MITIGATING DIFFERENTIAL TROPOSPHERE EFFECTS FOR GPS-BASED VOLCANO MONITORING

Craig Roberts and **Chris Rizos**
Satellite Navigation & Positioning Group
School of Geomatic Engineering
The University of New South Wales
Sydney NSW 2052, AUSTRALIA

BIOGRAPHY

Craig Roberts graduated with a B.Surv. (SAIT) in 1988. He has worked as a private surveyor, a geodetic engineer with UNAVCO in Colorado, USA, and as an orbit specialist with the GeoForschungsZentrum, Germany. He is currently a Ph.D. student at the School of Geomatic Engineering, The University of New South Wales (UNSW), with an interest in developing and testing permanent GPS systems for volcano deformation monitoring.

Chris Rizos holds a B.Surv. and Ph.D., both obtained from UNSW. He has been an academic staff member of the School of Surveying (renamed the School of Geomatic Engineering in 1994) since 1987 and was promoted to Professor in 2000. Chris is leader of the Satellite Navigation and Positioning (SNAP) group which specialises in addressing precise static and kinematic applications of GPS. He has published over 100 papers, as well as having authored and co-authored several books relating to GPS and positioning technologies.

ABSTRACT

The UNSW-designed GPS volcano monitoring system installed on Gunung Papandayan seeks to characterise the ground deformation within the volcanic edifice. Hourly baseline solutions produce a time series of data designed to detect any ground motion. Differential tropospheric effects between GPS receivers separated by a large change in height (in this case up to 1400m) impact on the quality of this time series data, particularly in the case of the vertical component. This increased variability constrains reliable ground deformation detection to the decimetre level. The Saastamoinen troposphere model is recommended as the most suitable to account for the hydrostatic (dry) part and non-hydrostatic (wet) part of the delay. A time series of data from the SAGE (New Zealand) network is processed using Saastamoinen modelling for varying session lengths. This time series is re-processed using the Saastamoinen model as an a-priori model and estimating one additional residual relative zenith delay parameter per session during the baseline computation. GPS baseline processing is more of a challenge in this case due to the short session length and reduced number of observations from a single-frequency GPS system. In comparison to the modelling approach, the parameter estimation technique is not affected by changes in local weather (which manifest as short-term trends in the height component) and demonstrates a lower standard deviation. In addition, the processing is more reliable. Power spectral analysis of these time series also reveal a daily multipath signal in the case of the parameter estimation approach, which is not evident from the time series derived by tropospheric modelling only.

1. INTRODUCTION

The UNSW designed GPS based volcano monitoring system has undergone limited testing to investigate its reliability at Gunung Papandayan in west Java, Indonesia. It is an L1-only system, limiting its application to deforming regions with baselines no longer than approximately 10km. Over such distances the effects of the ionosphere can be largely ignored, and it would be expected that baseline accuracy at the centimetre level could be achieved. The aim of such a system is to provide reliable time series data of the three baseline components (E, N, H) to a known level of accuracy and precision in order that any measure outside these known bounds can be unambiguously identified as some form of deformation.

Tropospheric delay on the GPS signals is identified as a significant error source in regional volcanic environments by virtue of the large change in height between a stable base station receiver and monitoring receiver(s) situated in the zone of deformation. Gurtner et al. (1989) state that tropospheric modelling is only valid for a flat earth. A large height difference for the baseline points can introduce a bias of the order of 2–5mm per 100m height difference. This atmosphere-induced error in the vertical component far exceeds the inherent geometric weakness of GPS (Yunck, 1993). The assumption that tropospheric effects for short baselines can be ignored is no longer valid in such cases. This is due mainly to daily variations of temperature and humidity causing the tropospheric effects derived from standard models such as the Saastamoinen, Hopfield, Black, etc., to be in error, particularly with regard to the heights of points (Rührnöβl et al., 1998). The high and variable water content present in equatorial and tropical regions exaggerates this effect further (Mendes, 1999).

For a volcano monitoring application this is problematic as the most likely signal indicating some pending activity occurs in the vertical component. The aim of this research is to reduce the *variability* in the height component for regional equatorial, low-cost continuous GPS volcano monitoring systems, thereby increasing the accuracy and reliability of the forecasting of pending volcanic activity.

Time series data from the Southern Alpine Geodetic Network (SAGE) in New Zealand indicates a variation of up to 20cm in the height component even after tropospheric modelling (Figure 1). This is clearly not due to the stations moving due to some geological deformation. Despite standard troposphere models using global atmospheric constants, which may not be relevant to the local environment, the introduction of local meteorological measures does not enhance the height repeatabilities. Estimating a residual relative zenith delay parameter provides a more reliable height estimate and an improved scatter (standard deviation) in the results. The data set is processed four times using different observation session lengths and compares standard tropospheric modelling to the troposphere parameter estimation technique. Power spectral density plots help to characterise any signals present in the resultant time series data.

2. BACKGROUND – how good are the models anyway?

Tropospheric delay models are based on a model of a 'standard atmosphere', comprising global measures of temperature lapse rates, tropopause heights, refractive index and inversion heights, all empirically derived from radiosonde soundings of the atmosphere (which are themselves corrupted by systematic biases and random errors). Global constants within some models take no account of latitudinal and seasonal variations of parameters in the atmosphere. *Surely local measures of temperature, pressure and relative humidity would better model local conditions?*

This assertion was tested on six small-scale networks with large differential heights from the Southern California Integrated GPS Network (SCIGN) and the SAGE network where meteorological observations were also recorded (Roberts, 2001). The standard Saastamoinen troposphere model, as recommended by Mendes (1999), was applied to the data during baseline computation. Time series analysis indicated no correlation between the resultant height component and the corresponding temperature and relative humidity measures. Reprocessing the same baselines using local meteorological values in the tropospheric delay models showed an equivalent mean value and a larger scatter. Brunner & Tregoning (1994) drew the same conclusions and explained this counter-intuitive result as being due to ground proximity effects corrupting meteorological observations.

Roberts (2001) also computed a local value for the temperature lapse rate based on three years of radiosonde soundings from two radiosonde stations located near Gunung Papandayan. The local value matched closely the global estimate and resulted in negligible change to the results. It appears therefore that the existing tropospheric delay models are as good as they can be, and that the effects of differential troposphere on the height component must be estimated as an additional parameter during baseline estimation.

3. DATA PROCESSING

Data from the single-frequency GPS receiver network on Gunung Papandayan was not considered suitable for investigations into differential troposphere at this stage. The extreme data noise, believed to be due to ionospheric disturbances (Janssen et al., 2001), precluded processing of this data. Data from the SAGE network, New Zealand, were chosen to simulate the network conditions expected to be experienced on Gunung Papandayan. The two stations QUAR and KARA are separated by 9.2km and 1350m in elevation, a network scale equivalent to that of the Papandayan network. The data used was during the same period as the noisy Indonesian data set, but was located in mid-latitudes, which would ensure significantly reduced ionospheric disturbances during the current solar maximum. Only the L1 measurements were processed using the in-house UNSW Baseline software for a 21-day time series of 1-hour data sessions. The effect of the ionosphere was ignored for such a short baseline and the standard Saastamoinen tropospheric delay model was applied at both ends of the baseline. Even after correcting for the troposphere, the results of processing a non-equatorial baseline indicates that the variability in the height component is much larger than for the easting and northing components (Figure 1). The standard deviation in the easting, northing and height components is 7, 11 and 43mm respectively.

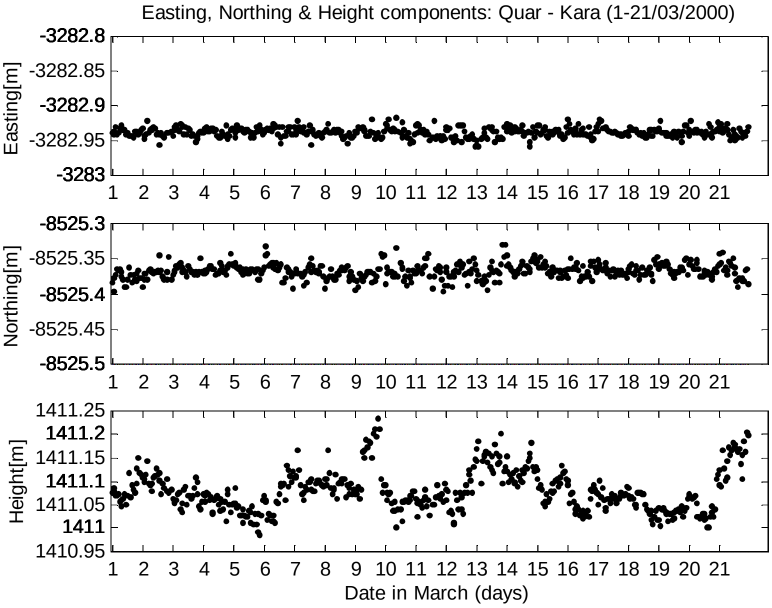

Figure 1: *Time series of 1-hour sessions from Baseline with standard Saastamoinen troposphere modelling QUAR – KARA, 1 – 21/03/2000 easting, northing and heights.*

Tropospheric delay modelling using the Baseline software was compared with the parameter estimation approach using the Bernese V4.2 software. The two software packages were checked using a test 24-hour data set and both were processed using modelling to confirm their compatibility. This same test data set was then used to test the effect of errors in starting coordinates, session length and the relationship between the tropospheric delay estimate and the height component. When satisfied that both softwares computed identical results, the whole 21-day time series was processed using the Bernese software for 1-hour sessions, and estimating one relative residual zenith delay parameter per session (Figure 2). The standard deviation in the easting, northing and height components is 7, 9 and 32mm respectively.

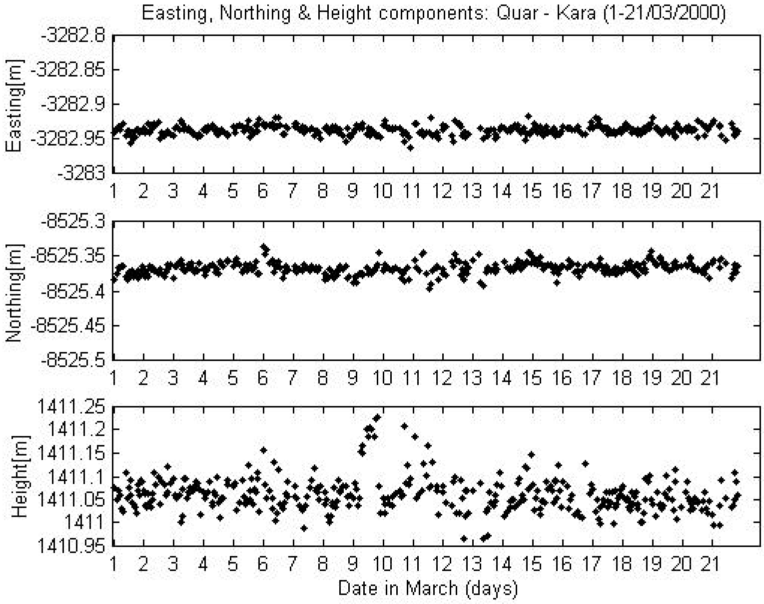

Figure 2: *Time series of 1-hour sessions from Bernese with Saastamoinen parameter estimation cos(z) mapping function. QUAR – KARA, 1 – 21/03/2000 easting, northing and heights.*

Visual inspection of Figure 2 reveals a height component more centred around a mean value than is the case for modelling. This suggests that the parameter estimation approach is less influenced by local atmospheric conditions. Such a result is desirable for a deformation monitoring system designed to detect movements of the ground surface on a continuous basis. 3-hour sessions were also processed for both the modelling and parameter estimation approaches (Table 1). (Note: One parameter per 3-hour session was estimated.)

Table 1: *Average values and standard deviations for 1-hour & 3-hour sessions using the Baseline and Bernese software packages.*

	EAST	NORTH	HEIGHT	DISTANCE
1-hr sessions **Baseline**	-3282.9382 0.0068	8525.3676 0.0103	1411.0797 0.0432	9233.1885 0.0126
3-hr sessions **Baseline**	-3282.9385 0.0059	8525.3684 0.0094	1411.0811 0.045	9233.1895 0.0115
1-hr sessions **Bernese**	-3282.9375 0.0067	8525.3676 0.0087	1411.0623 0.0324	9233.1856 0.0111
3-hr sessions **Bernese**	-3282.9375 0.0061	8525.3679 0.0086	1411.0616 0.0351	9233.1854 0.0102

From Table1 the standard deviation for the height component derived from the parameter estimation approach is smaller than for the case of tropospheric delay modelling. There is a slight improvement in all components (except the height component) when a longer session length is used. This is to be expected as the amount of observation data is increased, improving the chances of correct ambiguity resolution and better estimation of the residual relative troposphere delay. Various researchers (Gurtner et al., 1989; Tralli & Lichten, 1990; Abidin et al., 1998) have recommended a minimum session length of about one hour and even more; especially for single-frequency data. For the 1-hour sessions, processed using Bernese software, from 504 computed baselines, 147 ambiguity-fixed solutions were obtained (29.2%). However, in the case of the 3-hour sessions, from 168 baselines, there were only six solutions when the ambiguities were not fixed (3.6%) – a dramatic improvement! As the session length increases, the effect of carrier phase multipath should be averaged and hence its impact on the baseline solution is reduced.

However, the session length must not be so long as to mask any short-term deformation signature that may be present in the data. Also note, from Table 1, that there is an offset between the two solutions for the height component, based on tropospheric delay modelling and parameter estimation (also translated as a smaller bias in the derived baseline length).

The residuals from the GPS baseline processing reflect the quality of modelling in the least squares estimation. The residuals may contain mis-modelled or imprecisely estimated tropospheric effects, as well as biases due to the ionosphere, multipath and instrument noise. Introducing extra parameters into the observation equations (and hence the design matrix) can help to randomise the resulting residuals, however it is unclear if the new parameters are "soaking up" more than the desired biases. Beutler et al. (1988) claim that estimating too many parameters may weaken the solution considerably. For this reason it is recommended that only one extra residual tropospheric parameter per session should be estimated, together with the monitor station coordinates and the double-differenced ambiguities.

For a one-way phase observation, the true value comprises the *computed* values and *corrections* to these computations.

$$\begin{aligned}\Phi = {} & \frac{r(\overline{X},\overline{Y},\overline{Z})}{l} + \overline{N} + \overline{Trop} + \\ & \frac{1}{l}.\frac{fr}{fX}\,dX + \frac{1}{l}.\frac{fr}{fY}\,dY + \frac{1}{l}.\frac{fr}{fZ}\,dZ + \frac{fN}{fN}\,dN + \frac{fTrop}{f\,dz}\,dz + e\end{aligned} \qquad (1)$$

The first three terms on the top line of Eqn. (1) are the computed part of the observation equation and are denoted using a bar over these terms. The next five terms on the second line define the corrections, and it is these corrections which influence the design matrix of the least squares estimation procedure. This is the crucial step for residual tropospheric parameter estimation.

The δz term refers to the residual relative zenith delay term for the two stations. It is difficult to describe its physical meaning. Hence it is the correction to the estimate of the relative troposphere between the two stations that is sought. Brunner & Tregoning (1994) define residual zenith delay as the difference between the actual zenith delay and that calculated from a standard model.

This extra parameter is intended to absorb the effects of the mis-modelled tropospheric delay (Rothacher et al., 2000). Therefore there should exist a correlation between the height component in the time series and the value of the tropospheric parameter estimate. This assertion is made in Roberts (2001), and a negative correlation coefficient of –0.6 is reported. It is suggested that this correlation coefficient is a means of determining the quality of a particular tropospheric parameter estimation.

4. DATA ANALYSIS

The height components of the four derived time series (Table 1) were analysed using digital signal processing techniques to detect any repeatable signal present in the data, which could indicate either diurnal movement or an unidentified systematic bias in the system. Welch's averaged, modified periodogram method was used to produce power spectral density (psd) estimates of the discrete-time signal of heights. The application of an overlapping Hanning window in the psd computation improved the readability of the frequency domain plots (Mathworks, 1998). Figures 3 & 4 show the psd analysis for the 1-hour and 3-hour sessions resulting from Baseline processing and tropospheric modelling, and Figures 5 & 6 show the corresponding analysis from Bernese processing and parameter estimation.

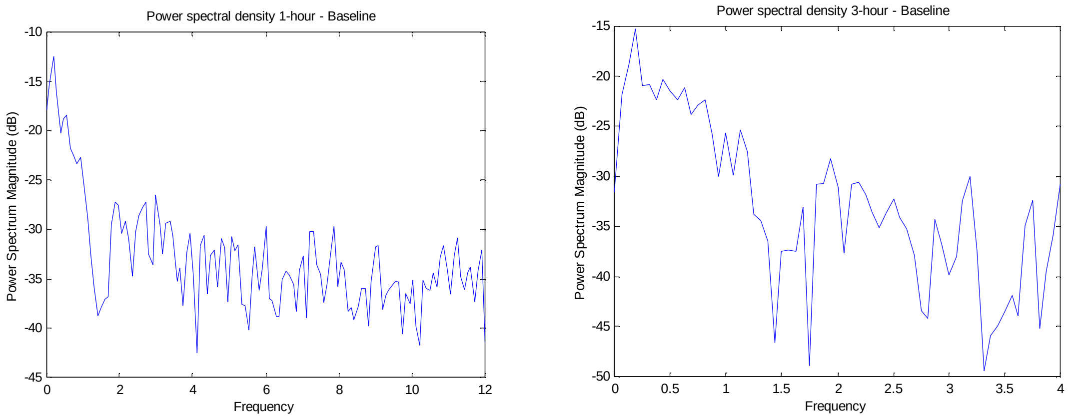

Figure 3 & 4: *Power spectral density graphs for the Baseline results using modelling for the 1-hour (left) and 3-hour sessions (right).*

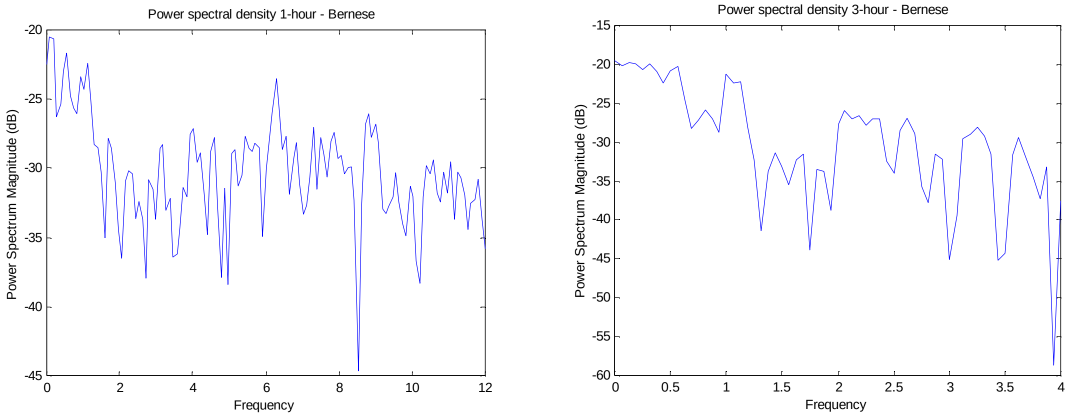

Figure 5 & 6: *Power spectral density graphs for the Bernese results using tropospheric parameter estimation for the 1-hour (left) and 3-hour sessions (right). The peak corresponds to a 24-hour repeat period.*

The frequency axis is in units of cycles/day with the low frequency information to the left grading to higher frequency to the right. The peak value around less than one cycle/day is referred to as "red noise" and is a typical signal present in geophysical data. The objective of stochastic modelling in GPS data analysis is to reduce this red noise (Peter Morgan, personal communication). In Figures 3 & 4, perhaps another peak can be seen at around 2 cycles/day (or every 12 hours) but this is a far less significant signal than that of the red noise.

Figures 5 & 6 also show this red noise effect but there also appears to be a clearer signal at 1 cycle/day. Figure 5 shows a peak at 6 cycles/day (or every 4 hours) but this is not detectable (and therefore cannot be verified) from Figure 6 due to the sampling frequency of 3-hours (i.e. session length). From the Nyquist's sampling theorem (Bateman et al., 1989), the minimum detectable signal must be at least twice the sampling frequency.

For clarity both power spectral density plots for the Baseline and Bernese approaches are plotted on the same axes. This highlights the agreement between the processing for the 1-hour and 3-hour session cases (Figures 7 & 8).

The plots using the Baseline software have no recognisable signal apart from the red noise mentioned earlier. However, the plots using the Bernese processing show a definite peak, for both the 1-hour and 3-hour session processing, at the 1 cycle/day (or every 24 hours). This peak most likely corresponds to a multipath signal repeating every sidereal day due to the satellite constellation pattern repeating daily (though four minutes earlier each day). Han & Rizos (1997) identified this multipath phenomenon in mine environments, and proposed a bandpass filter to account for this predictable signal. This procedure will be investigated in future research in an effort to reduce the multipath effect, and thereby increase the accuracy of the estimated height component.

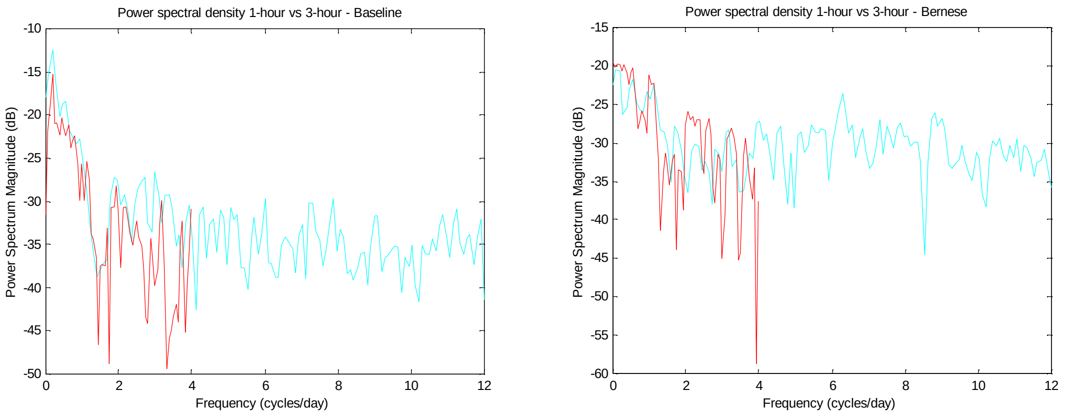

Figure 7 & 8: *Comparison of power spectral density graphs for Baseline (left) & Bernese (right) results for 1 (cyan) & 3-hour (red) sessions.*

CONCLUDING REMARKS

This paper has demonstrated that for small-scale networks with large changes in height between stations, processing using the conventional short-baseline modelling approach produces unrealistic results. Estimating a residual relative tropospheric delay parameter improves the reliability of the processing (small standard deviation of the time series), and the results also cluster around a mean value. As the data is single-frequency carrier phase only, a minimum of 1-hour observation sessions is recommended.

Although the data was of a high quality, using top-of-the-range GPS receivers, choke ring antennas and stable monuments, processing of the L1-only data was an onerous task with much manual attention required, particularly for the modelling approach. This suggests that for an automatic processing system, dual-frequency data will ensure higher confidence in the processed baselines.

Signal processing analysis indicates that no signal can be detected in the time series produced by modelling as the scatter and trend in the data is erratic. A distinct multipath signal does appear in the more reliable, Bernese-processed data using parameter estimation. A bandpass filtering technique will be investigated, in order to eliminate this systematic bias and reduce the variability of the estimated height component.

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