Experiences with a Mixed-Mode GPS-Based Volcano Monitoring System at Mt. Papandayan, Indonesia

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ABSTRACT

During the past few years a methodology has been developed for processing data collected by GPS networks consisting of a mixed set of single-frequency and dual-frequency receivers. The strategy is to deploy a few permanent, 'fiducial' GPS stations with dual-frequency, geodetic-grade receivers surrounding an 'inner' network of low-cost, single-frequency GPS receivers. Such a configuration offers considerable flexibility and cost savings for geodynamic applications such as volcano deformation monitoring, which require a dense spatial coverage of GPS stations, and where it is not possible, nor appropriate, to establish permanent GPS networks using dual-frequency instrumentation.

This configuration has recently been tested at the Mt. Papandayan volcano in West Java, Indonesia. The two-stage network design consists of an inner network of four single-frequency Canadian Marconi (CM) GPS receivers surrounded by three dual-frequency Leica CRS1000 GPS receivers. The inner network logged and transmitted GPS data from the 'slave' stations located on the volcano, to a base station. The combined processing of the CM and Leica receiver data was performed offline so as to investigate the performance of such a mixed-mode system. The basis of the processing methodology is to separate the dual-frequency, 'fiducial' station data processing from the baseline processing involving the single-frequency receivers on the volcano. The data processing for the former was carried out using a modified version of the Bernese software, to generate a file of 'corrections' (analogous to Wide Area DGPS correction models for the distance dependent biases -- primarily due to atmospheric refraction). These 'corrections' will then be applied to the double-differenced phase observations from the inner receivers to improve the baseline accuracies (primarily through empirical modelling of the residual atmospheric biases that otherwise would be neglected). A description of the field testing (and its challenges) during February-March 2000, together with a discussion of the results are presented.

1 INTRODUCTION

The aim of this project is to demonstrate that a continuous low-cost GPS monitoring system is an appropriate method for ground deformation monitoring to aid volcano hazard mitigation. The objective is to provide centimetre accuracy, three-dimensional coordinates of stationary points. Re-measuring these same points on a continuous basis (up to many times a day) will produce a time series of coordinates which can be further analysed in order to extract possible deformational signals of the volcano. The system design requirements dictate the use of low-cost components so that a station setup will cost less than US$3000 (including monuments).

A single-frequency, carrier phase-tracking system is appropriate for small-scale continuous GPS networks if the baseline lengths are not longer than 10 kilometres. This ‘rule-of-thumb’ implies that the differential ionospheric and tropospheric delays between the two receivers is essentially zero, and therefore does not impact on the baseline result. Orbit bias over such short distances can also be ignored (Rizos, 1997). Presently, however, with the onset of a solar maximum, ionospheric disturbances have indeed corrupted baseline measurements over distances less than 10km on Mt. Papandayan, adversely affecting baseline *repeatability.*

In order to ensure cm-level accuracy for baseline lengths (particularly those exceeding 10km), the single-frequency network has been augmented by the addition of an outer ‘fiducial’ network of high-quality GPS receivers. This dual-frequency network surrounding the deformation zone of the volcano is used to generate 'correction terms' in order to improve the accuracy of the single-frequency baselines.

This paper describes the design of the inner and fiducial networks, and the ionospheric correction model proposed for this mixed-mode system. The problems encountered with its installation on Mt. Papandayan (Fig 1.1) and the extraordinary effects of the ionosphere on baseline repeatability and the 'correction terms' experienced during this period will be discussed.

Fig. 1.1: Mt. Papandayan volcano in West Java, Indonesia

2 INNER NETWORK DESIGN AND EQUIPMENT

The University of New South Wales (UNSW) has coordinated the design and assembly of the deformation monitoring system. Rizos et al. (2000) describes the four-station inner network of low-cost, single-frequency GPS receivers. The network array consists of one base station situated at the Papandayan observatory and three ‘slave’ stations located approximately 8km away in the zone of deformation around the crater of the volcano. Each station comprises five components: (1) GPS/PC module, (2) radio modem sub-system, (3) monument, (4) GPS antenna, and (5) power supply.

Custom-built GPS/PC modules integrate a single-frequency, Canadian Marconi GPS board with an 8086 PC board which controls data decoding, file management and communications. GPS data are logged hourly at all stations whereafter the base station sequentially polls the three slave stations and downloads their binary data files via a VHF radio link. This data are then automatically converted to RINEX format and stored on a hard disk at the base station. Therefore 24 one-hour files are stored daily for each station.

Berntsen 3D monuments 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 (VSI) was sought to locate the stations in order to most likely detect any deformations of the volcano. A 1.5m fibreglass pole is used to mount a MicroPulse L1 lightweight survey GPS antenna at all stations.

The slave stations are powered by 12 VDC lead acid batteries charged continuously by solar panels. The base station is powered by AC power backed up by an uninterrupted power supply (UPS) to guard against spikes, surges or blackouts. The UPS has been additionally modified with larger backup batteries and an extra battery charger to provide continuous operation during extended blackouts (not uncommon in rural Indonesia). Figure 2.1 shows the main components of the slave station equipment: GPS/PC module, radio modem, single-frequency antenna and cables.

All systems and communications software to operate this inner network was developed at UNSW to achieve maximum flexibility. All baselines presented in this paper have been post-processed using the UNSW Baseline software.

Fig. 2.1: Single-frequency GPS station equipment

3 FIDUCIAL NETWORK DESIGN AND EQUIPMENT

A fiducial network of three dual-frequency GPS receivers surrounding the deformation zone of the volcano is used to generate empirical 'correction terms' (e.g. Rizos et al., 1998; Rizos et al., 1999). These double-differenced corrections are then applied to the data from the single-frequency baselines in the inner network on the volcano to account for residual atmospheric biases.

As described in Han (1997), the fiducial network should ideally surround the inner single-frequency network leaving it in the centre of the triangle. Figure 3.1 shows the ideal network configuration where the triangles denote fiducial stations while the dots indicate single-frequency sites.

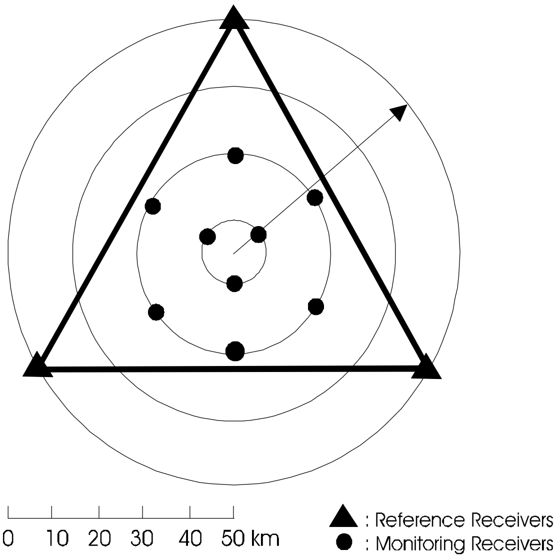

Fig. 3.1: Ideal network configuration

However, this ideal configuration could not be achieved due to the need for continuous AC power and secure locations for the stations in a rather remote part of West Java, Indonesia. The fiducial network comprises three GPS stations located in Bandung, Galunggung and Pameungpeuk, forming a 72km-60km-85km triangle enclosing the deformation zone of the volcano. This configuration leaves the inner network close to the baseline Bandung-Pameungpeuk, but still well inside the triangle (Figure 3.2). The equipment used includes Leica CRS1000 dual-frequency receivers equipped with choke ring antennas, a 120 Ah battery and a battery charger (Fig. 3.3 and 3.4). The battery charger and battery were used to guard against power outages.

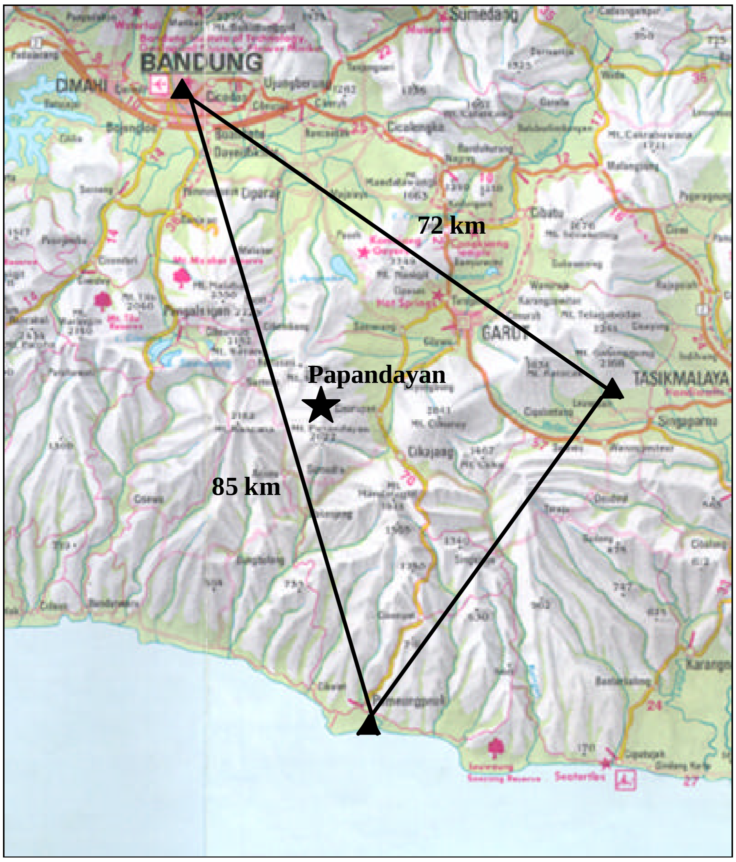

Fig. 3.2: Actual network around the Mt. Papandayan volcano

Fig. 3.3: GPS antenna in Bandung

Fig. 3.4: Fiducial GPS station equipment

4 USING THE FIDUCIAL NETWORK TO MITIGATE IONOSPHERIC EFFECTS

The ionosphere is that part of the Earth's atmosphere located in the height range of 50km – 1000km above the surface and has a major effect on GPS signals travelling from the satellite to the receiver.

The ionosphere is most active in a band extending up to approximately 20° on either side of the magnetic equator. This is also one of the two regions where small-scale ionospheric disturbances (scintillations) mainly occur, the other being the high-latitude region close to the poles. Scintillations are short-term signal variations in amplitude and phase. In the equatorial region scintillations occur between approximately one hour after sunset until midnight (Klobuchar, 1996) and should have disappeared by 3am local time (IPS Radio & Space Services, 2000). The occurrence of scintillations also varies with the seasons. Between April and August they are less severe in the American, African and Indian longitude regions, but are at a maximum in the Pacific region, while the situation is reversed from September to March (Seeber, 1993). In mid-latitudes scintillations are rarely experienced, but Medium-Scale Travelling Ionospheric Disturbances (MSTIDs) occur frequently, mainly during daytime in the winter months, during periods of high solar activity, with a maximum around local noon (Wanninger, 1999).

While dual-frequency receivers can account for the ionospheric delay effect directly by the appropriate linear combination of measurements from both frequencies, single-frequency receivers cannot. Around the Mt. Papandayan volcano, a fiducial network of three dual-frequency receivers surrounding the deformation zone is used to generate 'correction terms', which can then be applied to the single-frequency observations to try to account for these effects.

A linear combination model has been proposed by Han & Rizos (1996) and Han (1997), which can account for orbit bias and ionospheric delay, as well as mitigate tropospheric delay, multipath and measurement noise across the network. Data from the fiducial GPS reference station network can be used to derive empirical corrections to the double-differenced carrier phase data formed between the stations of the inner network. The procedure is described in Chen et al. (1999) and summarised below.

The double-differenced observable can be written as:

$$\nabla\Delta f = \nabla\Delta r + \nabla\Delta dr + l \cdot \nabla\Delta N - \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta d^{j}_{mp} + e_{\nabla\Delta f} \tag{1}$$

where $\nabla\Delta$ = double-difference operator
ϕ = carrier phase observation in units of metres
ρ = vector between receiver station and satellite
d = effect of ephemeris errors
λ = wavelength of the carrier phase
N = integer ambiguity for a particular satellite-receiver pair
d_{ion}, d_{trop}, d^{φ}_{mp} = ionospheric delay, tropospheric delay, multipath effect
$\varepsilon_{\nabla\Delta\phi}$ = carrier phase observation noise for a particular one-way observation

Assuming the number of GPS reference stations is three, the above equation can also be written in the form of a linear combination (Han, 1997):

$$\nabla\Delta f_{u,3} - \left[a_1 \cdot V_{1,3} + a_2 \cdot V_{2,3}\right] = \nabla\Delta r_{u,3} + l \cdot \nabla\Delta N_{u,3} + e_{\sum_{i=1}^{3} a_i \cdot \nabla\Delta f_i} \tag{2}$$

The parameters α_I can be determined based on the conditions given in Han & Rizos (1996) and Wu (1994):

$$\sum_{i=1}^{3} a_i = 1, \ \sum_{i=1}^{3} a_i \cdot \left(\vec{X}^s - \vec{X}_i\right) = 0 \text{ and } \sum_{i=1}^{3} a_i^2 = \min \tag{3}$$

where X^s = satellite position vector and X_i = receiver station position vector.

The residual vectors are formed from the double-differenced observations between reference stations 1 & 3 and 2 & 3:

$$V_{1,3} = \nabla\Delta f_{1,3} - \nabla\Delta N_{1,3} - \nabla\Delta r_{1,3}$$
$$V_{2,3} = \nabla\Delta f_{2,3} - \nabla\Delta N_{2,3} - \nabla\Delta r_{2,3} \qquad (4)\ \&\ (5)$$

The correction term $\left[a_1 \cdot V_{1,3} + a_2 \cdot V_{2,3}\right]$ can now be determined, and the linear combination between two stations j and k of the inner network (base and slave station on the volcano) can be written as:

$$\nabla\Delta f_{k,j} - \left[a_1^{k,j} \cdot V_{1,3} + a_2^{k,j} \cdot V_{2,3}\right] = \nabla\Delta r_{k,j} + l \cdot \nabla\Delta N_{k,j} + e_{k,j} \qquad (6)$$

where $\alpha_i^{k,j}$ = difference in the α_i value for stations k and j.

By forming the double-difference between the inner single-frequency stations, and using the residual vectors from the fiducial reference stations, the inner stations' coordinates can be determined without the need to use any GPS reference station observations.

At Mt. Papandayan, holding one fiducial site (Bandung) fixed, the baselines to the other two sites are processed and correction terms are obtained for both baselines. These are then weighted according to the position of the inner stations inside the triangle to generate double-differenced corrections for the inner baselines between the base and slave stations on the volcano.

5 PROBLEMS ENCOUNTERED DURING FIELD TESTING

During field testing in February-March 2000 many problems had to be overcome. At the single-frequency GPS sites on the volcano, corrosion due to sulphur gas had severely rusted some of the metal drums containing the equipment during the seven months the equipment had been left on site (Fig. 5.1). Strong winds destroyed one solar panel although it was anchored to the ground with concrete. All aluminium and fibreglass components, as well as all surfaces covered with electrical isolation tape, proved resistant to corrosion from the acidic gases. Caustic soda placed inside the drums proved to be an effective method to negate sulphur gas attack on the equipment.

The uninterrupted power supply (UPS) unit and battery charger at the base station were modified to guarantee continuous, spike-free power. At the fiducial stations several power outages resulted in data loss due to defect/unreliable battery chargers. As AC power outages are not uncommon in Indonesia, care has to be taken to guard against these conditions, so as to ensure a continuous data set. The PC-based system at the slave stations proved to be unreliable because the amount of available flash PROM (Programmable Read-Only Memory) and RAM (Random Access Memory) decreased over time causing the survey to stop. In future a micro-controller-based system will be used instead. One GPS antenna, two antenna cables, one radio and many fuses needed to be replaced.

Regarding software, initial problems with the in-house baseline software written at UNSW had to be solved. The correct decoding of binary CM data into RINEX format had to be carried out. A lack of navigation data from broadcast ephemerides was sometimes experienced. This problem is being addressed. In general, it was difficult to process the single-frequency data collected in the equatorial region during a solar maximum due to an extremely high noise level.

Fig. 5.1: Heavily corroded metal drum at the GPS slave station Kawah

6 PRELIMINARY L1-ONLY BASELINES ON MT. PAPANDAYAN

Time series results of uncorrected data from the inner network are presented below from July 1999 (an earlier campaign) and March 2000. The data were post-processed using the UNSW in-house baseline processing software. A double-differencing strategy was used and the standard Saastamoinen model was used for tropospheric modelling. Given the length of the baselines (maximum about 8km), broadcast ephemerides were considered sufficiently accurate for baseline processing (Rizos, 1997). (Several baselines were computed using both broadcast and precise ephemerides with no appreciable difference in baseline accuracy confirming Ibid, 1997.) No ionospheric modelling was attempted due to the relatively short baseline lengths.

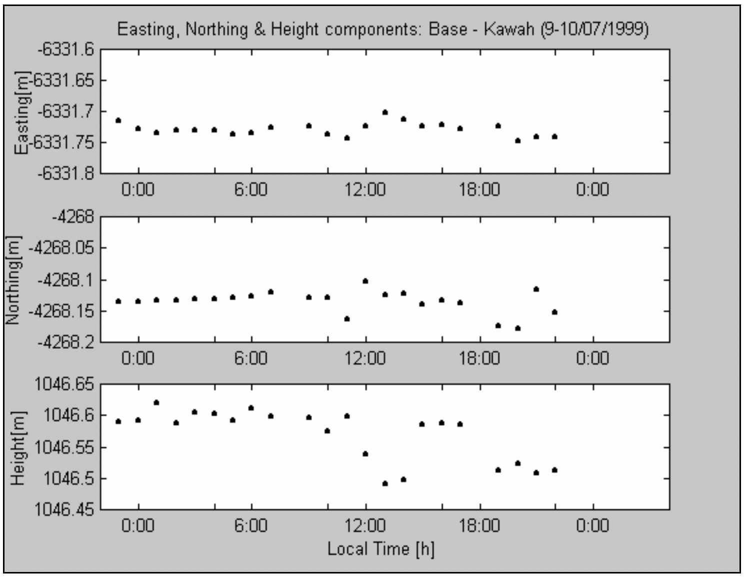

Fig. 6.1: L1 baseline solutions Base – Kawah (July 1999)

Looking at the data collected in July 1999 (Fig. 6.1), the easting and northing components show a scatter of around 1.4cm and 3.7cm with corresponding standard deviations of 1.1cm and 1.8cm respectively. For the height component the scatter is around 6.0cm with a standard deviation of 3.9cm.

Figure 6.2 shows the baseline results from the data collected in March 2000. The easting and northing components show a scatter of around 2.2cm and 6.8cm with corresponding standard deviations of 1.3cm and 3.9cm respectively. For the height component the scatter is around 6.5cm with a standard deviation of 3.5cm. These computations assume that there is no movement of the ground surface, and from this small data set certainly no conclusions can (or should) be drawn. Also note that there appears to be more data gaps in the March 2000 data. In fact data *were* measured during these periods, however, the results were so noisy that it was impossible to derive a meaningful baseline result. It is unclear why this occurred but given that exactly the same hardware and software was used for both data sets, the authors believe that the increasing activity of the ionosphere due to the on-coming solar maximum is the main contributor to this extra noise.

Also note that data gaps appear in a somewhat diurnal manner for the March 2000 data, with data gaps occurring around sunset and continuing until the early hours of the next morning. Seeber (1993) states that ionospheric scintillation effects are most prominent at these times, and particularly around March for Indonesia. This could explain the poor data quality. Additionally, Campos et al. (1989) experienced similar problems with the ionosphere during the previous solar maximum. They report relative errors of up to 30ppm for a 12km baseline using L1-only data at a latitude of 8°; conditions very similar to those encountered by the authors. Section 7.3 of this paper discusses the large 'correction terms' obtained when using the ionospheric correction model proposed by the authors. The unstable nature of the ionosphere at this time, and hence the high noise level of the GPS data logged, hindered the data processing.

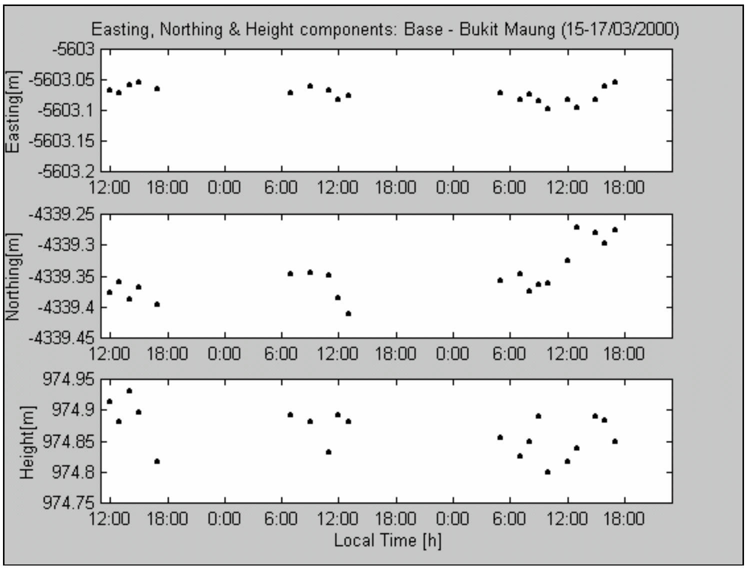

Fig. 6.2: L1 baseline solutions Base – Bukit Maung (March 2000)

Unfortunately due to the many hardware, software and environmental problems encountered at the time of deployment and observation, a longer and more continuous data set could not be collected and tested. Many of the hardware faults in the GPS/PC modules can be attributed to the low-performance PC used and its restriction to the DOS operating system (an operating system not designed for real-time applications). UNSW is currently investigating changing the hardware of the GPS/PC modules to a micro-controller-based system for increased reliability.

7 ANALYSIS OF IONOSPHERIC CORRECTIONS

7.1 Analysis of field data collected at mid-latitudes

In order to appreciate what to expect when using the double-differenced 'correction terms', two data sets collected in the mid-latitude region were analysed. Data for different baseline lengths was collected in Japan on 2 January 1997 and 7 March 2000. While the solar activity was rather low in January 1997, it was approaching a maximum during March 2000.

In order to investigate the ionospheric effect on baselines of different lengths, under different solar activity conditions, seven baselines with distances ranging from 26km to 101km were studied. The GPS stations belong to the Hokkaido network, which is part of Japan's GEONET network, and are equipped with dual-frequency receivers. The data were processed with a modified version of the Bernese software package to generate the empirical corrections. In order to draw conclusions relevant to the volcano application, the following analysis is only concerned with L1 correction terms.

Figure 7.1 shows the standard deviation of the double-differenced 'correction terms' for different baseline lengths in January 1997 and March 2000. The effect of the increased ionospheric activity due to the solar maximum period in the year 2000 is obvious. It can be seen that the standard deviation increases linearly with increasing baseline length. Under solar maximum conditions this trend is much more severe.

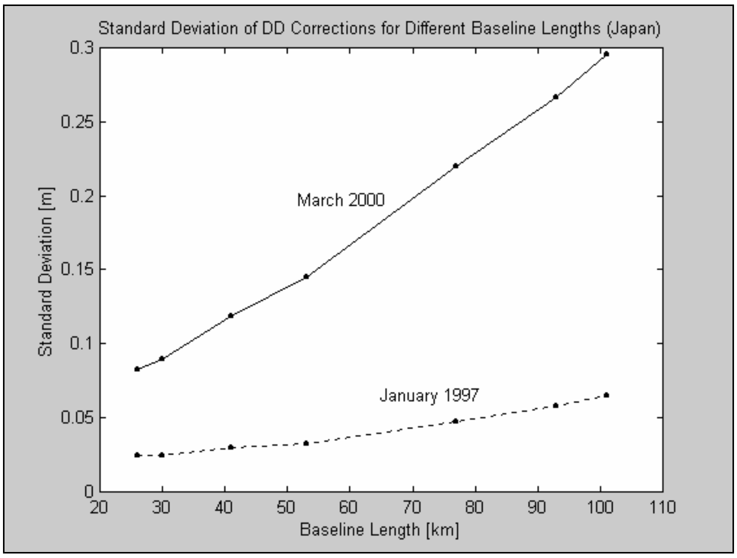

Fig. 7.1: Standard deviation of double-differenced correction terms for different baseline lengths under low and high solar activity conditions

Figure 7.2 shows the minimum and maximum correction values obtained for different baseline lengths. It can be seen that the magnitude of the 'correction terms' for longer baselines increases rather rapidly during solar maximum conditions. However, the magnitudes of these biases are not like a function of distance, hence it is difficult to predict what should be the dimensions of the reference station network that would faithfully model the distance-dependent biases. Clearly more tests are needed to investigate the behaviour of the biases before making recommendations concerning the reference station spacing.

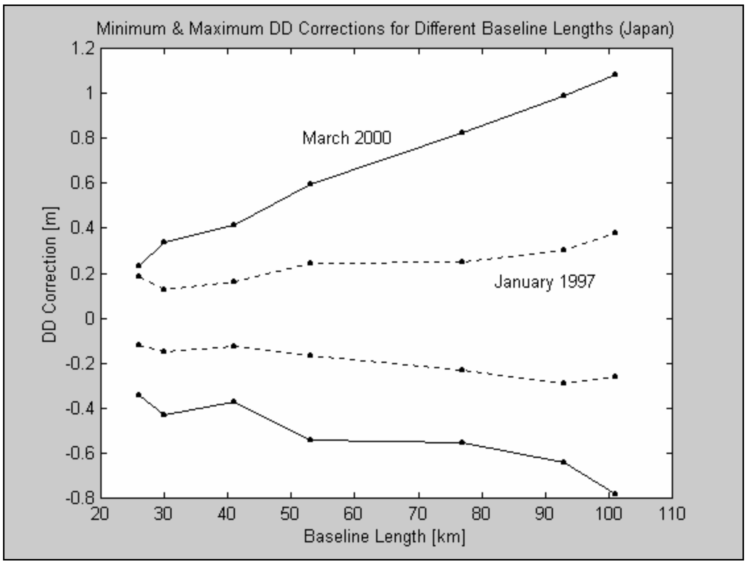

Fig. 7.2: Minimum and maximum double-differenced correction terms obtained for different baseline lengths

Figure 7.3 shows the double-differenced corrections for a 77km baseline over 24 hours in January 1997 and then again in March 2000. While the ionosphere remains very calm, and doesn't show much change during the 24-hour observation period in 1997, the effect of the increased ionospheric activity due to a solar maximum in the year 2000 is clearly seen. Here, the diurnal variability of the ionosphere in mid-latitudes can easily be recognised. As expected, the ionosphere is most active during daylight hours between 8am and 6pm local time, and calms down over night. Between the years 1997 and 2000 the standard deviation increased by a factor of 4.6. The magnitude of the 'correction terms' only ranges from –0.232m to 0.248m in 1997, while they vary from -0.555m to 0.824m in 2000.

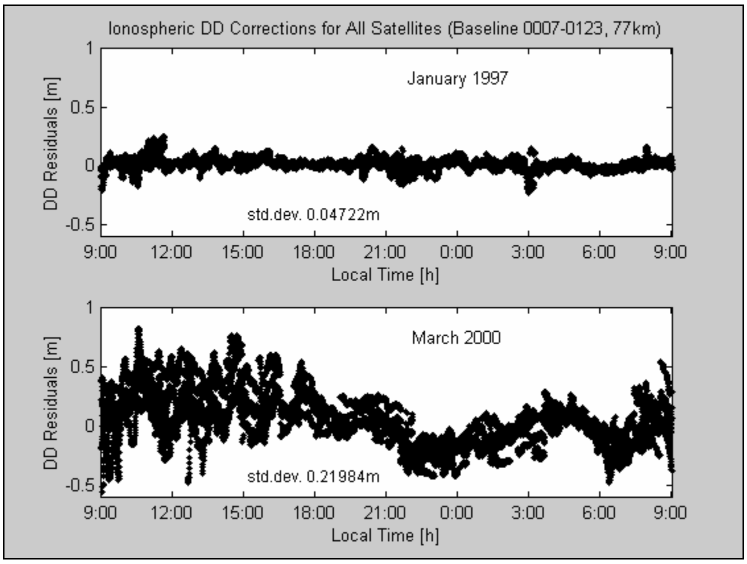

Fig. 7.3: Double-differenced corrections for a 77km baseline over 24 hours under different solar activity conditions

7.2 Analysis of field data collected in different geographical regions

The effect of the ionospheric layer on a certain baseline length as a function of geographical location was also investigated. The magnitudes of the double-differenced 'correction terms' for a 30km baseline located in mid-latitudes (Japan) and in the equatorial region (Singapore) were compared. The data were collected under solar maximum conditions on 7 March 2000, and the results are shown in Figure 7.4. The more severe ionospheric delay effects in the equatorial region are obvious. In Singapore the magnitude of the minimum and maximum corrections are –0.610m and 0.681m, respectively, with a standard deviation of 0.170m, while in Japan the values only range from –0.146m to 0.126m with a standard deviation of 0.089m. The standard deviation has doubled while the maximum/minimum values have increased by a factor of 4. In addition, it can be seen that the ionospheric effect is mainly a daytime phenomenon in mid-latitudes. However, the graph shows that there is also a lot of ionospheric activity between local noon and sunset in Singapore. This is contrary to the expectation that most of the ionospheric activity occurs between sunset and midnight in equatorial regions. This might be due to intensified small-scale disturbances in the ionosphere during a period of increased solar activity.

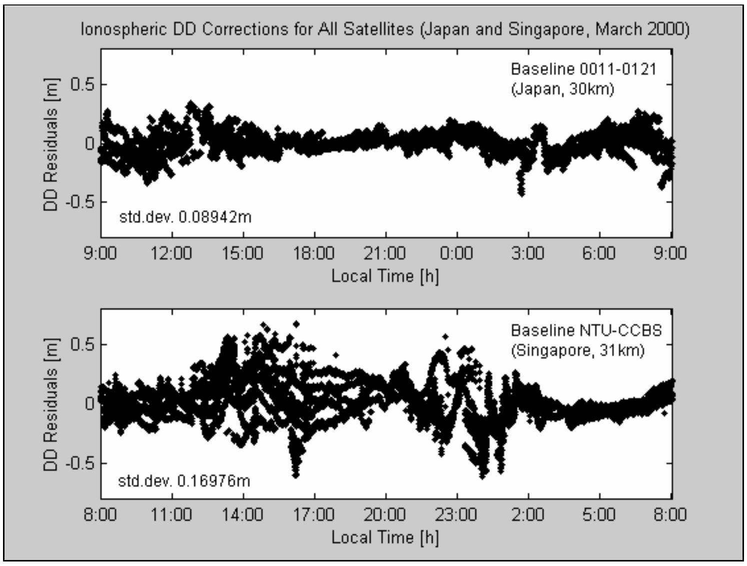

Fig. 7.4: Double-differenced corrections for a 30km baseline over 24 hours in different geographical regions (mid-latitude region and equatorial region)

7.3 Analysis of field data collected at the Mt. Papandayan volcano

The ionospheric activity at the Mt. Papandayan volcano is expected to be higher than in Japan. While the Japanese test network is located in the mid-latitude region, Mt. Papandayan is very close to the magnetic equator. Here, the most severe ionospheric effects are scintillations, which are generally present between approximately one hour after local sunset to midnight. Figure 7.5 shows the double-differenced 'correction terms' generated by the three fiducial baselines BAND-PAME (85km), BAND-GALU (72km) and GALU-PAME (60km) over 24 hours on 7 March 2000. It can be seen that the 'correction terms' for the two baselines BAND-PAME and BAND-GALU, which are supposed to generate the corrections to be used in the data processing, are very large. In fact, they appear to be too large to be representative of the network area. The magnitude of the 'correction terms' range from –5.556m to 4.597m (BAND-PAME) and from –2.976m to 2.830m (BAND-GALU), with standard deviations of 1.025m and 0.719m respectively. The 'correction terms' for the third baseline range from -1.563m to 1.504m with a standard deviation of 0.377m, giving slightly more realistic values. This confirms the fact that the reliable generation of 'correction terms' require shorter baselines of the reference station network. However, it is not possible to predict a priori what the optimal (ie largest) spacing is. Unfortunately, an empirical process for testing reference station geometry will be necessary, on a case-by-case basis. It can be seen that the maximum ionospheric effects are present between local sunset and midnight, which is as expected. However, there is also a lot of activity between 3pm and sunset. As mentioned before, this could be explained by intensified disturbances in the ionosphere caused by increased solar sunspot activity.

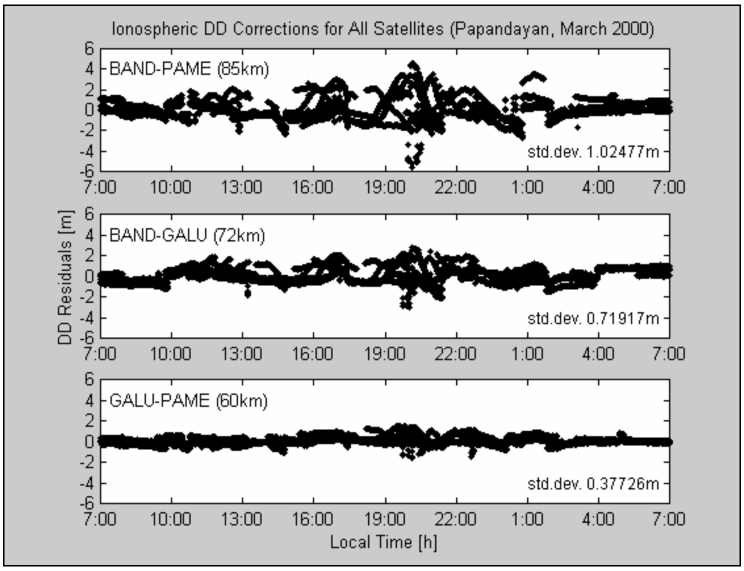

Fig. 7.5: Double-differenced corrections for the fiducial baselines at Mt. Papandayan, Indonesia over 24 hours in March 2000.

8 CONCLUDING REMARKS

The design of a mixed-mode GPS volcano monitoring system on Mt. Papandayan in West Java, Indonesia has been described. Field testing revealed severe effects of the ionosphere on single-frequency baseline repeatability and on the 'correction terms' intended to mitigate the ionospheric effects.

The variability of the single-frequency baselines measured in July 1999 and March 2000 has highlighted the extreme nature of ionospheric disturbances in equatorial regions during a solar maximum. The data quality from July 1999 was clearly higher than from March 2000. Given the short length of the baselines, no ionospheric modelling was used for the post-processing of the L1 data, however, the extreme data noise in March 2000 precluded the processing of some baselines. These data gaps appear to display a diurnal pattern, which could be explained by an anticipated higher probability of phase scintillations, or simply due to a higher Total Electron Content value, compared to the July 1999 data. The unusually large ionospheric corrections determined using the correction generation algorithm proposed in this paper lends weight to the claim that the ionosphere is the cause of this noise.

A range of data sets were processed in order to investigate the nature of the empirically derived double-differenced 'correction terms' generated to improve the accuracy of the single-frequency network on the volcano. The GPS data were analysed at a variety of baseline lengths, in different geographical locations and at different periods of sunspot activity (and hence ionospheric conditions). The following conclusions can be drawn:

- The standard deviation of the double-differenced 'correction terms' increases linearly with increasing baseline length.
- A large increase in solar activity is evident between the 1997 and 2000 data sets.

- During solar maximum conditions the magnitude of the 'correction terms' for longer baselines in the mid-latitudes reaches a few cycles. This indicates that longer baselines might not be able to generate reliable corrections under these conditions.
- Increased ionospheric activity during the daytime in mid-latitudes and after sunset in the equatorial region is evident. As expected, the ionospheric effects for sites at the equator are much larger compared to mid-latitude sites.
- The distances between the fiducial stations around the Mt. Papandayan volcano should be reduced to those which can demonstrate the ability to generate reliable corrections during solar maximum conditions, as being currently experienced in 2000-2001.

If the fiducial sites are appropriately chosen, it is possible to use one fiducial network to generate corrections for a number of different volcanoes within the triangle. Hence, the cost of this mixed-mode volcano deformation monitoring system can further be reduced. However, if the fiducial triangle is too large, reliable corrections cannot be obtained.

Future generations of this volcano monitoring system will utilise a micro-controller-based system which is better suited to real-time applications. It is hoped that with an appropriately designed fiducial network surrounding the inner single-frequency network it can be demonstrated that the ionospheric correction terms can indeed enhance baseline accuracy even during times of high ionospheric activity. Additionally the second author is investigating the effects of differential troposphere on height repeatability in equatorial regions.

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