limit the cost for one receiver station (including monuments and labour) to $US 3000 (Rizos et al., 1997a). The actual cost exceeded this target only by around $US 500, leaving the total cost for the entire four-station network below the cost of one
state-of-the-art GPS receiver, which can cost of the order of $US 20,000 or more (Roberts, 2002).

### 2.5 A Mixed-Mode GPS Network for Volcano Deformation Monitoring

Low-cost GPS networks for deformation monitoring rely on the use of single-frequency GPS receivers. While these receivers are significantly cheaper than dual-frequency instrumentation, they cannot directly account for the ionospheric delay because they only make measurements on one frequency. For short baselines of up to 10km or so, it is generally assumed that the GPS signals propagate through essentially the same portion of the atmosphere and the biases therefore mostly cancel out when the double-differenced observable is formed. However, most of the world’s volcanoes are situated in the equatorial region, an area prone to highly disturbed ionospheric conditions. The resulting effects on the GPS signal are further amplified during the present solar sunspot maximum. Ionospheric disturbances have indeed corrupted baseline measurements over distances less than 10km on Mt. Papandayan, adversely affecting baseline repeatability (Janssen et al., 2001).

During the past few years a methodology has been developed for processing data collected by mixed sets of single-frequency and dual-frequency GPS receivers. For example, Hartinger & Brunner (2000) and Brunner et al. (2000) report on a system to monitor landslides in the Austrian Alps. The UNAVCO L1 system on the Popocatépetl volcano, mentioned in section 2.3.2.3, is expected to be extended by using two dual-frequency receivers to aid atmospheric modelling in the near future (Meertens, 1999).

In order to obtain centimetre-level accuracy for the system deployed on Gunung Papandayan, the single-frequency network has been augmented by the addition of an outer fiducial network of dual-frequency GPS receivers (Rizos et al., 1997b). As discussed in chapter 4, this dual-frequency network surrounding the deformation zone of the volcano is used to generate empirical ‘correction terms’, which are then applied to the inner single-frequency data during baseline processing. This mixed-mode GPS network approach can account for the ionospheric biases that would normally be neglected in a system using single-frequency instrumentation only.
As described by Han (1997), the fiducial network should ideally surround the inner single-frequency network. Figure 2.13 depicts the ideal network configuration where the triangles denote fiducial stations, while the dots indicate single-frequency receiver sites. The fiducial reference stations are to be situated outside the deformation zone of the volcano but within the local tectonic region. Their precise coordinates can be updated regularly by connection to the IGS network. Sites should have stable monumentation, a clear view of the sky and minimal multipath disturbance due to reflections from nearby structures. Security and power issues are significant and have to be addressed in order to enable long-term continuous operation of the fiducial network.

![Fig. 2.13: Ideal network configuration of a mixed-mode GPS deformation monitoring network](image)

Obviously this *mixed-mode* GPS network strategy is not restricted to volcano deformation monitoring, but can also be utilised for a wide range of other deformation monitoring applications. Moreover, existing dual-frequency networks can be cost-effectively densified by large numbers of single-frequency GPS receivers.

### 2.5.1 February/March 2000 Deployment

The fiducial network surrounding Gunung Papandayan was first deployed in February/March 2000. The selection of sites with (more or less) continuous AC power at
secure locations in a rather remote part of West Java proved to be a big challenge. The initial network comprised three GPS stations located at the ITB in Bandung, the VSI observatory at Galunggung and the National Aeronautics and Space Agency (LAPAN) observatory in Pameungpeuk, forming a 72km-60km-85km triangle surrounding the deformation zone of the volcano. This configuration left the inner network close to the baseline Bandung-Pameungpeuk, but still well inside the fiducial triangle (Fig. 2.14). The figure also shows the altered fiducial network used during the July 2001 deployment (see next section).

![Fiducial network for the Feb/Mar 2000 deployment (left) and the July 2001 deployment (right)](image)

The equipment used at all fiducial stations comprised Leica CRS1000 dual-frequency GPS receivers equipped with choke ring antennas, a 120Ah/12V DC lead acid battery and a battery charger (Fig. 2.15). Reliable power supply always is a significant issue in GPS network design, and is particularly challenging in Indonesia. In order to guard against the rather common power outages of up to 6 hours (only the site in Bandung had continuous AC power during the entire campaign), the following configuration was used. An ‘intelligent’ battery charger connected to a 12V DC lead acid battery is plugged into mains power to continuously charge the battery whenever AC power is available. The charger automatically trickles the charge when the battery is approaching full charging capacity. The GPS receiver is connected to the battery, which continues to supply power.
in the event of a blackout. Spikes and surges in the AC power are absorbed by the battery charger, and the battery, and therefore do not affect the GPS receiver.

In general there are two types of batteries on the market, the so-called (wet) float/cranking batteries and (dry) deep cycle batteries. While the former are designed to provide large amounts of power over a short period of time (e.g. to start a car engine), the latter provide relatively low continuous power over a long period of time. Hence, a deep cycle battery would be preferable for the task of powering a GPS receiver. Nevertheless, a (wet) lead acid cranking battery is used due to its significantly lower cost and ready availability in Indonesia. (Note that the same applies for the single-frequency stations of the inner network.) The size of the battery was chosen to guarantee continuous power even during extended AC power failures. As the CRS1000 draws approximately 15 Watts at 12V, which translates into 1.25Ah, a 120Ah battery is sufficient to cover blackouts of up to three days.

A GPS choke ring antenna consists of concentric rings of aluminium or brass mounted on a circular base surrounding a microstrip patch located flush with the plane of the rings (see Figures 2.16 and 2.17). This design has proven to be very effective in terms of multipath protection and phase centre stability. It is the standard antenna used by the IGS
in their global GPS network, hence choke ring antennas were utilised at all fiducial network stations around Gunung Papandayan. In addition, antenna sites were carefully selected away from reflecting surfaces (as much as this was possible under the given circumstances) in order to further minimise the effects of multipath. Figure 2.16 depicts the construction of a wooden antenna platform at Galunggung with the help of a local carpenter. Note that these sites were only intended to be temporary, for demonstrating the ‘proof-of-concept’. In the case of an actual installation for volcano monitoring purposes, the sites would be installed in a manner appropriate for long-term operation of permanent reference stations.

Communication with the GPS receiver is established via a laptop computer, which can be used to download data files and check the status of the receiver while it is operating, but does not have to be continuously connected to the receiver. The Leica CRS1000 is equipped with 60MB of flash memory, so it can conveniently store data files (collected at a 15s data rate) for several weeks without the need for downloading. Eventually, however, the downloading process will be automated in order to make the GPS data available as quickly as possible to satisfy near real-time data processing.

Problems encountered during the first deployment of the fiducial network surrounding Gunung Papandayan were mainly concerned with the continuous supply of power. The battery chargers originally used proved to be unreliable and inadequate for recharging the
batteries fast enough after a power outage. As a result, the battery went flat on a number of occasions, causing the survey to be interrupted. In addition, one battery charger was damaged by a power surge.

At Kawah, one of the single-frequency GPS sites on the volcano, strong winds destroyed one solar panel by tearing the entire solar panel frame from its concrete mounts. Fortunately, the second solar panel survived and could be reinstalled to supply power after a new frame had been built. (The power system for the slave stations had been over-engineered, so the operation of just one solar panel is sufficient to supply continuous power, given that there are not too many sun-free days.)

Any metal surfaces, such as the metal drums originally housing the equipment and the barbed-wire fence at Kawah, were severely affected by the sulphur gas from the volcano’s crater. However, all aluminium and fibreglass components, as well as all surfaces covered with electrical isolation tape, proved resistant to corrosion from the acidic gases. Furthermore, caustic soda placed inside the drums proved to be an effective means of negating the sulphur gas attack on the equipment.

The antenna cable and GPS antenna at Nangklak were found to be faulty and had to be replaced. The 30m antenna cable at the base station was unknowingly cut by farmers despite being housed in PVC tubing and was repaired on-site. Many other minor problems, such as blown fuses and some baud rate incompatibilities, were also experienced during the February/March 2000 deployment.

The PC boards used in the GPS/PC modules at the slave stations proved to be problematic because the amount of available flash-PROM (Programmable Read-Only Memory) and RAM (Random Access Memory) decreased over time, causing the survey to stop (see Roberts, 2002). This was later rectified by obtaining new flash-PROMs and modifying the software used to operate the slave stations. However, many of the hardware faults in the GPS/PC modules can be attributed to the low-performance PC used and the DOS operating system (an operating system not designed for real-time applications). Efforts are underway to change the hardware of the GPS/PC modules to a micro-controller-based system for increased reliability.
Unfortunately due to the many hardware and software problems encountered at the time of deployment, an extensive, continuous data set with all seven stations of the mixed-mode GPS network operating simultaneously could not be collected. Data processing of the outer network revealed that the fiducial baselines were too long to generate reliable ‘corrections’ under severe ionospheric conditions, such as those experienced in the equatorial region during a solar maximum (see section 4.6.4). As a result, the ‘corrections’ could not be applied to the single-frequency data set collected on the volcano. Data processing of the single-frequency network proved to be extremely difficult due to the unstable nature of the ionosphere at the time of observation, resulting in a very high noise level of the GPS data logged (Janssen et al., 2001).

2.5.2 July 2001 Deployment

Following modifications to the hardware and software the system was redeployed in July 2001. Two new fiducial sites were chosen in Pangalengan and at the VSI observatory at Guntur, effectively reducing baseline lengths to form a 31km-53km-52km triangle around Gunung Papandayan (Fig. 2.14).

The faulty battery chargers were replaced with higher quality battery chargers designed to operate under conditions of fluctuating voltages and AC mains frequencies. An output current of 14A ensures fast recharging, even if power is drawn from the battery while the charging is in progress. In addition, a power surge protector was introduced to guard the battery charger against spikes and surges in the AC power. Figure 2.17 shows the setup at Guntur, where a stable fence post was modified with a screw thread embedded in additional concrete in order to mount the GPS antenna. In Pangalengan the antenna was installed on the roof of an elevated building, using a stable, wooden platform similar to the one shown in Figure 2.16.

At the single-frequency GPS sites on the volcano, the metal drums originally used to house the equipment had been corroded beyond recognition during the two years they had been left on site since the first installation of the single-frequency system on the volcano in 1999. They were replaced with robust plastic drums (see Fig. 2.11), which are
expected to resist sulphur gas attack while still being strong enough to protect the equipment from vandalism. Indeed, the slave station at Kawah was badly vandalised. A new solar panel frame was built in Australia and reinstalled. The radio antenna cable had been severed and needed to be repaired, and a new fence was erected.

![Fig. 2.17: Fiducial network: GPS antenna at Guntur (left) and GPS station equipment consisting of power surge protector, battery charger, battery and Leica CRS1000 GPS receiver (right)](image)

Problems encountered during field-testing were few compared to the first deployment of the mixed-mode system in 2000. At the fiducial site in Pameungpeuk peculiar AC power conditions were experienced. Although the same site had been successfully occupied in the previous year, it was impossible to operate the GPS receiver while the battery was connected to the battery charger (and subsequently to AC power) because the entire setup became ‘alive’. Attempts to negate the situation by ensuring sufficient isolation and earthing proved to be unsuccessful. In the end, a LAPAN observer was appointed to swap the used battery with a fully recharged one at the same time every day – a process that took no more than a couple of minutes, sacrificing only a few epochs of data. (The reader should be reminded that at this stage the UNSW-designed system was a ‘proof-of-concept’ system.)

Both the inner, single-frequency network and the fiducial, dual-frequency network operated well, and three weeks of continuous data were collected. Processing of the data
unfortunately did not show any improvements when the empirical ‘corrections’ were applied. A discussion of the results is given in section 5.5.

2.5.3 Data Processing Strategy

Depending on the type of movement expected in a deformation monitoring application, different data processing strategies can be used. If ‘slow’ deformation at a constant rate is expected (e.g. tectonic plate movement or ground subsidence), the data is usually processed in static sessions of a few hours to a few days in length, assuming no movement during the session. This is generally done in post-processing mode, as the deformation does not pose an imminent threat to surrounding structures or the population inhabiting the area. In this case parameters describing precise satellite orbits and polar motion, which are generally not available in real-time, can be used to improve the quality of the solution. This procedure is typically used for processing large scale, global networks in order to detect plate motions where a comparison of several campaigns is usually sufficient to derive the average rate of tectonic motion. However, if the deformational signal is expected to take place over a short period of time (‘sudden’ deformation, e.g. caused by earthquakes) and/or varies with time (‘fast’ continuous deformation, e.g. long suspension bridges), the sampling interval must be increased accordingly. This suggests the use of continuous GPS networks, using short static sessions, or epoch-by-epoch solutions (resembling a kinematic processing strategy). If the deformation can cause failure of the deforming body (e.g. a collapsing dam or bridge, or an erupting volcano), a (near) real-time, epoch-by-epoch solution is desired in order to detect the deformation as soon as it occurs, so as to initiate warning and evacuation procedures.

In the case of volcano monitoring the deformation is expected to be of a mixed nature. During periods of quiescence the deformation will be slow (or not present at all), while increased activity will cause ground movements of increasing magnitude due to magma intrusion in the hours to days prior to an eruption. Hence, a near real-time, epoch-by-epoch solution is preferred in order to detect movements on the flanks of a volcano over a relatively short period of time. This can be interpreted as a ‘slow kinematic’ approach, where a static receiver moves slowly but continuously due to ground surface movement. In contrast to a true RTK system where only coordinate positions are stored and analysed,
the raw GPS data is also being archived. Hence the raw data can be post-processed in longer observation sessions in order to detect long-term deformational signals and to periodically connect the sites to the ITRF through the IGS network. A fully automated system would then be able to ‘switch’ between epoch-by-epoch processing and hourly or daily solutions, depending on the nature of the deformation.

The baseline processing software developed at UNSW has been modified to enable epoch-by-epoch processing in multi-baseline mode. Routines to optimise the number of double-differenced observations used in the data processing (see chapter 3) and to implement the use of ionospheric ‘corrections’ (see chapter 4) have also been added.

### 2.5.4 Starting Coordinates

GPS stations designed for deformation monitoring must be referred to one (or more) fixed points that are assumed to be unaffected by the local ground displacement. The IGS network provides a global infrastructure of GPS coordinates in the ITRF with an accuracy at the sub-centimetre level, to which smaller networks can be connected (IGS, 2002b).

A regional GPS network used for deformation monitoring therefore needs accurate ‘starting’ coordinates. These can be obtained in a number of ways, listed in order of accuracy (Roberts, 2002):

1) Rigorously connect one or more or all of the monitoring stations to the IGS network in a global solution using long observation sessions and considering all geodetic effects,
2) rigorously connect one or more or all of the monitoring stations to a local part of the IGS network (i.e. 10 or less stations only) in a regional solution also using long observation sessions and considering all geodetic effects,
3) connect to the nearest IGS station and transfer the absolute coordinate to the reference station of the local network, or
4) compute a single point positioning solution of the base station of the local network independent of the IGS network.
The first three methods provide centimetre-level coordinates, while the last method should provide an absolute coordinate of approximately 5-10m accuracy. It should be noted that an absolute starting coordinate for a reference station in a deformation monitoring network at metre-level accuracy can still resolve centimetre-level relative coordinates between stations in the network. Nevertheless, it is desired to obtain absolute starting coordinates of the highest possible accuracy.

The absolute coordinate of a GPS reference station can be interpreted as a four-dimensional quantity, i.e. the position \((X,Y,Z)\) at a certain time epoch. As the entire surface of the earth is in constant motion, global velocity vectors can be applied to all stations in the network to account for any secular crustal effects. This is especially important if the network straddles a tectonic plate boundary.

The ‘starting’ coordinates of the mixed-mode GPS network at Gunung Papandayan are obtained according to method (3), in a two-step process. First, the fiducial network stations established in February/March 2000 were connected to the nearest IGS station at Bakosurtanal (BAKO), whose coordinates are known with an accuracy of approximately 1cm (IGS, 2002b). Secondly, the derived coordinates for the fiducial sites were held fixed and the base station coordinates for the inner single-frequency network were computed.

Three 24-hour sessions of dual-frequency data collected at the fiducial GPS stations were used to connect all three fiducial sites independently to the IGS station at Bakosurtanal. The Bernese software (Rothacher & Mervart, 1996) was used to compute coordinate values using precise ephemerides and conventional long static baseline processing procedures. Three coordinate sets were obtained for each fiducial site and the mean was then computed. In a second step, these fiducial coordinates were held fixed and three baselines using 24 hours of single-frequency data were processed to determine the coordinates of the base station at Gunung Papandayan. The resulting three coordinate sets showed differences of up to 1m, possibly due to the high ionospheric activity at the time (baselines of up to 60km observed on L1 only). Using the Bernese software, from these three coordinate sets a mean value was generated, which could be claimed to have an
accuracy of 1m or better. Table 2.1 lists the starting coordinates used for the single-frequency network on Gunung Papandayan.

Tab. 2.1: ITRF2000 starting coordinates for the single-frequency inner network on Gunung Papandayan

<table>
<thead>
<tr>
<th>Station</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>-1933614.0131</td>
<td>6025645.7317</td>
<td>-802279.9143</td>
</tr>
<tr>
<td>Bukit Maung</td>
<td>-1928406.6847</td>
<td>6027755.3781</td>
<td>-806707.8448</td>
</tr>
<tr>
<td>Nangklak</td>
<td>-1927104.2280</td>
<td>6028391.0919</td>
<td>-807450.2857</td>
</tr>
<tr>
<td>Kawah</td>
<td>-1927737.2506</td>
<td>6028054.2288</td>
<td>-806646.1924</td>
</tr>
</tbody>
</table>

In 2001 a slightly different approach was used to obtain starting coordinates for the fiducial network sites. The AUSPOS Online GPS Processing Service (Geoscience Australia, 2002) is provided free of charge by Geoscience Australia and is able to process GPS data collected anywhere on earth. GPS data submitted via the internet are processed by connecting the user site to the three nearest IGS sites, providing coordinates at the centimetre-level for 24-hour data files. For each of the fiducial network stations seven 24-hour data files were used to obtain coordinates. From these seven coordinate solutions, a mean value was generated. For the sake of completeness, Table 2.2 lists the coordinates of all fiducial stations occupied during the campaigns at Gunung Papandayan.

Note that the coordinates of the site occupied in successive years differ slightly because during reinstallation the antenna was not mounted in exactly the same position.

Data processing results and analyses using these coordinates are given in section 4.6.4 and chapter 5 of this thesis.

Tab. 2.2: ITRF2000 starting coordinates for the dual-frequency fiducial network at Gunung Papandayan

<table>
<thead>
<tr>
<th>Year</th>
<th>Station</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Bandung</td>
<td>-1915926.4768</td>
<td>6036457.8403</td>
<td>-759944.4172</td>
</tr>
<tr>
<td></td>
<td>Galunggung</td>
<td>-1967112.5935</td>
<td>6013829.5148</td>
<td>-804979.3261</td>
</tr>
</tbody>
</table>
### Table 2.1: Volcano Coordinates

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pameungpeuk</td>
<td>-1921225.3645</td>
<td>6022771.6076</td>
<td>-843402.2881</td>
</tr>
<tr>
<td>Guntur</td>
<td>-1941161.3710</td>
<td>6024021.5960</td>
<td>-794042.8210</td>
</tr>
<tr>
<td>Pameungpeuk</td>
<td>-1921225.4130</td>
<td>6022771.7460</td>
<td>-843402.3270</td>
</tr>
<tr>
<td>Pangalengan</td>
<td>-1911887.9510</td>
<td>6034118.5770</td>
<td>-793233.9550</td>
</tr>
</tbody>
</table>

Augmenting the single-frequency system with a fiducial network of three expensive, dual-frequency GPS receivers may seem to contradict the aim of a low-cost system, but this mixed-mode approach is proposed in order to generate centimetre-level coordinate accuracies under solar maximum conditions, as were experienced during the period this research was conducted. In addition, if the fiducial sites are appropriately chosen, it is possible to use one fiducial network to simultaneously generate ‘corrections’ for a number of different volcanoes within the triangle. This is particularly useful in the case of Indonesia, where a large number of volcanoes are located in a comparatively small area. For instance, one fiducial network could service L1 deformation monitoring networks on Gunung Papandayan, Gunung Guntur and Gunung Galunggung. Furthermore, with the ever-increasing number of continuous dual-frequency networks being established around the world, these could provide a convenient backbone for densification with single-frequency GPS receivers.

The ideal GPS volcano deformation monitoring system simultaneously satisfies the criteria of high accuracy, low-cost, continuous measurements with real-time data access and full automation. However, in practice the realisation of such a system is usually a compromise due to many factors (e.g. logistics, funding, accessibility, magnitude and frequency of expected movements, data handling, power supply and communications).