Low-Cost Deformation Measurement System for Volcano Monitoring

Craig ROBERTS, Cedric SEYNAT, Chris RIZOS and Graeme HOOPER, Australia

Key words: Low-cost, deformation, volcano, GPS

SUMMARY

Ground deformation due to volcanic magma intrusion is recognised as an important precursor of eruptive activity at a volcano. The Global Positioning System (GPS) is ideally suited for this application. With the advent of inexpensive GPS receiver boards, the development of a low-cost GPS-based volcano monitoring system is now possible. It provides an expendable way of measuring volcanic activity.

This paper presents a novel, autonomous, deformation monitoring system based on the use of the low-cost Novatel Superstar II receiver. The system uses several of those GPS units, one of which being at a known reference location and the others being scattered around the area of interest. The GPS Superstar II receivers provide measurements of the L1 carrier phase and of the GPS ephemeris. Those measurements are logged at a user-defined sampling rate, and transmitted via a radio link to a central processing station. The post-processing engine uses those data in ambiguity resolution and baseline computation algorithms. The measurement of changes in GPS baseline easting, northing and height components over time forms the basis for measuring the volcano's expansion prior to eruption.

The paper reviews the major practical design considerations for GPS-based volcano monitoring systems, together with the dominant error sources. The data processing steps necessary to obtain the baseline between the reference receiver and each slave unit is also detailed. The system validation is presented, showing the performance results obtained for several baseline lengths, data sampling rates and observation session lengths. Each hardware and software component is described, as well as the system architecture and the special challenges in deploying and operating such a system in an inhospitable environment.

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1. INTRODUCTION

It is now well established that GPS can be applied to volcano monitoring to improve forecasting and perhaps even prediciton of impending eruptive activity. In principle differential GPS baselines between a stable, known reference location and an array of monitor stations situated around the zone of deformation measure changes in GPS baseline easting, northing and height components over time. These repeated measurements are compared to monitor the volcano's activity and warn of any threatening activity.

The quality of the GPS receiver and its peripheral equipment (including software) define the quality of a deformation monitoring system. For instance using a high quality geodetic style GPS receiver with a choke ring antenna, a highly accurate deformation monitoring system would be expected. Some commercial examples of high quality monitoring systems include Condor – 3D monitoring systems (Condor, 2004) and Epoch-by-Epoch^{TM} (Geodetics, 2004). However the cost of just one monitoring station becomes prohibitive and therefore the number and distribution of monitoring stations is restricted. This is particularly at issue in developing countries where funds for such infrastructure are scarce.

It is a fact that the highest precision, lowest noise differential GPS solution is the L1-fixed solution (Rizos, 1997). Even using dual frequency observations, software will first attempt to reliably resolve an L1-fixed solution. The relatively low cost of L1-only receiver boards therefore provides an opportunity for low-cost deformation monitoring systems to operate in small-scale environments ie up to 10-15 kms. For baselines longer than this, the differential ionospheric effect degrades baseline accuracy requiring dual frequency observations to account for this effect to maintain baseline accuracy (Parkinson & Spilker, 1996).

This paper presents a deformation monitoring system (DMS) based on the use of the low-cost Novatel Superstar II receiver. The system can be considered a second generation to the University of New South Wales prototype system previously tested on Mt Papandayan, Indonesia (Roberts, 2002). The first generation prototype system used GPS/PC modules thereby requiring software to be written in the DOS operating system onto low-cost industrial PCs. DOS is not designed for real-time applications and consequently many problems hampered development of this system.

The second generation system replaces the industrial PC with a ZiLOG eZ8, 8-bit Central Processing Unit (CPU) with added benefits such as more stable communications software, lower power requirements, smaller size and a more reliable operation overall.

A technical description of the DMS system architecture is presented with specific considerations for operation of such a system in a volcanic environment, some cost advantages and results of some limited testing in Melbourne, Australia. The system described here is versatile as it can be configured in many different ways depending on the application. In that respect, the use of the DMS for volcano deformation monitoring is one of the possible applications. It is anticipated this system will be deployed and tested on an active Indonesian volcano in the future.

2. DEFORMATION MONITORING SYSTEM DESCRIPTION

2.1 System Overview

The Deformation Monitoring System (DMS) is composed of a set of Carrier Phase Capture (CPC) units recording GPS data, and storing those data onto flash memory. The units are also equipped with a radio modem, and the recorded data are transmitted by radio at regular intervals to a master control station. The Master Control Station (MCS) schedules the radio downloads and processes the data to compute the baselines between the CPC units. The data processing is based on double differences of GPS carrier phase, between "slave" units scattered across the area to monitor (e.g. the volcano) and a "master" unit, of known location (typically located at the location of the master control station). Figure 1 summarises the DMS system architecture.

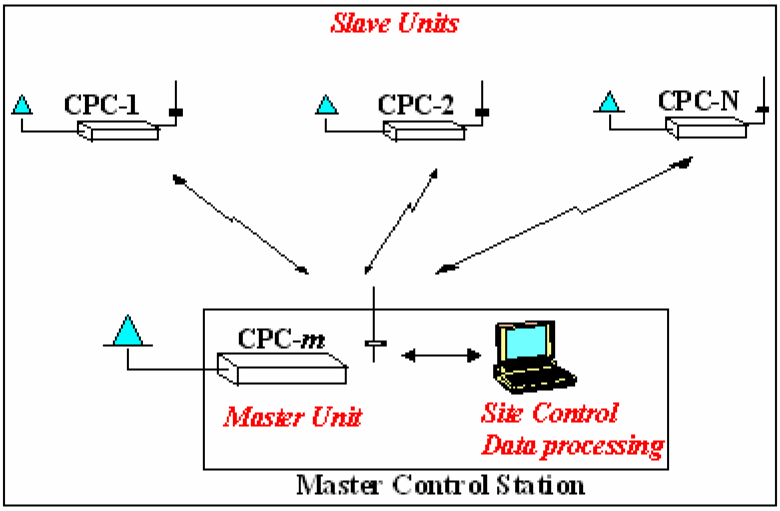


Figure 1 – DMS System architecture

2.1.1 Hardware Description

The Carrier Phase Capture unit is composed of 4 main elements:

- The Novatel Superstar II GPS receiver collects and outputs navigation data, satellite ephemeris and carrier phase. Those data are output in the native Superstar binary format. The GPS can be configured to also output other binary messages if required.
- The Atmel AT45DB321B DataFlash is a serial interface memory unit with about 4 MB of storage space. It is used in the CPC to store the GPS data described above and other log information.
- The AeroCom Radio Modem is used in the CPC to receive commands from the master control station and to transmit logs and the recorded GPS data.

- Operations by the 3 elements above are controlled by the ZiLOG eZ8, 8-bit Central Processing Unit (CPU). Serial communication between the eZ8 CPU and the other elements above is achieved with Universal Asynchronous Receiver/Transmitter (UART) controllers.

The architecture of the CPC is generic and can suit a number of applications. The other piece of hardware of the system is the master control station. It processes the data received from the slave and master units to compute baselines and generate the volcano monitoring information. The master control station also commands the system operations, in particular the radio data downloads from the slave units. It is a standard laptop computer.

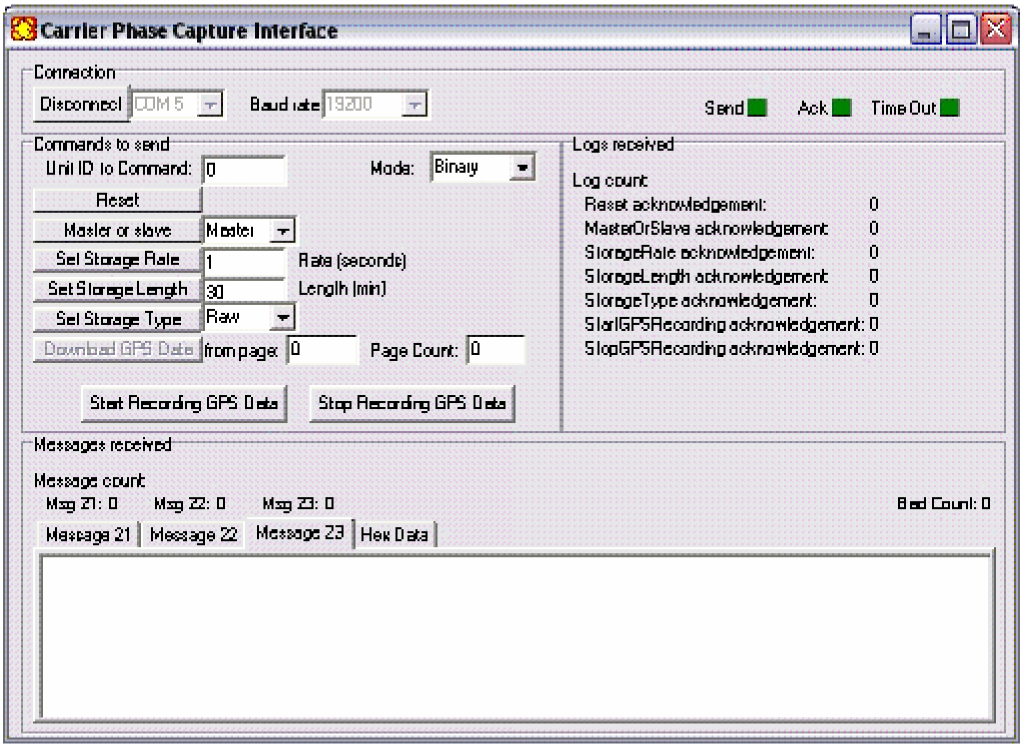
2.1.2 Software Description

The necessary software for the DMS is divided in 2 main components:

- The software written on the eZ8 CPU:
  - handles the GPS data and their recording to the flash memory,
  - interprets the commands received by radio or I/O port,
  - responds to those commands (e.g. data download via radio).
- The software written on the master control processor:
  - sends download commands to the CPC units,
  - receives and records the downloaded data,
  - processes the GPS data to output the baseline between the master and slave units.

The software written on the eZ8 CPU is based on low-level embedded code and is not detailed here. However it is interesting to note that most of the functionality takes the form of simple C-language routines and as such the CPC can be re-programmed and reconfigured easily and with limited development effort. This is an important element contributing to the low cost of the system, in terms of its development and maintenance.

The control software at the MCS is controlled via a user interface running under Microsoft Windows (2000 or XP). The application is presented in Figure 2.



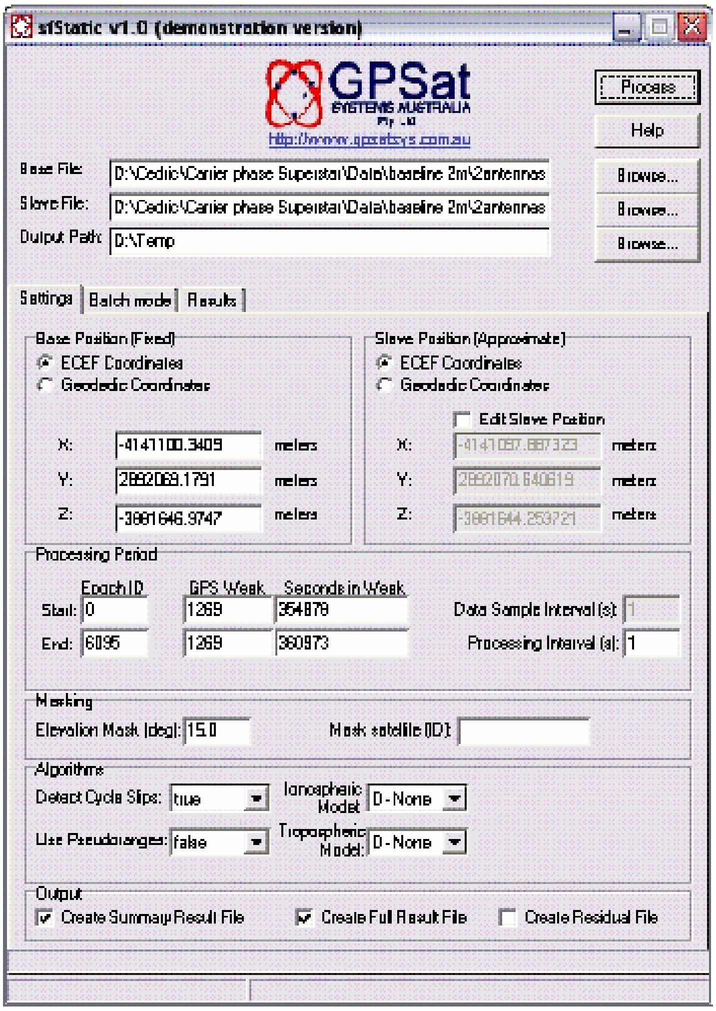
COM 5
Baud rate: 19200
Unit ID to Command: 0
Mode: Binary
Master or slave: Master
Set Storage Rate: 1 Rate (seconds)
Set Storage Length: 30 Length (min)
Set Storage Type: Raw
from page: 0
Page Count: 0

Log count
Reset acknowledgement: 0
MasterOrSlave acknowledgement: 0
StorageRate acknowledgement: 0
StorageLength acknowledgement: 0
StorageType acknowledgement: 0
StartGPSRecording acknowledgement: 0
StopGPSRecording acknowledgement: 0

Message count
Msg 21: 0
Msg 22: 0
Msg 23: 0
Bad Count: 0

Figure 2 – User interface of the Master Control Station

The computation of the baseline between a reference station at known location and a slave unit is based on single frequency (L1) carrier phase measurements. It uses a standard double difference algorithm for ambiguity resolution and baseline computation. The processing of the data uses another simple user interface in order to facilitate the processing by the user. Figure 3 shows the user interface required to easily setup and start the process. The processing algorithm is called *sfStatic*.



Base File: D:\Cedric\Carrier phase Superstar\Data\baseline 2m\2antennas
Slave File: D:\Cedric\Carrier phase Superstar\Data\baseline 2m\2antennas
Output Path: D:\Temp

Base Position (Fixed)
● ECEF Coordinates
○ Geodetic Coordinates
X: -4141100.3409 meters
Y: 2892069.1791 meters
Z: -3881646.9747 meters

Slave Position (Approximate)
● ECEF Coordinates
○ Geodetic Coordinates
☐ Edit Slave Position
X: -4141097.887323 meters
Y: 2892070.640619 meters
Z: -3881644.253721 meters

Processing Period

	Epoch ID	GPS Week	Seconds in Week
Start:	0	1269	354878
End:	6095	1269	360973

Data Sample Interval (s): 1
Processing Interval (s): 1

Masking
Elevation Mask (deg): 15.0
Mask satellite (ID):

Algorithms
Detect Cycle Slips: true
Use Pseudoranges: false
Ionospheric Model: 0 - None
Tropospheric Model: 0 - None

Output
☑ Create Summary Result File
☑ Create Full Result File
☐ Create Residual File

Figure 3 – User Interface of the baseline processing algorithm

3. CONSIDERATIONS FOR DEPLOYMENT AND OPERATION OF THE DMS

3.1 Hardware Issues

The hardware used for the DMS is described above in section 2. This is a considerable advance on the first generation system. The Novatel SuperstarII displays very stable carrier tracking characteristics comparable to an equivalent dual-frequency tracking device. Previous laboratory test results at UNSW and UNAVCO have shown that the L1 carrier tracking loops inside Novatel single-frequency GPS receivers are as good as those in dual-frequency receivers (Roberts 2002)

Currently several GPS antennas are being considered. With the emphasis of the system being on low-cost, the current choice of antenna is a right-hand circular polarised, passive antenna. The performance results presented later in this paper have used such an antenna.

The total power consumption of the CPC units is about 0.7W in idle mode. A monitoring system must be appropriately designed to deal with the extreme conditions experienced in volcanic environments such as extreme heat (from the weather above and the surface below the volcano), sulphur gas corrosion, solar conditions for solar panel recharging, lightning protection, wind, rain, monsoon conditions, vandalism and damage by animals. Obviously budget restrictions for a low-cost system will limit the extent to which protection against these environmental considerations can be exercised.

3.2 Error Mitigation

The following comments summarise the findings from the first generation system investigated in Roberts (2002).

3.2.1 GPS Baseline Solutions

It is crucial for highest precision baseline solutions that ambiguities are resolved correctly.
To ensure correct ambiguity resolution for L1-only data (ie a reduced number of measurements), at a 15 second sample rate, the session length should be no shorter than 1 hour. Conversely, to ensure the troposphere is regularly estimated, the session length should be no greater than four hours. A 3-hour session length provides a good compromise between reliability and resolution of a geophysical signal estimated from single-frequency data. The field tests shown in section 4 show a range of baseline results for different sample rates and session lengths.

3.2.2 Troposphere

A characteristic of network design in volcano monitoring is that there is usually a large change in height between a stable reference station and an array of monitor stations. For such small-scale networks with large changes in height between stations, processing using the conventional short-baseline modelling approach produces unreliable results due to differential troposphere effects not accounted for by standard models. Estimating a residual relative tropospheric delay parameter improves the reliability of the processing (small standard deviation of the time series), and the results cluster around a mean value. This has been demonstrated with data from the SAGE-NZ network and Papandayan 2001, under the assumption that the GPS points are stationary (Roberts, 2002).

The Saastamoinen troposphere model and mapping function are considered to be of sufficient accuracy as an a-priori troposphere parameter estimate. It is recommended that the estimated parameters be X, Y, Z, N (ambiguity) and one extra residual relative zenith troposphere parameter per session. This requirement for an extra parameter to account for differential tropospheric effects also effects the session length for reliable baseline processing as more data is required in order to solve the normal equations.

3.2.3 Ionosphere

Investigations from the first generation system were conducted between 1998 – 2001 during a solar maximum. It was concluded that single-frequency data, on its own, were not suitable for high precision (ie better than 5cm in the vertical), small scale networks (less than 10km baselines) in equatorial regions during solar maximum conditions. Ionospheric biases must be either eliminated using an ionosphere-free linear combination (ie dual frequency data and therefore no longer low-cost) or corrected using information derived from an external, fiducial network of dual-frequency receivers.

Additionally Janssen (2003) found that even using an outer fiducial network of dual frequency GPS receivers to map and empirically correct the local ionosphere, equatorial regions, such as Indonesia still severely restricted the length of fiducial baselines (and therefore the coverage) for an operational algorithm.

Numerous studies into operational network RTK style systems rely on dual frequency measurements to account for atmospheric biases (Dai et al (2003), Wanninger (1999), Wübbena et al (2001)). However none offer a correction model for L1 only data for small scale networks bounded by CORS infrastructure. It is anticipated that the second generation system will provide high precision baseline accuracy during solar minimum periods but this precision will degrade with increased ionospheric activity. This problem remains a research challenge in equatorial regions.

3.2.4 Multipath

Roberts (2002) demonstrated how a simple FFT filter eliminated multipath effects and therefore reduced the variability (and standard deviation) of the time series data at Papandayan and the SAGE-NZ network. Although DSP techniques are proposed to account for multipath effects, and have proven to be successful, subsequent systems could accommodate additional ground planes on GPS antennas to reduce multipath at the source. This is a relatively low-cost modification.

4. COST CONSIDERATIONS

For a low cost system the L1 only GPS receiver is the main cost saving, providing that baseline lengths remain relatively short, to exploit the high precision of the L1 fixed GPS baseline solution. As the baseline length extends, software improvements are key to squeezing out higher precision from an L1 only system. As discussed in section 3 an FFT filter to account for multipath and parameter estimation for residual zenith troposphere delay can be implemented to improve baseline precision without improved or additional hardware.

Roberts (2002) found that for a high precision monitoring system, a good quality GPS antenna was required to ensure good repeatability in baseline solutions. Additionally Meertens (1998) demonstrated a significant improvement in data quality by equipping antennas with an additional groundplane. Such a low-cost addition could be considered for the DMS. In its current configuration, each CPC unit is expected to cost under 1500 Australian Dollars.

The depth and stability of monuments for the monitor stations is also restricted by the low-cost nature of the DMS system, however for cm-level precision, relatively stable marks are inexpensive. The GPS antenna is mounted on suplhur gas resistant fibreglass poles 1.5 m above the ground surface.

A significant cost saving for the second generation system arises indirectly due to the lower power requirements of the GPS receiver and radio modem. This power saving requires a smaller sized battery bank and solar recharging array which has a major impact on the total cost of monitor stations.

In addition to the equipment cost, another important factor to consider is the operational cost and maintenance cost. The DMS uses a simple user interface based on the Windows operating system, where minimum user interaction is required. The automation of the process means that the system requires low supervision while operating. For that reason, the time and associated cost necessary to operate the system and obtain results is reduced.

5. PERFORMANCE TEST RESULTS

The DMS has been extensively tested for different baseline lengths. The tests were conducted as follows. GPS L1 carrier phase, pseudoranges and ephemeris data were collected and recorded with the CPC units at a sampling rate of one second. Data were collected from 2 units, one of them being at a known surveyed location. For each data collection session, the same data were also collected with high-end dual frequency Novatel receivers using the same GPS antenna as the CPC units. The dual-frequency data were post-processed to output baselines that can be used as an independent reference against which the results from the single-frequency data are compared. The post-processing of the single-frequency data collected with the CPC units was done in batches of fixed duration. For example, for a total time length of collected data of 3 hours, baselines were computed in the N batches of length DT [0,DT], [DT,2DT], [2DT,3DT], …, [(N-1)DT,NDT] until the end of the session is reached (i.e. for (N+1)DT>3 hours). Several batch lengths were tested (DT=600s, 1000s, 2000s, 5000s). In addition, for each of those batches, the collected data were used in two sample rates: 1 second and 5 seconds. Table 1 summarises the tests that were conducted and are reported in subsequent tables of this paper.

Test Number	Data sample rate	Slave Unit location name	Approximate baseline	Total length of collected data
	1s	GPSat Systems offices	2 m	6095 seconds
	5s			
	1s	Latrobe University, Victoria	1.2 km	9063 seconds
	5s			
	1s	Northland, Victoria (morning)	3.8 km	10291 seconds
	5s			
	1s	Northland, Victoria (afternoon)	3.8 km	7461 seconds
	5s			
	1s	St. Helena, Victoria	6.3 km	7052 seconds
	5s			
	1s	Diamond creek, Victoria	11.0km	7535 seconds
	5s			

Table 1 – Overview of the performance tests

The wide range of baselines lengths tested here, together with the several time lengths of batches, allows a solid estimation of the system performance. The very short baseline test (2 metres, test number 1 and 2) allows the estimation of the system intrinsic noise. The purpose of the test number 5 to 8 was to determine the variation of the performance with time of day for an approximately identical baseline length of about 3.8km. The following sections summarise the main conclusions from the ongoing tests.

5.1 Success Rate

The success rate displayed in the last column of the tables above is the percentage of batches of length DT from which a baseline was successfully obtained. The success rates for all test runs are plotted in Figure 4.

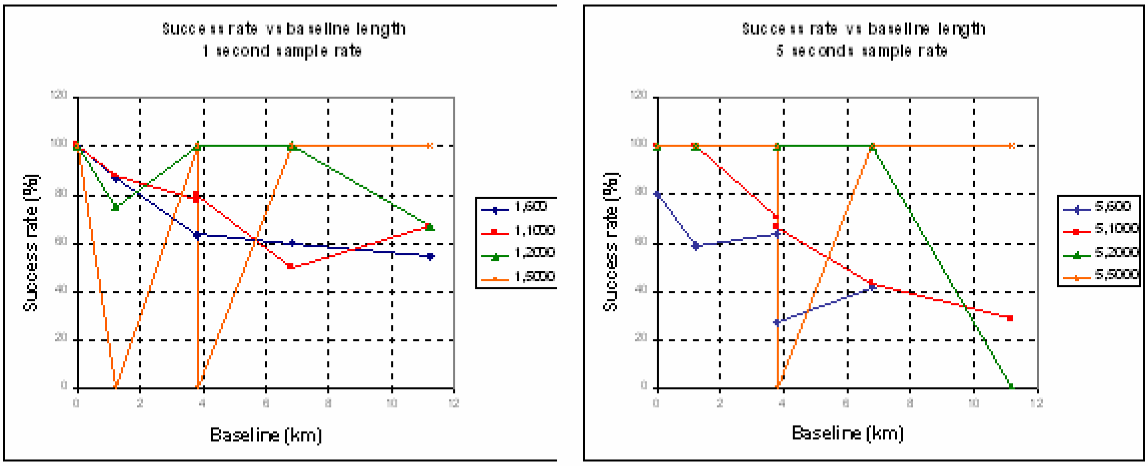


Figure 4 - Success rate against baseline length, for all runs and the 1s (left) and 5s (right) sample rates

Overall the success rate decreases with increasing baseline length, with the exception of the test run made with a batch length of 5000s. This latter case is due to the fact that, for such a length of data, only one batch can be run for the total data set, and therefore the success only takes the values 0% or 100%. For other lengths, the decrease with increasing baseline is apparent and, the results show that for a consistent and robust determination of the baseline, it is desirable to use at least 2000s of data. With such a length of data, the ambiguities are solved correctly 100% of the time for baselines up to 6.8 km. One exception is visible on the left plot in Figure (1s sample rate), where the success rate for the 1.2km baseline is down to 75%. In this particular case one single run failed to succesfully output a baseline, out of the total 4 runs. The reason for this failure is related to the occurence of severe cycle slips during the data collection, from which the processing engine did not recover. Robust cycle slip detection and mitigation is one of the areas currently under consolidation in the processing engine.

When using 2000s of data for processing the baselines, the success rate remains identical regardless of the sample rate (1s or 5s). This points to the conclusion that a 5s sample rate should be used, data can be collected by the CPC units over longer periods.

5.2 Comparison Between the Single Frequency and Dual Frequency Solution

The baseline computed by sfStatic with single frequency data is compared here to the baseline computed from dual frequency data and computed with the Novatel software package *SoftSurv*. In the plots presented in Figure 5, the difference (sfStatic – SoftSurv) is divided by the total baseline and expressed in parts per million (ppm).

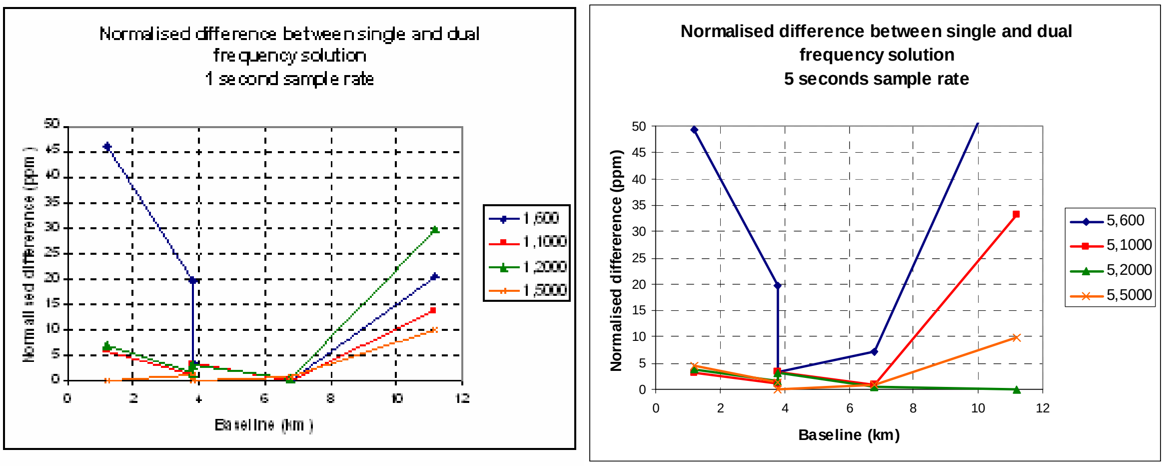


Figure 5 – Difference between baseline length obtained from the single frequency data (with sfStatic) and dual frequency data (with SoftSurv). The difference is normalised by the baseline length and expressed in parts per million (ppm). The 1s (left) and 5s (right) sample rates are shown for all batch lengths

The plots above show that the difference between the single-frequency and dual-frequency solutions is of the order of 5 ppm. The single-frequency solution obtained from the shorter batch length (600s), deviates more significantly from the dual-frequency solution. For other batch lengths, the results are comparable in magnitude up to a baseline length of 6.8km, after which the single-frequency solution starts to degrade. Using either a 1s or 5s sample rate does not affect the overall difference, indicating once again that the conclusion that a 5s sample rate is well suited, as it allows data recording for longer periods without degrading the overall accuracy of the system. For the longest baseline (11km) the accuracy starts to degrade, showing the limitations of the single frequency system described in this paper, as compared to dual-frequency systems.

5.3 Accuracy Measure

sfStatic produces a measure of the accuracy of its baseline, based on the approach presented in (Han & Rizos, 1996). As opposed to the difference with respect to an external reference used in the previous section, the accuracy measure is determined internally by the sfStatic process. It uses the covariance matrix associated to the baseline coordinates, normalised to account for time correlation between consecutive GPS measurements. This internal accuracy measure is shown in Figure 6, normalised by the total baseline length.

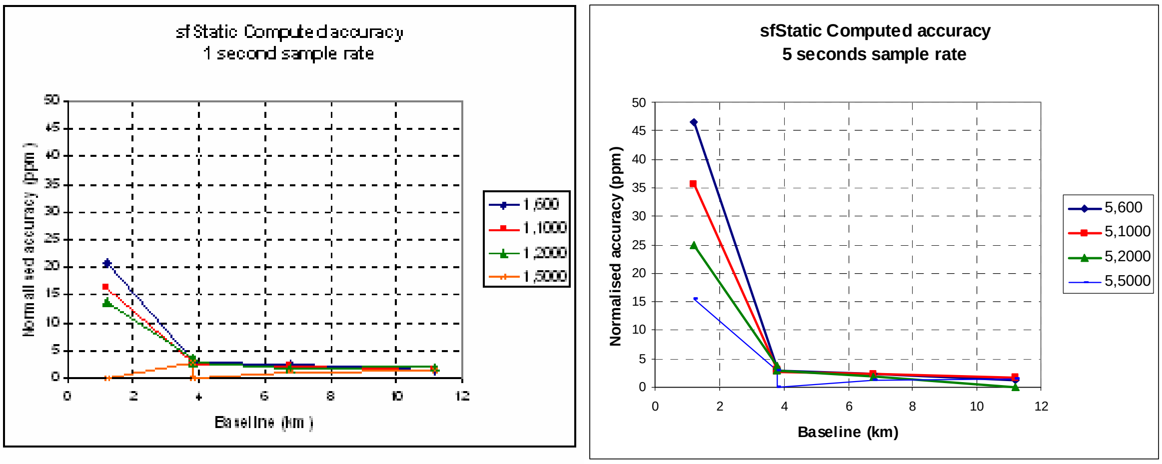


Figure 6 – Accuracy measure computed by sfStatic, normalised by the baseline length and expressed in parts per million (ppm). The 1s (left) and 5s (right) sample rates are shown for all batch lengths

Excluding the shorter baseline of 1.2km, the accuracy measure output by sfStatic is about 2 to 3 ppm. This is of the same order of magnitude as the difference between sfStatic and the dual-frequency reference baseline discussed in the previous section. This result shows that the accuracy measure given by sfStatic can be used as a reliable estimate of the baseline accuracy, except in two notable cases:

- for short baselines (1.2km data set here) the accuracy measure degrades significantly, and is about 3 times larger than the external accuracy plotted in Figure 5. This is due to some background constant noise in the sfStatic process, independent from the baseline length. The accuracy plotted in Figure 6 being normalised, this noise is more apparent for the shorter baseline case.

- for long baselines (11km), the accuracy measure still remains at low values of about 2ppm, despite the large external accuracy displayed in Figure 5. This shows the limitation of the sfStatic process for long baselines.

6. CONCLUSIONS

The deformation monitoring system presented in this paper represents the next generation to the University of New South Wales prototype system previously tested on Mt Papandayan, Indonesia (Roberts, 2002). It uses a low cost Superstar receiver to make carrier phase measurements used in a single frequency process to compute baselines. Low-cost is achieved by using inexpensive components throughout the system, and their intrinsic higher noise levels are compensated by software filtering and pre-processing. Improvements in hardware have also reduced the power budget thereby reducing the size and cost of supplying power using batteries and solar panels.

The system is currently undergoing thorough testing and evaluation. The preliminary results of which are presented in this paper. Performance tests were conducted for several baseline lengths and the data were processed using 2 sample rates (1s and 5s) and 4 different data lengths (600s, 1000s, 2000s, 5000s). The conclusion from those tests is that the optimal use of sfStatic is made by processing a mimimum of 2000s of data, with a sample rate of 5s. sfStatic outputs baselines accurate to 5ppm for baseline lengths less than about 7km.

Additional development and testing efforts are currently under way. They focus on improving the success rate of sfStatic. In order to achieve this improvement in robustness, additional data are currently being collected and processed, and algorithm development is under way in the area of cycle slip detection and mitigation. It is expected that a fully tested and robust solution based on sfStatic and the CPC units will be available by the end of 2004.

Additional software enhancements such as FFT filtering to remove multipath effects and the estimation of an additional residual zenith troposphere delay parameter will be implemented in future versions of sfStatic. However mitigating ionospheric effects remains a problem, particularly when operating in an equatorial region. Investigations such as using one dual frequency receiver as a base station and applying local corrections could provide a compromise between cost and precision. This approach will be investigated during future testing.

7. ACKNOWLEDGEMENTS

Jun Zhang from the School of Surveying and Spatial Information Systems, University ofNew South Wales wrote the sfStatic code.

8. ACRONYMS

CPC	Carrier Phase Capture
CPU	Central Processing Unit
DMS	Deformation Monitoring System
GPS	Global Positioning System
MCS	Master Control Station
UART	Universal Asynchronous Receiver/Transmitter

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BIOGRAPHICAL NOTES

Dr Craig Roberts is a Lecturer in Surveying/GPS at the University of New South Wales, Sydney, Australia. He has lectured at RMIT University in Melbourne for two years. He graduated from the University of South Australia with a Bachelor of Surveying in 1988. He began his career as a private surveyor in Adelaide. He has since worked as a Geodetic Engineer at UNAVCO, Colorado, USA involved with GPS for geodynamic studies. Later he was employed by the GeoForschungsZentrum, Germany where his main focus was orbit determination and prediction for a number of geodetic research satellites.

Dr Cedric Seynat is currently a satellite navigation engineer at GPSat Systems Australia. Prior to joining GPsat Systems, he worked for VEGA GmbH, in Germany, in the definition phase of the Galileo project, where he was involved in Galileo simulation tools. Cedric holds a PhD in satellite radar interferometry and photogrammetry, and a Masters in Space Engineering from Cranfield University, England.

Professor Chris Rizos is currently Head of School in the School of Surveying and Spatial Information Systems. He has been researching the technology and high precision applications of GPS since 1985. He has published over 200 papers, as well as having authored and co-authored several books relating to GPS and positioning technologies. Chris is a Fellow of the Australian Institute of Navigation, a Fellow of the International Association of Geodesy, chair of the IAG's Commission 4 "Positioning and Applications", and a member of the Governing Board of the IGS.

Mr Graeme Hooper is the founding engineer of GPSat Systems, a satellite navigation engineering business providing innovative satellite navigation equipment, system solutions and technical services to regional markets. Graeme has previously worked as a design engineer for Rockwell in the USA.

CONTACTS

Dr. Craig Roberts & Professor Chris Rizos,
School of Surveying and Spatial Information Systems[1],
The University of New South Wales,
Sydney NSW 2052,
AUSTRALIA
Tel. +61-2-9385 4464
Fax + 61-2-9313 7493
Email: c.roberts@unsw.edu.au, c.rizos@unsw.edu.au,
Web site: www.gmat.unsw.edu.au

Dr. Cedric Seynat & Mr. Graeme Hooper,
GPSat Systems Australia Pty. Ltd.[2],
Suite 1, 22 Aberdeen Road,
McLeod Victoria 3085,
AUSTRALIA
Tel. +61-3-9455 0041
Fax + 61-3-9455 0042
Email: cedric.seynat@gpsatsys.com.au , graemeh@gpasatsys.com.au,
Web site: www.gpsatsys.com.au