Chapter 6

SUMMARY AND CONCLUSIONS

6.1 Summary

Ground deformation of a volcano is considered a sure indicator of impending eruptive activity. GPS is ideally suited for detecting and monitoring such deformation. A network of continuously operating single-frequency GPS receivers located on a volcano can be a cost-effective option to assist hazard mitigation. However, due to the use of only one frequency, the ionospheric delay cannot be accounted for, resulting in degraded baseline accuracies. This is of concern particularly in the equatorial region during times of maximum solar activity, as the ionosphere is highly disturbed and variable (spatially and temporally). In order to detect ground displacements at the centimetre-level under these conditions, the effect of the ionosphere on the GPS signal has to be properly considered, even for short baselines of less than 10km in length.

In this thesis, a *mixed-mode* GPS network approach has been suggested, in order to enhance the existing continuous low-cost GPS-based volcano deformation monitoring system on Gunung Papandayan in West Java, Indonesia. A sparse fiducial network of geodetic-quality dual-frequency GPS receivers surrounding the deformation zone is used to generate empirical 'correction terms' that attempt to model the regional ionospheric conditions in the area. These corrections are then applied to the single-frequency data during baseline processing to improve the accuracy of the results. This approach offers considerable cost savings for deformation monitoring applications, which require a dense spatial coverage of GPS stations, and where it is not feasible to establish permanent GPS networks using expensive dual-frequency instrumentation.

Due to the close proximity of active volcanoes in Indonesia, such a fiducial network could be established to encompass more than one active volcano, and therefore provide 'correction terms' for several single-frequency volcano networks. For example, the Papandayan, Guntur and Galunggung volcanoes in West Java could be combined in such a way. Furthermore, the ever-increasing number of permanent dual-frequency GPS networks established around the world could provide such a fiducial network at virtually no extra cost.

The fiducial 'correction terms' are generated using a modified version of the Bernese GPS processing software. Algorithms were developed to integrate these corrections into the UNSW-developed baseline processing software used to process the inner single-frequency network, and to generate epoch-by-epoch solutions in multi-baseline mode. Special considerations for GPS receivers located on the flanks of the volcano, such as the obstruction of the sky caused by the volcano itself, were taken into account.

Although this thesis mainly focuses on volcano deformation monitoring, the methodology can be utilised for a variety of monitoring applications, such as for tectonic fault lines, landslides, land subsidence, open-cut mines, dams, bridges, high-rise buildings, etc.

6.1.1 Deployment of a Mixed-Mode GPS Network at Gunung Papandayan

The single-frequency GPS volcano deformation monitoring system on Gunung Papandayan in Indonesia was augmented with a fiducial network of dual-frequency receivers in order to model the ionospheric conditions across the area. During the deployment several hardware and software problems had to be overcome, a major issue being the continuous supply of power. The fiducial baseline lengths had to be adjusted in order to account for the severe ionospheric conditions present in close proximity to the geomagnetic equator during a solar maximum period.

6.1.2 Optimising the Number of Double-Differenced Observations

Commercially available GPS processing software packages are only capable of baseline-by-baseline processing, neglecting the correlations that arise when a network of GPS receivers is operated simultaneously. If the data are processed in multi-baseline mode, however, all baselines are processed together, enabling more precise deformation monitoring. In the case of volcano deformation monitoring the ground displacements are expected to be complex. In periods of quiescence the deformation will be slow or even negligible, while increased volcanic activity will cause movements of increasing rate due to the expansion of the subterranean magma chamber. Hence, a near real-time, epoch-by-epoch solution is preferred in order to detect movements of the flanks of a volcano as quickly as possible.

For a number of GPS deformation monitoring applications the deforming body itself blocks out part of the sky, thereby significantly reducing the number of satellites being tracked by the monitoring receivers. If the usual base station / base satellite approach is used in the multi-baseline data processing, only the satellites common to all network sites are used in the solution. This can result in a relatively low number of double-differenced observables, and the loss of valuable information. Considering the special conditions around a volcanic edifice, a method to optimise the number of double-differenced GPS observations by generating a set of independent double-differenced combinations was implemented. This method considers satellites visible by a small number of network stations only, making use of vector space methods and the geometric characterisations of Boolean matrices, based on the algorithm by Saalfeld (1999).

A numerical example using data collected in a 6-station test network in Sydney demonstrated that the proposed data processing strategy significantly improved GPS baseline results. The number of double-differenced observables available to compute a solution was maximised by using all available information, therefore enhancing the quality of the results. The number of double-differenced observables at each epoch was increased by an average of about 10, and a solution could be obtained even if less than four common satellites were received simultaneously at all network stations. The standard deviation of the root mean square could be reduced by 34%, implying an improved quality of the baseline components.

6.1.3 Investigation of the Empirically-Derived Correction Terms

A fiducial network of dual-frequency GPS receivers surrounding the deformation zone is used to generate 'correction terms' in order to model the regional ionosphere in the area. Han & Rizos (1996d) and Han (1997) have proposed a linear combination model, which can account for orbit bias and ionospheric delay, as well as mitigate tropospheric delay, multipath and measurement noise across the GPS network. Using this model, empirical corrections can be derived, and then applied to the double-differenced carrier phase data formed between the stations of the inner single-frequency network. The double-differenced 'correction terms' are generated using a modified version of the Bernese GPS processing software.

In order to investigate the nature of the empirically-derived corrections a range of data sets were processed. The GPS data analysed were collected over a variety of baseline lengths, at different geographical locations, and in different periods of sunspot activity (and therefore varying ionospheric conditions).

A large increase in ionospheric activity between the years 1997 and 2000 (the most recent solar maximum) was evident. The differences in the diurnal behaviour of the ionosphere in mid-latitudes and the equatorial region were obvious, and the ionosphere was identified as the main systematic error present in the double-differenced residuals. It was found that the standard deviation of the double-differenced 'correction terms' increases linearly with increasing baseline length, the rate of increase being much more severe under solar maximum conditions.

In periods of heightened solar activity the magnitude of the corrections for longer baselines in the mid-latitude region reached a few cycles, indicating that longer baselines may not be able to generate reliable 'correction terms' under these conditions. This is particularly of concern for GPS networks located in close proximity to the geomagnetic equator, as the effects of the ionospheric delay at GPS sites in the equatorial region are much larger compared to those at mid-latitude sites. It is therefore necessary to carefully choose the baseline lengths of the fiducial network in order to produce corrections that reliably model the condition of the ionosphere present in the area. However, the magnitude of these biases is not entirely a function of distance, hence it is difficult to predict what should be the ideal dimensions of the reference station network. This has to be investigated on a case-by-case basis.

6.1.4 Mixed-Mode GPS Network Processing

Increased ionospheric activity during a solar maximum period, especially in the equatorial region, precludes high-quality GPS deformation monitoring results using single-frequency instrumentation only. The addition of a sparse, external network of geodetic-grade dual-frequency receivers to create a mixed-mode GPS network can, in principle, provide empirical corrections in order to model the regional ionosphere.

In order to test the feasibility of the proposed methodology of processing a mixed-mode GPS network for deformation monitoring applications, data from several GPS networks were processed. These networks were located at different geomagnetic latitudes and the data were collected under solar maximum conditions.

The significant effect of the ionosphere on GPS baseline repeatability was evident in the data analyses. It was shown that the correction generation algorithm can successfully model the ionospheric delay (at least to some extent) if the fiducial baseline lengths are not 'too long'.

In the mid-latitude region, single-frequency baseline repeatability was clearly improved by applying the 'correction terms', which were generated by the fiducial dual-frequency network surrounding the deformation zone. The standard deviation of the GPS baseline results was reduced by almost 50% for the horizontal components and almost 40% for the height component. For single-epoch baseline solutions, standard deviations of less than 1cm horizontally and 1.5-3cm vertically were achieved.

Unfortunately these promising results could not be repeated for GPS networks situated in the equatorial region. Here, the empirical 'correction terms' were found to be very large (of the order of several cycles), even for comparatively short (17-24 km) fiducial baselines. This is indicative of severe ionospheric disturbances in close proximity to the geomagnetic equator during solar maximum periods. A data set collected in Hong Kong showed about 20% improvement in the standard deviation of all three components when corrections were applied. However, the standard deviation of the baseline components for single-epoch baseline solutions could not be reduced below the few-centimetre-level. Closer to the geomagnetic equator, at Gunung Papandayan, the single-frequency GPS baseline results could not be improved at all by applying the empirical corrections on an epoch-by-epoch basis, in spite of relatively short fiducial baselines of 31km and 53km in length.

It is concluded that the performance of the proposed processing strategy degrades with decreasing geomagnetic latitude. This is most likely due to extreme short-term variations in the ionosphere that cannot be modelled adequately during periods of maximum sunspot activity by just a few reference stations. Nevertheless, it has been shown that a mixed-mode GPS network can be a cost-effective tool for deformation monitoring if it is not subject to extreme ionospheric conditions, such as those experienced in close proximity to the geomagnetic equator during a solar maximum.

The optimal size of the fiducial network is dependent on whether the distance-dependent biases (mainly the ionospheric delay) can be realistically modelled with the proposed network configuration. This means that the size of the fiducial reference station network has to be carefully chosen, on a case-by-case basis, depending on the geographic location of the GPS receivers and the solar activity present in the area. While fiducial baseline lengths of several tens of kilometres are feasible for GPS deformation monitoring networks situated in the mid-latitude region, baselines have to be significantly shorter in the equatorial region in order to produce reliable ‘correction terms’ under solar maximum conditions. Obviously, the severity of the ionospheric effects on GPS baseline processing will be reduced with decreasing solar activity, which will reach its lowest level during the minimum period of the 11-year Solar Cycle.

The more complex ionospheric conditions present in close proximity to the geomagnetic equator require a more detailed model. For example, the interpolation of the ionospheric delay may have to be changed from the current linear process to a more complex interpolation procedure in order to account for intense small-scale disturbances. An increase in the number of reference stations might also appear to be of benefit in order to model the ionosphere in more detail. However, using data collected in the mid-latitude region, a study by Chen (2001) has found that baseline results did not improve by increasing the number of surrounding reference stations from three through to six. A reference station situated in the centre of the fiducial triangle could improve the modelling of the ionosphere. However, depending on the structure to be monitored, it may be very difficult to achieve this in practice because such a central reference station is required to be located outside the area of deformation. At Gunung Papandayan, an additional reference station could be installed next to the single-frequency base station at the foot of the volcano.

6.1.5 Real-Time Monitoring and Visualisation of Baseline Results

It was demonstrated how the baseline results obtained by the mixed-mode GPS-based deformation monitoring system can be used to detect ground displacements in real-time. The UNSW-developed Real-Time System Monitor (RTSM) software was utilised for this purpose. RTSM checks the quality of the GPS data and graphically presents the coordinate time series results, triggering an alarm whenever the detected deformation exceeds a pre-set limit.

As expected, significant deformation was not experienced in the data sets used in this study. The magnitude of the coordinate solution uncertainty at Gunung Papandayan precluded the detection of any small-scale deformation that might have occurred on the volcano. However, in appropriate circumstances, the continuous mixed-mode GPS network approach described in this thesis has the potential to detect ground deformation as it occurs, thereby contributing to hazard mitigation.

6.2 Suggestions and Recommendations for Future Research

The mixed-mode GPS network approach for deformation monitoring applications investigated in this thesis comprises an inner single-frequency network surrounded by an outer dual-frequency network, which is used to map the ionospheric conditions in the region and to generate corrections to account for these effects.

In this study the ionospheric ‘correction terms’ were generated in post-processing mode and applied to the single-frequency network in order to investigate the performance of the proposed data processing methodology. In the case of a long-term deployment of such a GPS-based deformation monitoring system, however, a near real-time solution is desired. Automatic baseline processing of the single-frequency network, with the addition of network-generated corrections, can be implemented. The GPS baseline results can then be automatically analysed in order to detect deformational signals and to present the results in an easy-to-understand manner, e.g. using the RTSM software. It is important to ensure that non-geodesists can understand and use this information for assessment of the hazards presented by a volcano (or any other deforming body that is being monitored) with minimum delay.

In order to move towards a 'true' real-time deformation monitoring system, the radio telemetry system used to transfer the GPS data from the slave stations to the base station can be improved. If the radios are set to an asynchronous mode and a unique address is assigned to each radio, data from all slave stations can be sent continuously and sorted by the base. This allows a larger number of slave stations in the network, because the radio polling methodology currently in use restricts the number of slaves on the deforming body. The ionospheric corrections should be transferred to the base facility in an RTK-like fashion to enable data processing without delay. Eventually this can result in an intelligent (volcano) deformation monitoring system that is able to switch between the processing of, say, hourly static sessions in quiescent periods and processing in RTK-mode if increased volcanic activity is observed.

The GPS/PC modules used for the single-frequency slave stations of the mixed-mode system on Gunung Papandayan use the DOS operating system. As DOS is not designed for real-time applications, the software must be carefully written to avoid problems with memory allocation. In order to remedy this disadvantage, subsequent versions of the GPS slave stations will utilise micro-controllers integrated with GPS OEM boards. This is expected to enhance reliability and to result in a more robust system.

A combination of GPS data with observations from GLONASS and Galileo satellites in the future can improve the volume of observations and the satellite geometry. Subsequently the reliability of the baseline results can be enhanced, especially for applications where the deforming body itself blocks out part of the sky. Obviously, the challenge lies in combining observations from different satellite systems and their respective 'correction terms' in order to generate one baseline solution. Pseudolites can also be used in this regard. However, for some applications it may be difficult to install them at stable locations above the monitoring receivers, as the pseudolite position needs to be free from displacements. Moreover, the distance of the pseudolite from the monitoring receivers has to be selected carefully in order to avoid in-band interference with the GPS signals.