Evaluating the Quality of GNSS CORS Data for Seismic Monitoring in the South-Eastern Caribbean

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SUMMARY

Tectonic plate motion across the Caribbean region generates significant seismic and volcanic activity that is potentially catastrophic to the many small island nations in the region. This was recently highlighted with the occurrence of the destructive earthquake in Haiti in January 2010. To investigate and understand the impact of the ongoing plate motion, a project initiated by the University of the West Indies Seismic Research Centre in 2007, has led to the establishment of a sparse network of continuously operating Global Navigation Satellite System (GNSS) reference stations (CORS) across the South-Eastern Caribbean. This network has been primarily established to support regional volcanic deformation monitoring and is augmented with measurement inputs from traditional land surveying techniques. More recently, the potential of the UWI cGPS network for tectonic observation is being investigated. This paper presents a detailed description of the current status of the UWI cGPS CORS network. It discusses the technical and practical characteristics of this network in terms of its capacity to provide the necessary spatial and temporal inputs to robust seismic monitoring. In addition, it presents some practical results obtained from analysing the quality of the data obtained from stations in the network, and discusses its potential for meeting the accuracy and integrity requirements of tectonic observation. Finally, it presents a perspective on future infrastructure and technical adjustments that may be necessary to strengthen the current network and enhance its utility for regional seismic and volcanic characteristics determination.

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1. INTRODUCTION

This paper presents an insight into the geological/seismic characteristics in the South-Eastern Caribbean and the potential threats posed to its inhabitants through tectonic related natural disasters. In parallel, the paper highlights the development of the local continuous GNSS infrastructure towards the monitoring of these phenomena. The current and future applications of this local network are presented along with possible applications and opportunities for collaboration with foreign-based institutions having an interest in the tectonics of the region.

1.1 Geology, Seismicity and Plate Motion in the South-Eastern Caribbean

The South-Eastern Caribbean is situated in the Lesser Antilles arc which constitutes the Eastern part of the Caribbean Plate. The arc is the result of volcanism and deformation brought on by the subduction of the North American Plate beneath the Caribbean Plate. The Lesser Antilles arc has had a marked history of seismicity and volcanism, particularly north of 14°N latitude, with major earthquakes (M>8) having taken place in 1690 and 1843 and many more significant earthquakes (M>6.5) occurring within the historical records and scientific catalogues. The study of seismic gaps has led to the conclusion that this region may witness a major earthquake in the near future (Dorel 1981).

In the South-Eastern Caribbean Basin, geodetic studies have led to the discovery of the Central Range Fault (CRF) in Trinidad as being the primary plate boundary structure accommodating strike-slip motion between the Caribbean and South American Plates as shown in Fig. 1 (Weber et al. 2001; Weber 2005; Weber et al. 2009). These studies incorporate the extensive use of space geodetic methods, using both campaign and continuous data.

Paleoseismic studies which followed the previous geodetic works led to the conclusion that the CRF is aseismic and locked. The fault could be holding an approximate 4.9 metres of potential slip which could be released in a future large earthquake (M>7) (Prentice et al. 2010).

A number of collaborative studies (Weber et al. 2001; Weber 2005; Weber et al. 2009) have added to the understanding of the relative plate motion of the Caribbean Plate with respect to the South American plate. Their analysis of the relative plate motion by geodetic methods, using continuous and campaign style GPS data, was fueled by the inadequacies of previous plate kinematic models to resolve this particular plate motion (Weber et al. 2001).

Weber et al. (2001) determined the relative motion of the Caribbean Plate with respect to the South American plate to be 20±3mm/yr towards S86°W ± 2°. This was at odds with existing predicted rates from what was arguably the best global kinematic plate model at that time, NUVEL-1A (DeMets et al. 1990; 1994), which predicted a rate of 13.5mm/yr towards 86°. Weber's rate was consistent with contemporary studies which looked at the Caribbean South American Plate motion in more detail. Perez et al. (2001) determined a rate of 20.2mm/yr towards S81.5°W.

More recent comprehensive global plate kinematic modeling has corroborated the findings of Weber el al. (2001) and Perez et al. (2001). The MORVEL (Mid Ocean Ridge VELocity) model predicts Caribbean South American plate motion of 20.0 ± 0.5mm/yr (1σ) towards S78.2°W ± 1.3° (DeMets et al. 2010). These new findings are more consistent with the above cited rates, for an understanding of the high obliquity the reader is referred to DeMets et al. (2010).

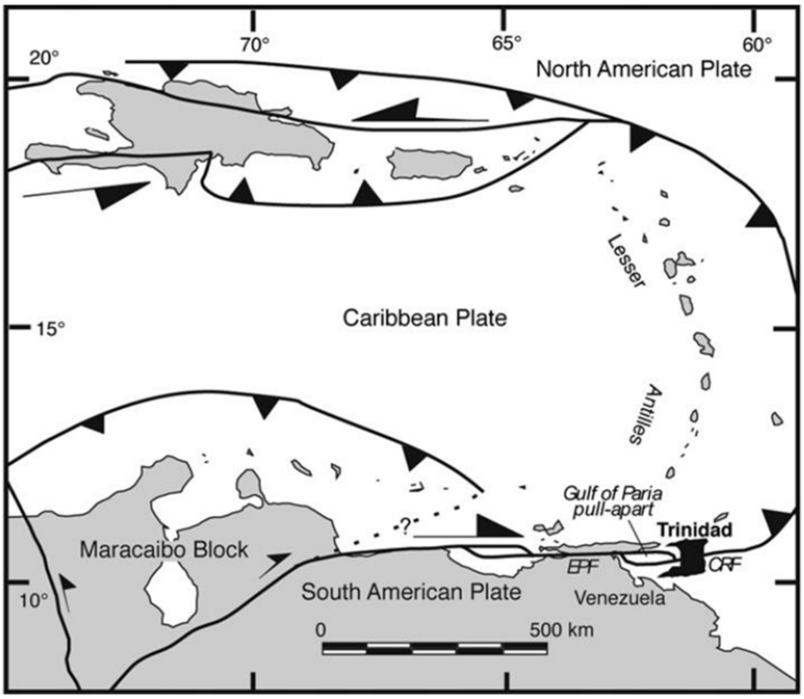

Fig. 1 Active fault system in Caribbean–South American plate boundary. (Weber et al. 2009).

2.0 THE UNIVERSITY OF THE WEST INDIES SEISMIC RESEARCH CENTER (UWISRC) CONTINUOUS GPS NETWORK

2.1 Introduction

The majority of understanding of the regional tectonics has been spearheaded by international researchers. A great deal of the geodetic data used in these studies has come from periodical re-occupation of campaign sites with GPS equipment and the synthesis of continuous data from international GNSS data providers. Over the past five years however, the University of the West Indies, in collaboration with other institutions, has embarked upon initiatives that will enable local researchers in the fields of geodesy and geology to pursue the monitoring and investigation of the regional tectonics, seismicity and disaster management/mitigation.

The UWISRC, through collaboration with Disaster Management agencies and the University

Corporation for Atmospheric Research (UCAR), operates an array of continuous GPS (cGPS) instruments that spans the Eastern Caribbean. The need for the cGPS array was first realized by the Caribbean Community Climate Change Centre, to augment their network of tide gauges. To serve this end, four cGPS stations were installed in Belize, St. Vincent, Dominica and Antigua with the help of the UWISRC and UWI, Department of Surveying and Land Information (now the Department of Geomatics Engineering and Land Management [DGELM]), in 2007.

Following the initial array deployment, the potential of a permanent cGPS array in the Eastern Caribbean to aid GPS volcano deformation surveys and determination of tectonic regime in the region was appreciated. The array has, since then, expanded to over 12 stations, as shown in Fig. 2, with an additional four stations contributed by the French Antillean observatories operated by the *Institut de Physique du Globe de Paris*.

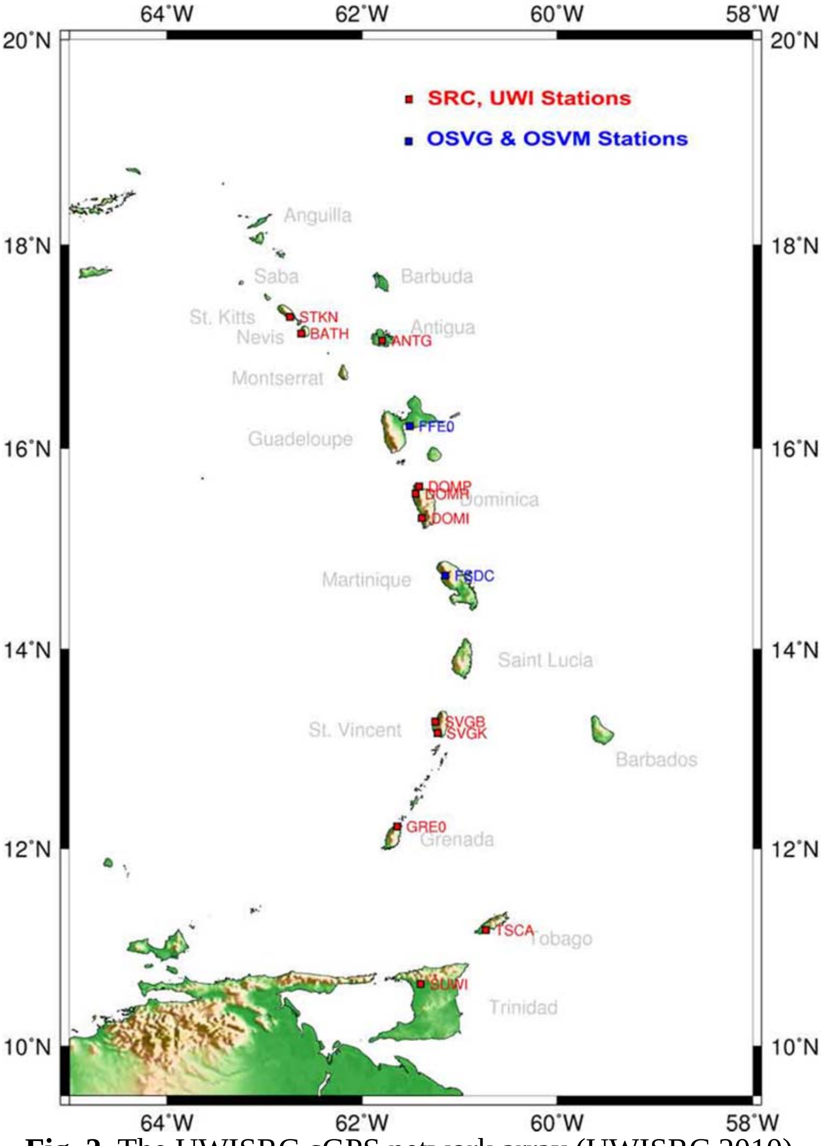

Fig. 2. The UWISRC cGPS network array (UWISRC 2010)

2.2 cGPS Network Description

Table 1 provides information about the current cGPS network including commission date; receiver/antenna type and coordinates. Due to the island configuration of the archipelago, the network geometry is not typical of CORS networks on mainland territories.

Table 1. Names of UWISRC stations, commission date; receiver/antenna type & coordinates

STATION	AGENCY	COMMISSION DATE	RECEIVER	ANTENNA	LAT	LONG	HEIGHT
STKN	SRC	2009/03/13	TRIMBLE NETRS	TRM41249.00	17.2956	297.2600	16.45
TSCA	SRC	2008/11/26	TRIMBLE NETRS	TRM41249.00	11.1771	223.9100	-14.71
ANTG	SRC	2007/01/01	TRIMBLE NETRS	TRM41249.00	17.0624	298.2060	31.58
BELZ	SRC	2007/01/11	TRIMBLE NETRS	TRM41249.00	17.4829	271.7970	4.97
DOMI	SRC	2007/03/12	TRIMBLE NETRS	TRM41249.00	15.3062	298.6110	-16.33
DOMR	SRC	2010/01/30	TRIMBLE NETRS	TRM41249.00	15.5570	298.5411	-16.77
DOMP	SRC	2010/02/19	TRIMBLE NETRS	TRM41249.00	15.6270	298.5780	0.20
SVGB	SRC	2007/03/23	TRIMBLE NETRS	TRM41249.00	13.2746	298.7500	282.00
SVGK	SRC	2008/12/24	TRIMBLE NETRS	TRM41249.00	13.1622	298.7720	2.58
GREO	SUOMINET	2007/01/01	TRIMBLE NETRS	TRM41249.01	12.2218	278.4282	17.53
BATH	SRC	2010/10/16	TRIMBLE NETRS	TRM41249.00	17.1324	297.3742	16.45

2.2.1 Site Selection

The array currently constitutes cGPS instruments, with the exception of volcanic monitoring sub-networks, with antennas mounted to reinforced concrete buildings' roof top. The buildings and their roof tops were chosen based on:

- sky view,
- possible multipath contributors,
- local geology,
- the stability of the structure (no torsion forces acting on building),
- security, and
- access to broadband internet.

2.2.2 Processing

Data is downloaded nightly to the UWISRC and daily position estimates of each station are determined by automatic processing using both IGS rapid and final precise ephemeris. This processing is achieved using the GAMIT\GLOBK software package developed by Massachusetts Institute of Technology, Scripps Institution of Oceanography, and Harvard University. GAMIT\GLOBK is also employed to combine data to produce velocities for each station.

Alternate processing strategies using the Bernese software package developed at the Astronomical Institute of the Bern University (AIUB), Switzerland, are also currently being investigated.

2.3 Current Applications – Development of an Eastern Caribbean Reference Frame

Currently, the UWISRC is using this cGPS array to determine an Eastern Caribbean Reference Frame which will greatly increase the precision of the processing of sub-networks that monitor volcano deformation. The use of cGPS in volcano deformation is extensive throughout the world but currently no reference frame that properly defines the Eastern Caribbean exists.

The realization of a reference frame is critical, especially in the case of the Soufriere Hills Volcano, Montserrat that has been erupting since 1995 and where cGPS monitoring is becoming a very useful tool in determining the activity of the volcano.

The UWISRC also employs the array in plate rigidity modelling to investigate the slab and fault characteristics of the Eastern Caribbean. This has direct implications in improving the understanding of the seismic hazard that is present in the region.

2.4 On the importance of continuous GNSS data

DeMets et al. (2010) cites higher weighted RMS (root-mean-square) misfits in the east and north velocity components of 18 stations used in defining the motion of the Sundaland plate as being typical of survey-mode GPS instruments. Therefore the importance of having quality geodetic grade measurements for the derivation of tectonic data is fundamental. The UWISRC uses geodetic grade antennas and receivers for optimum data capture. The outlined rigorous site selection process is employed to further mitigate any other errors that are within their control.

Geodetically derived angular velocities make up the sole independent standard against which geologically determined current angular velocities can be compared (DeMets et al. 2010). Therefore the work that the UWISRC and more recently, the UWI DGELM are doing towards the determination of such angular velocities is critical and merits a very careful and methodical approach.

3.0 DATA PROCESSING

3.1 Processing with GAMIT\GLOBK

Once cGPS array and international stations' data are available, processing using GAMIT is automatically carried out. Among several analyses that are made available, GAMIT produces daily position estimates and associated covariance matrices for station coordinates, earth-rotation parameters, orbital parameters, and source positions from the observations data. This is achieved by applying double differencing, modelling of satellite orbits using IGS precise ephermerises and the modelling of the stations' positions in an Earth-centred reference frame defined by satellites.

Double differencing is implemented by differencing the between station-differecnes and satellite-differences to remove cycle slips of the observed L1 and L2 carrier signals recorded by a receiver (Blewitt 1989; Dong and Bock 1989). Linear combinations of L1, L2 and LC phases are not implemented due to the very long baselines present in processing UWISRC stations with international stations (Dong and Bock 1989). Instead L1 and L2 phases are treated as indepedent observations in our analysis.

Also, particular to our analysis is the modelling of station's ground position. This numerical integration takes into account several geophysical phenomenon including the rotation, precession and nutation of the spin axis and the wobble motion of the spin axis with respect to the crust. Lunar and solar tides and the loading of ocean tides and the atmosphere is also taken into account. Propagation of delay of what is considered the neurtal portion atmosphere is also calculated to aid in phase modelling. These parameters are then fitted to the double-differencing analysis to produce a estimate positions and covariance matrice with Earth-rotation parameters which are then passed on to GLOBK.

If the data quality for each station meets several predetermined requirements the data-set is passed onto GLOBK which attempts to stablize the stations' positions with user-defined constraints in a specified reference frame by applying a Kalman filter to produce station position time series. In this stage UWISRC stations are generally loosely constrained due to poor a priori positions while international stations are tightly constrained with minimal adjustments being made.

4.0 RESULTS AND ANALYSIS

4.1 GAMBIT\GLOBK Results and Analysis

The results presented are statistical values that stand as quality indicators of the data at several of the cGPS array stations as processed using the GAMIT\GLOBK software. These values are critical towards determining the reliability of derived station coordinates and velocities and moreover, the quality of the entire network.

The results presented are for the period 2007/2008 and highlight the average daily total satellite observations (Fig. 3), average daily unresolved cycle slips (Fig. 4), average daily observation RMS values versus elevation angle (Fig. 5) and average normalised RMS values for station positions (Table 2). With respect to Table 2, the results yielded a $\chi^2 = 0.6$ goodness-of-fit when stations' positions were stabilized in the relatively stable South American ITRF.

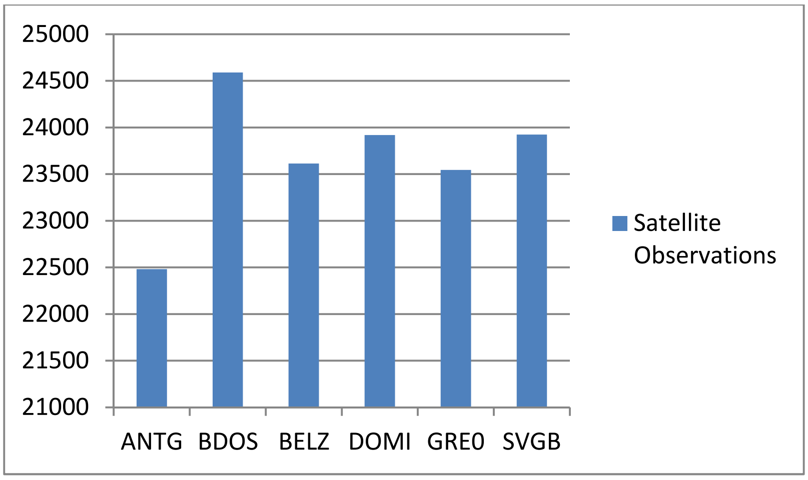

Fig. 3. Averaged daily total satellite observations for UWISRC stations. (BDOS is an NGS operated CORS station).

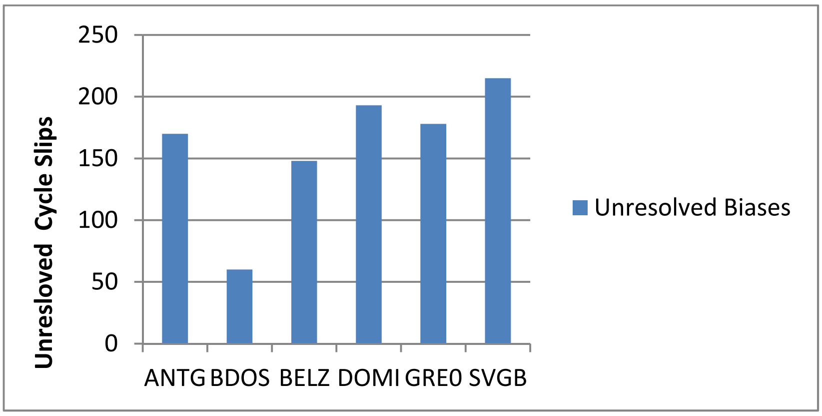

Fig. 4. Average daily unresolved cycle slipses of UWISRC stations. (BDOS is an NGS operated CORS station).

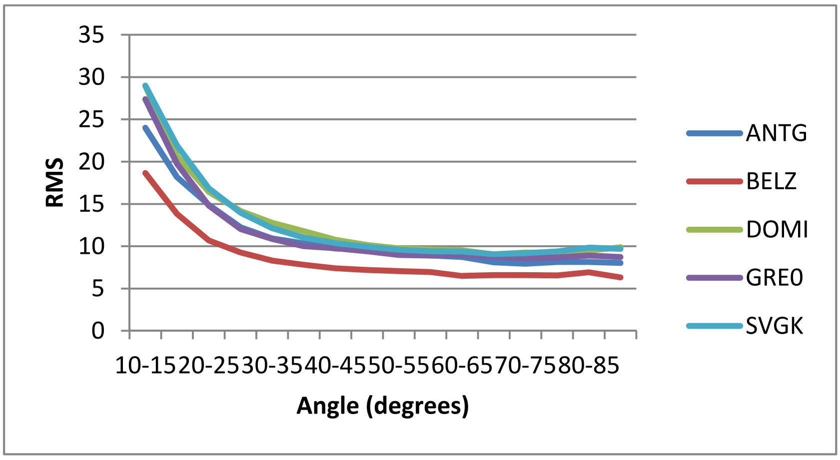

Fig. 5. Average daily RMS of observation with respect to elevation.

Table 2 Average NRMS of stations positions for the period of 2007 to 2008.

STATION	NRMS (mm)
ANTG	0.0051
BELZ	0.0054
DOMI	0.0049
DOMP	0.0102
DOMR	0.0059
GRE0	0.0050
STKN	0.0062
SVGB	0.0058
SVGK	0.0058
TSCA	0.0063

The processing results indicate that the data recorded by the UWISRC stations are contaminated by measurement errors and biases that impact on the overall quality of the position solution computed. These sources of errors and biases may arise from multipath, atmospheric fluctuations or satellite elevation dependencies.

It is entirely plausible that atmospheric fluctuations can contrubute to the high RMS of position estimates due to unpredictable propagation delay. With regards to the Eastern Caribbean, the atmosphere's thickness and water vapor content is seasonally in great flux. That coupled with most islands possessing mountainous centres that contribute to orogenic cloud formation, detected cycle slipses will be high and possibly impossible to model and elimate.

The contribution of multipath is more tractable since all stations were installed in very identical fashions. All antennas were installed on concrete roofs that may just contribute to multipath effects. The qualification of multipath for each site and its cause is currently being investigated. What is evident however is the requirement for robust quality control (QC) measures to be considered as part of the overall data processing architecture for the cGPS network.

The next section presents some preliminary QC data analysis results that form the basis for further research investigation in the are of GNSS QC for seismic monitoring.

4.2 cGPS Measurement Data Quality Control

Analysis of the raw GNSS measurements acquired at individual cGPS sites is a key component of the overall quality control process of assuring the integrity of the infrastructure. Stability assessments made on the basis of this measured data is directly a function of the quality of the measurements made. In this section, an assessment is made of the quality of the data collected at each of the cGPS sites over a 24 hour time period on the 2nd June 2010. The Leica SpiderQC^{TM} Software was used to produce the quality information presented here and a summary of the proccessing results are shown in Table 3.

Table 3 Summary statistics from Leica SpiderQC™ processing

Station Name	Overall	Cycle Slips	Multipath	Completeness	PDOP MAX
ANTG	FAIL	FAIL	PASS	FAIL	9.6
BELZ	FAIL	PASS	PASS	PASS	9.7
DOMI	PASS	PASS	PASS	PASS	9.7
DOMP	FAIL	FAIL	PASS	FAIL	10.6
DOMR	PASS	PASS	PASS	PASS	9.7
GREO	PASS	PASS	PASS	PASS	9.3
SVGB	PASS	PASS	PASS	PASS	9.6
SVGK	PASS	PASS	PASS	PASS	9.6
STKN	PASS	PASS	PASS	PASS	9.1

24 hour (30sec. recording interval) rinex files for each of the cGPS sites in column one were processed in SpiderQC. The second column shows the overall result of the QC tests completed. A pass indicates that both the general and GPS specific tests identified in the tables below have satisfied the minimum threshold levels specified. CORS station BELZ appeared to have experienced an anomaly with regards to a change in the recording internal during the data series, however the results of the other two sites ANTG and DOMP are presented in Tables 4, 5 and 6.

Table 4 Test results from Spider QC for station ANTG.

	Pass/Fail	**Details**
General Tests		
Epochs With Data:	Pass	Value 100.0 %, Threshold 99.0 %
File Format:	Pass	
RX Clock:	Pass	
Other:	Pass	
GPS Specific Tests		
Cycle Slips:	Fail	Value 67 slips, Threshold 43 slips
Multipath:	Pass	Value 0.26m MP1 / 0.36m MP2, Threshold 0.5 m
Data Completeness:	Fail	Value 93.4 %, Threshold 95.0 %
Navigation Data:	Pass	

Here it can be seen that the data from this station (ANTG) fails the QC tests, in terms of the number of cycle slips experienced and on the completeness of the data. In particular, satellite 16 (see Table 5) experiences a large number of cycle slips (20) with a corresponding loss of raw data recorded for that satellite.

Table 5 Satellite observation parameters for station ANTG

SV	Min Elev	Max Elev	Possible Observations	Actual Observations	Observations with Invalid Ephemeris	Cycle Slips
G2	15.04°	56.80°	890	890 (100.0 %)	0 (0.0 %)	0
G3	15.10°	83.70°	693	693 (100.0 %)	0 (0.0 %)	0
G4	15.01°	46.54°	931	931 (100.0 %)	0 (0.0 %)	1
G5	15.03°	53.35°	909	909 (100.0 %)	0 (0.0 %)	0
G6	15.01°	84.61°	671	671 (100.0 %)	0 (0.0 %)	9
G7	15.00°	69.30°	610	610 (100.0 %)	0 (0.0 %)	0
G8	15.01°	54.33°	659	606 (92.0 %)	0 (0.0 %)	5
G9	15.12°	78.66°	615	615 (100.0 %)	0 (0.0 %)	0
G10	15.06°	69.74°	755	718 (95.1 %)	0 (0.0 %)	6
G11	15.09°	86.34°	705	705 (100.0 %)	0 (0.0 %)	1
G12	15.00°	45.06°	803	803 (100.0 %)	0 (0.0 %)	0
G13	15.01°	42.39°	833	833 (100.0 %)	0 (0.0 %)	2
G14	15.05°	60.50°	854	854 (100.0 %)	0 (0.0 %)	0
G15	15.20°	74.35°	735	713 (97.0 %)	0 (0.0 %)	0
G16	15.03°	63.00°	834	803 (96.3 %)	0 (0.0 %)	20
G17	15.03°	60.39°	864	864 (100.0 %)	0 (0.0 %)	0
G18	15.07°	77.06°	734	734 (100.0 %)	0 (0.0 %)	0
G19	15.03°	78.74°	713	713 (100.0 %)	0 (0.0 %)	1
G20	15.04°	50.50°	730	730 (100.0 %)	0 (0.0 %)	0
G21	15.04°	61.89°	591	591 (100.0 %)	0 (0.0 %)	0
G22	15.02°	84.69°	663	663 (100.0 %)	0 (0.0 %)	0
G23	15.05°	51.59°	718	676 (94.2 %)	0 (0.0 %)	8
G24	15.00°	46.23°	797	748 (93.9 %)	0 (0.0 %)	7
G26	15.18°	68.26°	719	694 (96.5 %)	0 (0.0 %)	4
G27	15.01°	71.76°	616	616 (100.0 %)	0 (0.0 %)	0
G28	15.04°	89.12°	663	663 (100.0 %)	0 (0.0 %)	0
G29	15.04°	39.99°	843	842 (99.9 %)	0 (0.0 %)	3
G30	15.02°	65.40°	594	594 (100.0 %)	0 (0.0 %)	0
G31	15.02°	42.43°	953	953 (100.0 %)	0 (0.0 %)	0
G32	-	-	856	0 (0.0 %)	0 (0.0 %)	0

Similar results were experienced for DOMP which also failed the overall quality test. In this case the overall specific test results were more significant. It should be noted that these results are not entirely surprising for DOMP, as the station is on a ridge on the flanks of the Morne aux Diable volcano. This ridge is not the highest and it is very possible that the volcano is impacting the receiver sky view and GPS observations. The main function of this station is to monitor volcanic activity since the volcano is not dormant, so this represented the most suitable location to collect both seismic and cGPS data.

Table 6 GPS Test results from Spider QC for station DOMP

GPS Specific Tests		
Cycle Slips:	Fail	Value 408 slips, Threshold 44 slips
Multipath:	Pass	Value 0.45m MP1 / 0.44m MP2, Threshold 0.5 m
Data Completeness:	Fail	Value 88.8 %, Threshold 95.0 %
Navigation Data:	Pass	

Again, here the report shows a large number of cycle slips resulting in loss of raw measurement data. Further analysis indicates low satellite elevation as being the dominant effect on the quality of the measurement signal. However, the large number of measurements available still provides sufficient redundancy for final processing of the position solution as shown in Table 7. This table shows the results of a GPS Precise Point Positioning (PPP) solution determined using the Bernese GNSS processing software. The PPP solution allows for a further check on the integrity of the measured data at the CORS sites. When used in conjunction with the QC tests previously demonstrated, the PPP solution facilitates an additional robust and autonomous pre-processing step on the GNSS data used in the subsequent CORS stability analysis presented in this paper.

Table 7 Bernese PPP solution results

Station name	**Typ**	**Estimated value**	**RMS error**
antg	X	2882699.822	0.0211
antg	Y	-5374965.129	0.028
antg	Z	1859442.956	0.0109
belz	X	190774.3438	0.0161
belz	Y	-6082364.017	0.0288
belz	Z	1903871.323	0.0111
domi	X	2946569.18	0.0198
domi	Y	-5401941.821	0.0252
domi	Z	1672799.071	0.0099
domp	X	2939040.732	0.0483
domp	Y	-5395589.796	0.0695
domp	Z	1707131.085	0.0248
domr	X	2936451.601	0.0212
domr	Y	-5399030.819	0.0273
domr	Z	1699598.097	0.0102
gre0	X	2961421.072	0.0201
gre0	Y	-5486288.764	0.0257
gre0	Z	1341394.414	0.0088
stkn	X	2790091.957	0.0275
stkn	Y	-5415021.84	0.0305

It is noted at this stage the the quality assessment measures from SpiderQC support the results generated from the GAMIT\GLOBK processing, with both the 24 hour and longer period evaluations pointing to the need for robust quality control measures to be included as part of the data processing strategy for the cGPS network

5.0 CONCLUSION AND FUTURE DEVELOPMENTS

Initial quality assessments of the continually evolving UWISRC cGPS array bodes well for its future. Its context, purpose, development, applications and some quality excerpts from the processing done at the UWISRC have been presented to demonstrate this. It is certainly an encouraging prospect for the region that UWISRC staff continues to build upon its knowledge of processing techniques and wider applications of the network in light of the recent Haiti devastation of January 2010, and more recently, the Japan earthquake of March 2011.

Already efforts are being made to investigate the quality of the data further as well as applying processing techniques using alternate and sophisticated processing tools through the Bernese processing engine.

Also, the UWISRC has recently partnered with UNAVCO in the development of that latter's envisioned COCONET. COCONET is an NSF funded initiative for a Continuously Operating Caribbean GPS Observational Network (UNAVCO 2011).

The UNAVCO website describes the UNAVCO initiative thus,

> "*The international geoscience community is planning for Caribbean-wide GPS observations to support investigation of process-oriented science questions with direct relevance to Earth and atmospheric hazards, and to provide for regional capacity building focused on science and international collaborations" (UNAVCO 2011).*

It is the intention of the UWISRC to make the data from its cGPS array available for the COCONET initiative.

The near future may also witness the introduction of several more stations cGPS, in particular two stations near the CRF (Central Range Fault) in Trinidad. These planned stations are being installed with the cooperation of the Trinidad and Tobago Lands and Surveys division to serve both the surveying/geodetic and geologic communities. These future initiatives would greatly benefit from the implementation of robust quality control measures as part of the data collection and processing strategy.

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