A Study of the Use of GPS Sensors for Structural Monitoring of the Mactaquac Dam

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ABSTRACT:

The expansion of concrete caused by alkali-aggregate reaction (AAR) causes significant deformation at the Mactaquac Generating Station, Keswick Ridge, New Brunswick, Canada. Several technologies are used to monitor the deformation behaviour including strain gauges, crackmeters, borehole extensometers, fibre optic sensors and inverted pendulums. The inverted pendulums provide critical information regarding the overall tilt of the concrete structures. The expenses associated with installing such technology and the relatively short life expectancy (due to the large deformations that takes place either from the phenomenon of AAR or from remedial measures that are used to control the effects of AAR) have led engineers to investigate the potential of using GPS sensors to provide supplementary information about movement of the crest of the dam. Six GPS stations were installed at the Mactaquac Generating Station. Two stations were located at the ends of the Diversion and two more stations were located on the crest of the Main Spillway. Two stations were established as reference stations from which relative positions are calculated. Data from the first several months of installation are presented and analyzed. By comparing the displacement information obtained using GPS with the information obtained from the other sensors, conclusions are drawn from the perspective of assessing GPS as a tool for monitoring deformation in dams. Displacement update frequency, displacement accuracy and the overall contribution of the displacement information to the understanding of the deformation behaviour are considered.

RÉSUMÉ:

L'expansion du béton causée par la réaction alcali-granulats (RAG) provoque une déformation importante à la station de Mactaquac, Keswick Ridge, au Nouveau-Brunswick, Canada. Plusieurs technologies sont utilisées pour surveiller le comportement de déformation des jauges de contrainte, y compris, crackmeters, extensomètres de forage, des capteurs à fibre optique et pendules inversés. Les pendules inversés fournir des informations critiques à l'égard de l'inclinaison globale des structures en béton. Les dépenses associées à l'installation de cette technologie et l'espérance de vie relativement courte (en raison de fortes déformations qui se déroule soit à partir du phénomène de la RAG ou de mesures correctives qui sont utilisés pour contrôler les effets de la RAG) ont conduit les ingénieurs à étudier le potentiel de l'aide de capteurs GPS pour fournir des informations complémentaires sur le mouvement de la crête du barrage. Six stations GPS ont été installés à la station de Mactaquac. Deux stations sont situées aux extrémités de la dérivation et deux autres stations sont situées sur la crête du déversoir principal. Deux stations ont été établies de stations de référence à partir duquel sont calculées les positions relatives. Statistiques des premiers mois de l'installation sont présentés et analysés. En comparant les informations de déplacement obtenues à l'aide de GPS avec les informations issues des capteurs d'autres, les conclusions sont tirées de la perspective de l'évaluation de GPS comme outil de surveillance de la déformation dans les barrages. Fréquence d'actualisation de déplacement, la précision de déplacement et de la contribution globale de l'information de déplacement à la compréhension de la déformation sont pris en considération.

1 INTRODUCTION

The NB Power Mactaquac Generating Station (Figure 1) is located 20 kilometers north of Fredericton, New Brunswick, on the Saint John River and was commissioned in 1968. Today the station has six units with a generating capacity of 672 megawatts.

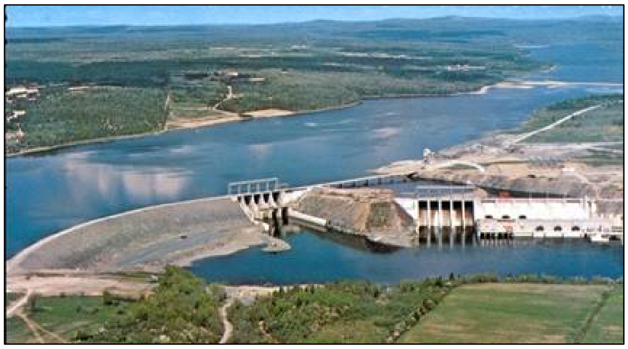

Figure 1. Mactaquac Dam, Keswick Ridge, NB (from Agora, 2008)

In the late 1970s, the dam began to show cracking concrete and separating joints. In the early 1980s, instrumentation was installed in the powerhouse and the water retaining structures to measure the effects of the openings and cracking. Instrumentation included borehole extensometers, tape extensometers, plumblines, inverted pendulums, 4-pin gauges, strain gauges, stress cells and joint meters. By 1985, structural problems were occurring including jamming of gate 10 at the intake spillway, more pronounced cracking of the concrete and expanding joint openings.

In the mid 1980s the phenomenon occurring at Mactaquac was identified as Alkaline Aggregate Reaction (AAR). In 1988, remedial measures began to relieve the stress caused by AAR and these activities continue such as diamond wire saw cutting that is used to make 15 millimeter slot cuts in the powerhouse and the water retaining structures. Before cutting, multi-strand tendons and anchors were installed on the downstream face of the intake to provide extra strength to the structure. To date, there have been 28 different areas cut with 15 of these requiring regular re-cutting due to the high AAR growth rate.

An extensive monitoring scheme is in place at Mactaquac to provide close scrutiny of the health status of the dam. Due to the large amount of time required to perform manual readings of some instrumentation, low cost automated systems that can achieve high accuracy are favored when implementing new technology. The use of ShapeAccelArray (SAA) technology is currently being investigated for monitoring tilt of the dam (Bond et al., 2009). It was also recently decided to investigate the potential of Global Positioning System sensors as part of the instrumentation program. A description of the GPS monitoring system implemented and an analysis of initial results is presented.

2 GLOBAL POSITIONING SYSTEM (GPS) FOR DEFORMATION MONITORING

Since the mid 1980s, GPS has been used for various positioning applications (Leick, 1994). As knowledge of GPS error sources and how to mitigate them improved, its use for precise monitoring applications grew. In particular, the use of Differential GPS, in which one receiver is located relative to another of known position ("baseline"), has allowed sub-centimetre accuracies to be commonly achieved. The use of GPS technology in various handheld devices and for vehicular navigation has driven the cost of OEM GPS boards to unprecedented lows.

GPS has the following favourable characteristics as a monitoring technology (Bond, 2007):

a) Line of sight is not required between stations;

b) Updates can be provided at frequencies of 1 Hz and higher;

c) 3 dimensional position information is provided;

d) Millimetre level position information is possible for short baselines (<10 km); and

e) By isolating information of interest from the GPS measurements (mainly in the measurement domain), GPS can also be used to determine orientation and vibration. This is possible even with limited satellite visibility.

Challenges associated with using GPS technology for monitoring applications include:

a) Supplying power to GPS units when a large number of targets must be monitored. GPS receivers collect data continuously and therefore must be powered at all times. Typically wireless communications devices are also required for data collection. Although both devices are low power consumers, the constant need for power can require large solar panels, in particular in northern areas.

b) Having good satellite visibility (at least four satellites are required to obtain a unique solution). In order to achieve the highest precision, there must be few obstructions near the GPS antenna and 6 or more satellite should be visible from all portions of the sky.

c) Identifying stable reference points. The assumption when performing differential GPS positioning is that the reference station is stable. If this is not the case, the GPS antenna being monitored will appear to be moving. Tremendous care must be taken in choosing suitable reference station locations as well as in choosing materials for mounting GPS antennas.

d) Minimizing the effects of multipath. Multipath is the arrival of the same GPS signal via multiple paths at the antenna, caused by nearby or remote reflectors. In deformation monitoring environments where multipath sources are abundant (e.g., building structures, vehicles) multipath can contaminate the position solutions. Practically every observation site is affected to some degree by multipath. Multipath biases can reach up to 4.8 cm for the original L1, GPS carrier-phase measurement (Georgiadou and Kleusberg, 1988).

e) Minimizing the effects of diffraction. Diffraction occurs when the GPS signal is obstructed but still arrives at the GPS receiver and is processed. The obstruction causes a longer propagation time which can cause carrier phase observation errors of up to several cm. Diffracted measurements are typically characterized by low Signal-to-Noise values. (Wanninger et al., 1999; Brunner et al., 1999; Richter and Euler, 2001)

2.1 Displacement Detection Example

To illustrate the capabilities of GPS technology for displacement detection, a simulation was conducted. The simulation environment consisted of a GPS reference station and a GPS monitored station with its antenna mounted on motorized translation stage (Figure 2). The translation stage allows both horizontal (east direction) and vertical movements of the monitored station antenna with sub-millimetre level precision.

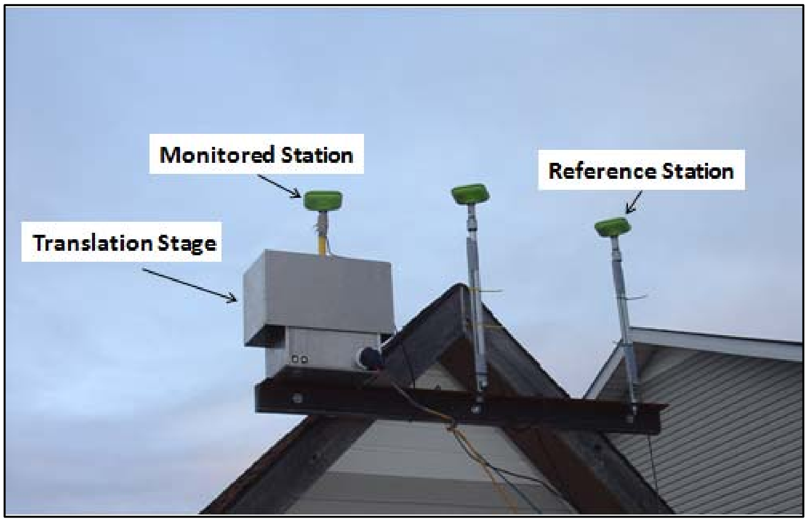

Figure 2: Displacement Detection Simulation Environment

After approximately 15 hours of stationary data collection, the monitored station's antenna was moved 5 mm in the east direction using the translation stage. Figure 3 illustrates the east component solutions as output by the processing software. The observations were collected at 1 Hz. Varying degrees of a low-pass filter time constant (1, 3, 6 and 12 hours) are applied to the 1 Hz solutions to illustrate the displacement trend. It can be seen that longer filtering time constants provide higher precision solutions but increase the time required for displacement detection. The 5 mm displacement is clearly illustrated by all filtered output types.

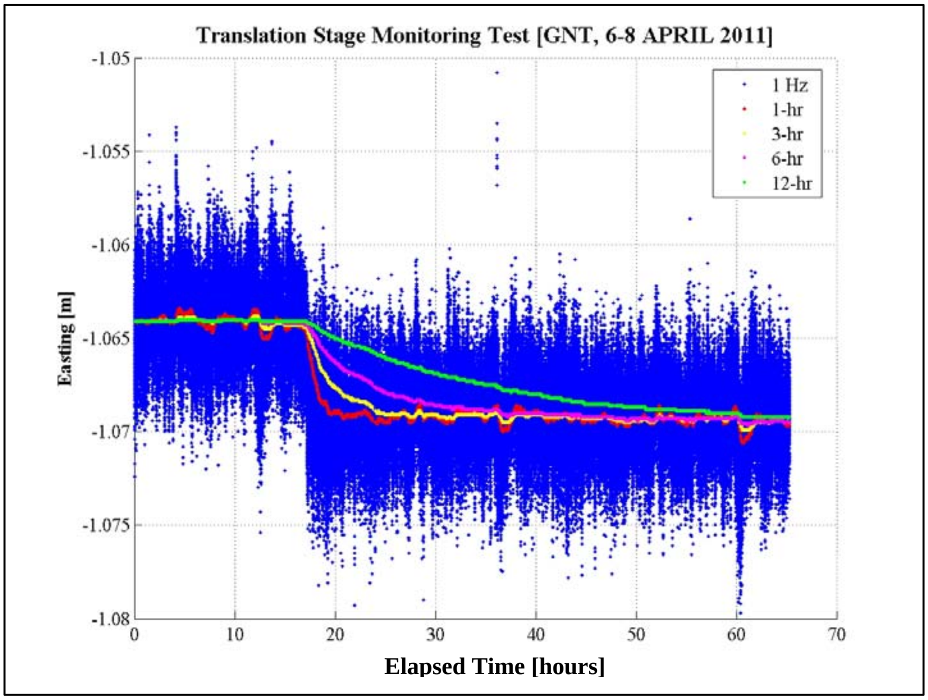

Figure 3: mmVu™ Software East Component Output

3 GPS MONITORING SCHEME

3.1 Network Configuration

Four areas of interest were identified on the Mactaquac Dam to be monitored with GPS based upon known deformation activity. Annual and thermal displacement information is summarized for these locations based upon local, right-handed coordinate systems at the Diversion and Main Intake (see Figure 4). The values are based upon inverted pendulum and plumb line readings. The upper limit of the thermal effects occurs in early September and the lower limit occurs in early March.

i. Station 1 - the East End Pier (EEP) of the main intake. The EEP's expected deformation behaviour is an annual cycle of 2.00 mm in the X1 direction and 1.35 mm in the Y1 direction. The maximum thermal effect is 2.00 mm in X1 and 3.00 mm in Y1.

ii. Station 2 - the West End Pier (WEP) of the main intake. The WEP's expected deformation behaviour is an annual cycle of 0.50 mm in the X1 direction and 0.60mm in the Y1 direction. The maximum thermal effect is 3.0 mm in X1 and 2.00 mm in Y1.

iii. Station 3 – The North End Pier (NEP) of the diversion. The NEP's expected deformation behaviour is an annual cycle of 0.60 mm in the X2 direction and 0.85 mm in the Y2 direction. The maximum thermal effect is 2.50 mm in X2 and 2.00 mm in Y2.

iv. Station 4 – The South End Pier (SEP) of the diversion. The SEP's expected deformation behaviour is an annual cycle of 0.70 mm in the X2 direction and 0.40 mm in the Y2 direction. The maximum thermal effect is 13.00 mm in the X2 and 2.00 mm in the Y2.

Two reference stations were chosen from which the relative positions of the above stations would be determined. The use of two reference stations allows for independent baseline solutions to be compared. The two reference stations are:

v. Station 100 – located on slab of bedrock ("Rock Island") between the Main Intake and the Diversion.

vi. Station 101 – located on bedrock to the north of the head pond.

Each station uses Javad Delta G2T dual frequency GPS receivers with Javad TriAnt antennas. Data is streamed from each receiver to a Gemini NavSoft Technologies' Solution Station running mmVu™ software. Moxa 2.4 Ghz WiFi infrastructure is implemented to facilitate data streaming. Three access points (AP 1, AP 2 and AP 3) are utilized to allow each receiver and the Solution Station to connect to the local network. The layout of the GPS network and communications infrastructure is illustrated in Figure 4.

Installation of the monitoring system took place over the month of December, 2010. Data collection and processing began January 6th, 2011. At the time of this paper, approximately five months of data and results were available. Reference Station 101 had not yet been installed, so all baselines were measured to Reference Station 100. The cost of the entire GPS monitoring system was less than the cost of installing one inverted pendulum instrument.

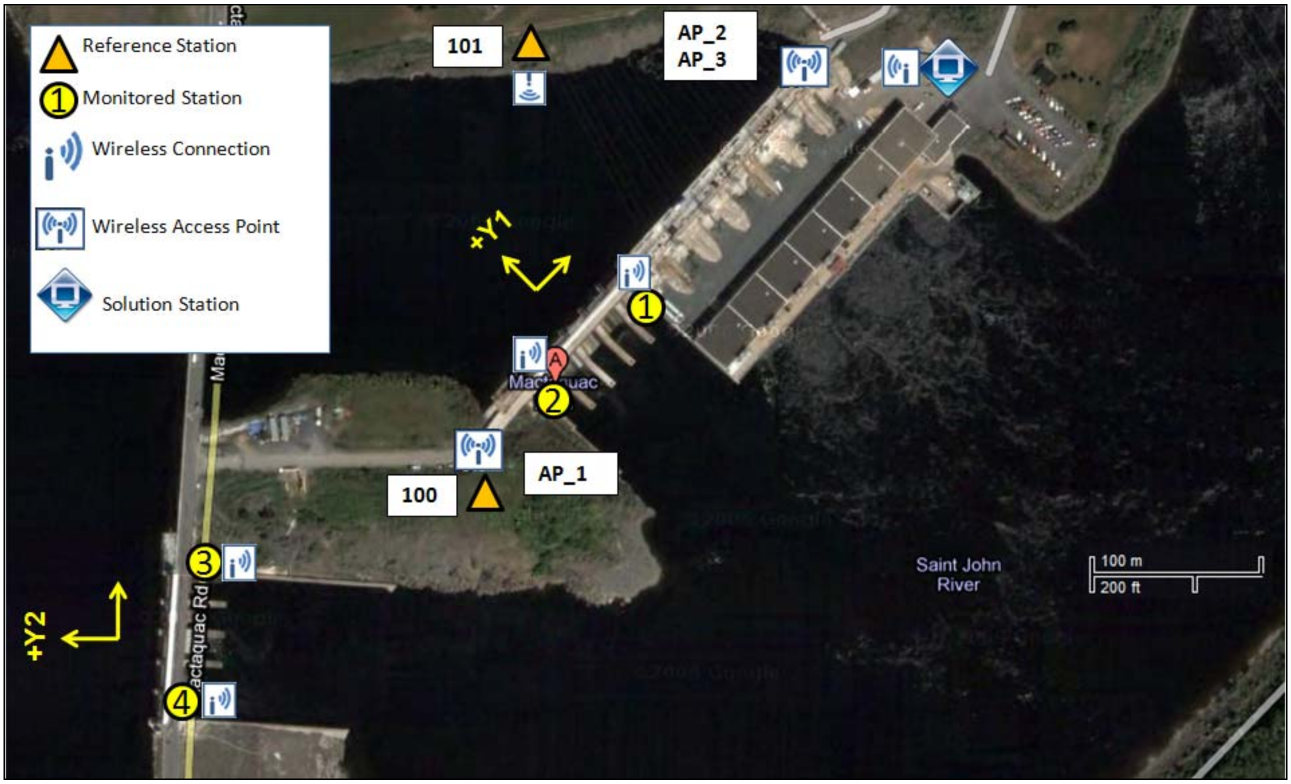

Figure 4: GPS Network with Communications Infrastructure (background image from Google Maps)

3.2 GPS Monitoring Challenges

Each of Stations 1 through 4 poses its own challenges in terms of using GPS for deformation monitoring. In particular, each of these stations is affected in varying degrees by challenges associated with satellite visibility, multipath and diffraction.

Station 1 is located within 2 metres of a transmission line tower (Figure 5). The tower is located to the north of the antenna. The tower causes blockages in satellite signal and is a multipath and diffraction source. The location of the obstruction is important. The design of the GPS satellite constellation is such that there is a void of GPS satellites in the North sky. Thus, if an obstruction must be nearby a GPS antenna, it is the least offensive if it is located to the north. Unfortunately, the size of this obstruction is so large and it is so close to the antenna that it will also block satellite signals coming from the northeast and northwest quadrants. Also contributing to multipath, diffraction and limited satellite visibility at this site is the large intake gate located to the northwest of the antenna.

Figure 5: Station 1 (near arrow) with and Station 2 (far arrow) locations

The transmission tower is a grid structure, so it allows GPS signals to pass through it. The effects of the obstruction on the satellite signal can be seen in Figure 6 which illustrates Signal-to-Noise Ratio (SNR) plots, (given by the dB-Hz unit) of satellite signals observed at Station 1 (top) and Station 4 (bottom). Station 100 is located in an area without obstructions. All satellite signals exhibit the signal signature shown where the SNR values gradually increase in value as the satellite rises and then decrease in value as the satellite sets. Station 1 tracks several satellites exhibiting the other signal signature shown, which is characteristic of a diffracted measurement. In this case, the previous parabolic signature is disrupted when obstructions increase the noise level in the observations. Noisier observations inevitably lead to noisier solutions unless they are properly handled.

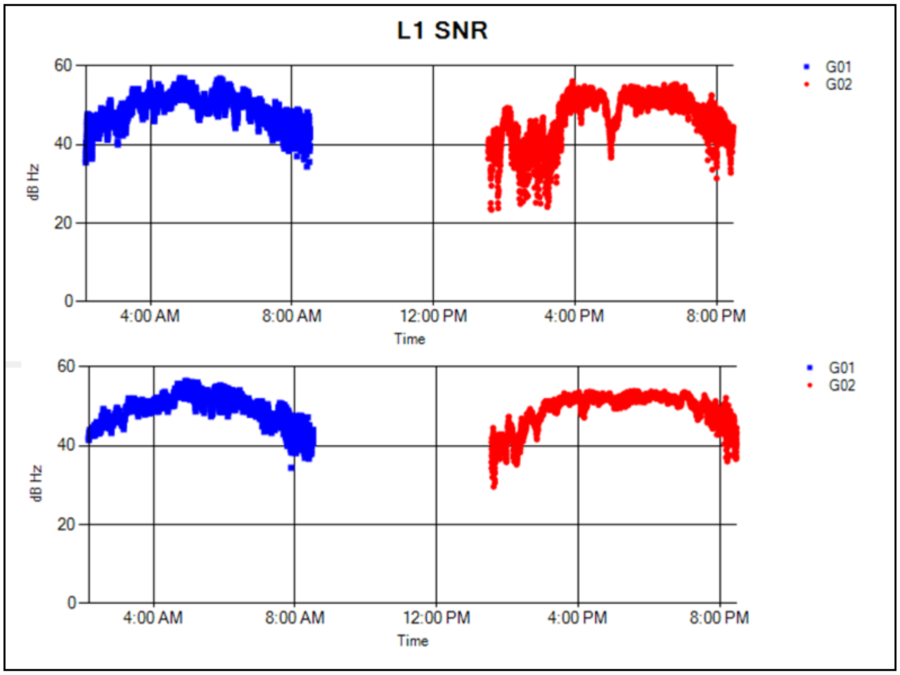

Figure 6: Comparison of SNR values for Satellite 01 and Satellite 02 observed at Station 1 (top) and Station 4 (bottom)

To further illustrate the challenges associated with using GPS at Station 1, Figure 7 illustrates measurement quality indicators for GPS satellite 06 while being tracked at Station 1 (top) and Station 3 (bottom). Profiled errors are generated by holding the position of the station fixed and calculating the variation in the observations. Typical values of the profiled errors for both the L1 and L2 GPS frequencies are less than 10 mm. Those shown for Station 1 are up to four times larger than what is normally expected. In contrast, when this same satellite is tracked at Station 3, the profiled errors are in the normal range. It should be noted that although this particular satellite shows better measurement quality at Station 3, many of the other satellites tracked at Station 3 illustrate the same degradation due to the presence of the gate as is later discussed.

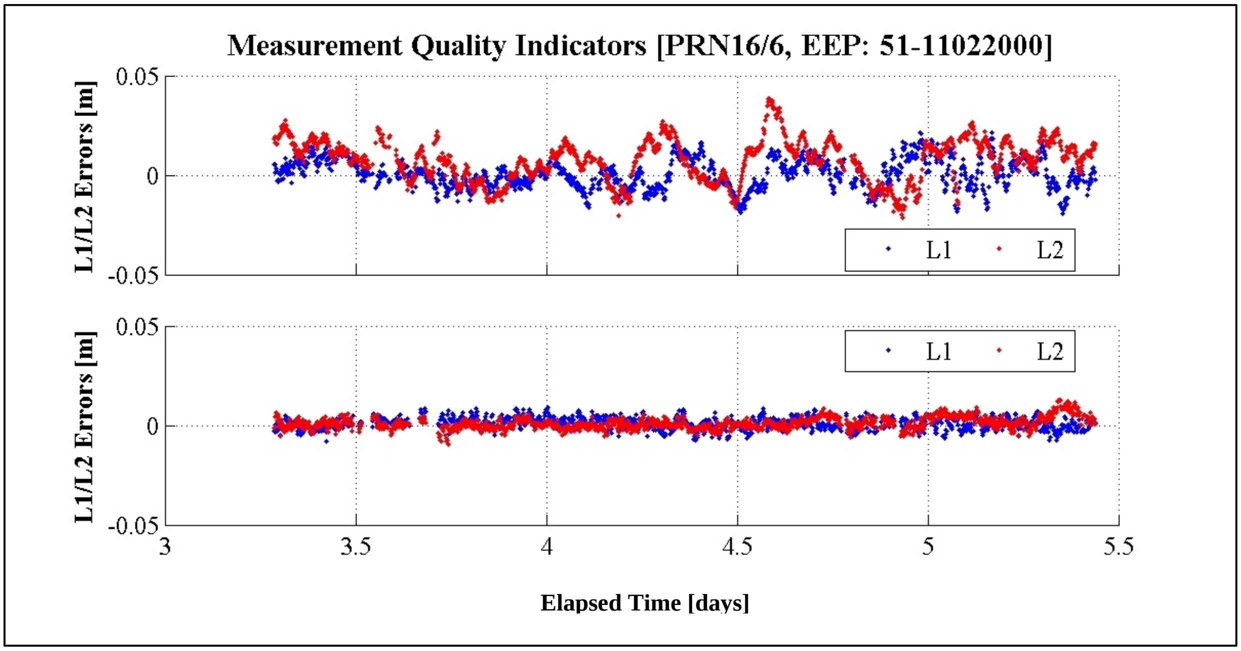

Figure 7: Measurement Quality Indicators for Satellite 06 at Station 1 (top) and Station 3 (bottom)

Station 2 is located at the opposite end of the gate shown in Figure 5, so it experiences blockages in satellite signals from the northeast quadrant. It does not have to contend with a transmission tower as is the case at Station 1.

Stations 3 and 4 are also located within proximity to another gate located on the Diversion (Figure 8). These stations are located further away from the gate than Stations 1 and 2, which slightly reduces its impact in reducing satellite visibility. The gate is located to the southwest of Station 3 and northwest of Station 4.

Figure 8: Station 3 (near arrow) and Station 4 (far arrow)

4 RESULTS

Data from each of the four monitored stations were processed to determine their positions relative to the location of Reference Station 100 ("baseline solution"). East, north and up components were calculated and then these values were transformed into the local coordinate systems used at the Main Intake and Diversion structures. Data were processed using Gemini Navsoft Technologies' precision positioning software (mmVu™). Solutions were calculated every 5 seconds, and these results were filtered in the processing engine to output 24 hour (subsequently shown in blue) and 7 day (subsequently shown in red) low-pass, filtered solutions.

Figure 9 and Figure 10 illustrate the along track (along the crest of the Main Intake), across track (across the crest of the Main Intake) and height component positions of the GPS antennas from 05 Jan 2011 to 31 May 2011at Stations 1 (EEP) and 2 (WEP) respectively. It can be seen that Stations 1 and 2 show similar displacement patterns. The following comments can be made:

a. Both Station 1 and Station 2 show the smallest movements in the along track directions. Over this 5 month period, less than 3 mm movement can be seen.

b. Both Station 1 and Station 2 show gradual changes in the across direction of about 8 mm which peak near the beginning of March and come back to their original positions towards the end of the month.

c. Both Station 1 and Station 2 show gradual changes in height of about 8 mm which peak near the beginning of March and come back to their original positions towards the end of the month.

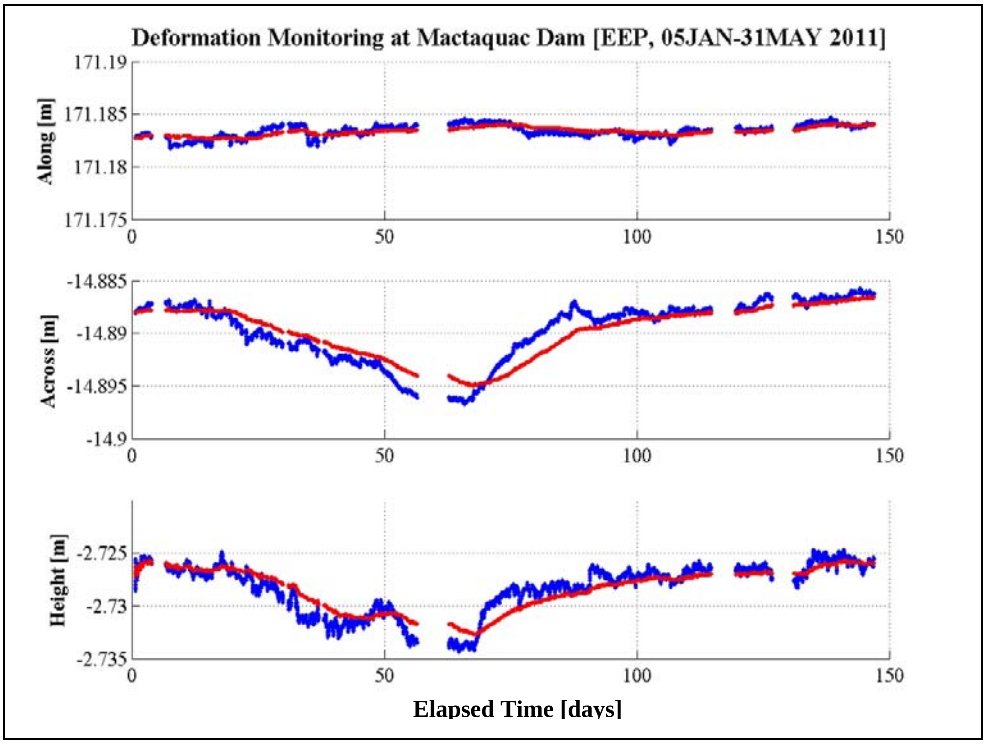

Figure 9: Station 100 to Station 1 (EEP) Baseline Solution Components

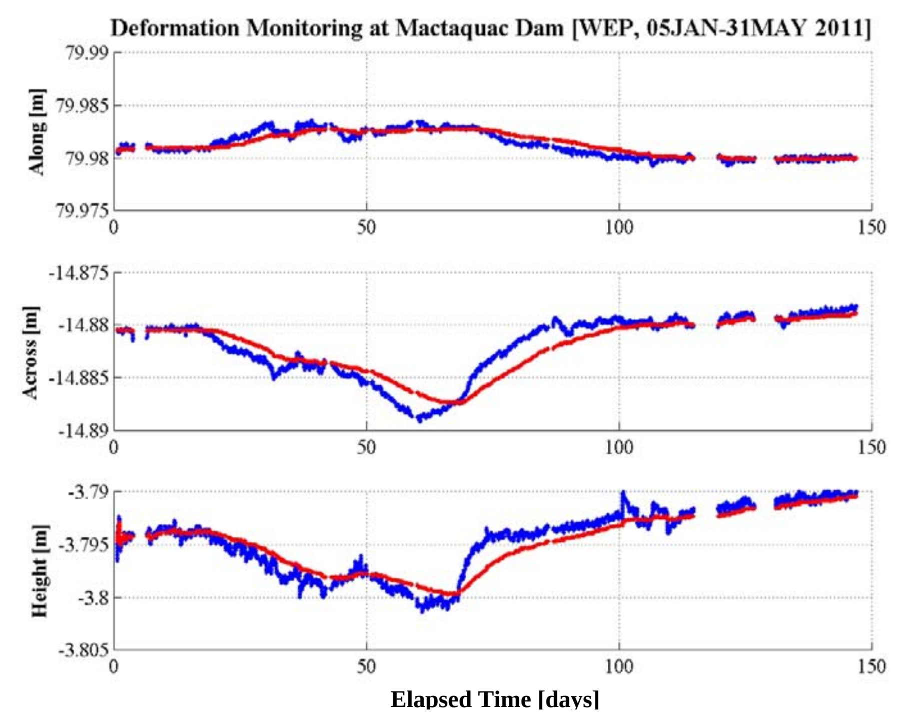

Figure 10: Station 100 to Station 2 (WEP) Baseline Solution Components

Figure 11 and Figure 12 illustrate the along track (along the crest of the Diversion), across track (across the crest Diversion) and height component positions of the GPS antennas from 05 Jan 2011 to 31 May 2011at Stations 3 (NEP) and 4 (SEP) respectively. The following comments can be made:

a. Both Station 3 and Station 4 show the smallest movements in the along track directions. Over this 5 month period, slightly more than 5 mm movement can be seen.

b. Station 3 and Station 4 undergo different displacement trends in the along track direction.

c. Both Station 3 and Station 4 show gradual changes in the across direction of about 8 mm which peak near the beginning of March and come back to their original positions towards the end of the month.

d. Both Station 1 and Station 2 show gradual changes in height of about 8 mm which peak near the beginning of March and come back to their original positions towards the end of the month.

Looking at the monitored stations collectively, it can be seen that all monitored stations experience the same gradual changes in both the across and height directions which peak near the beginning of March and come back to their original positions towards the end of the month.

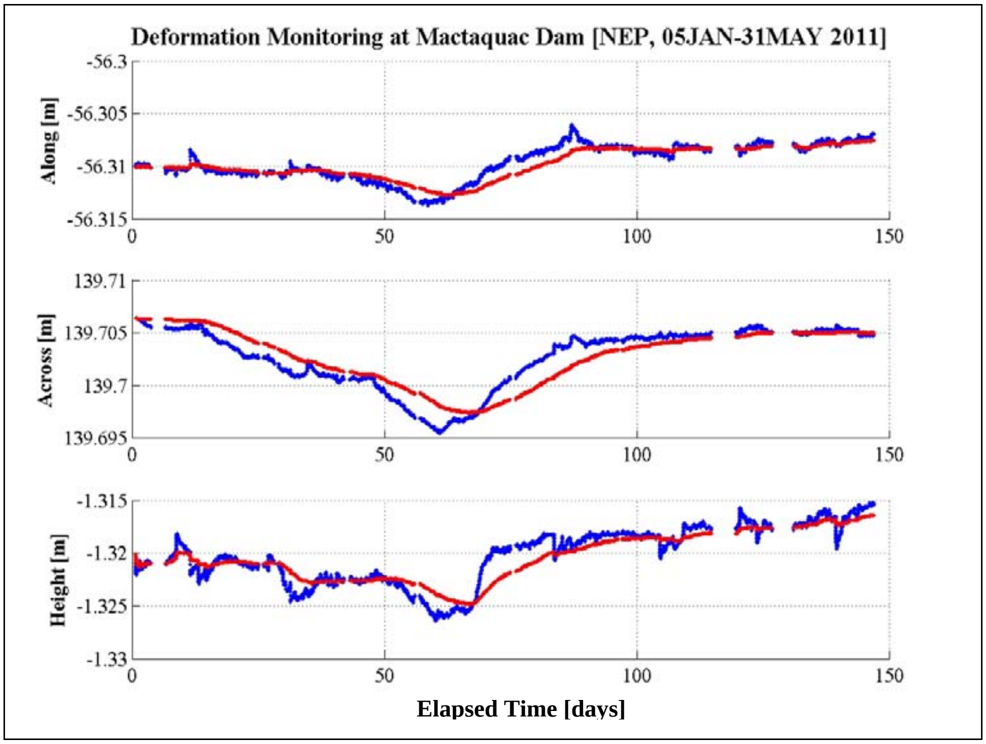

Figure 11: Station 100 to Station 3 (NEP) Baseline Solution Components

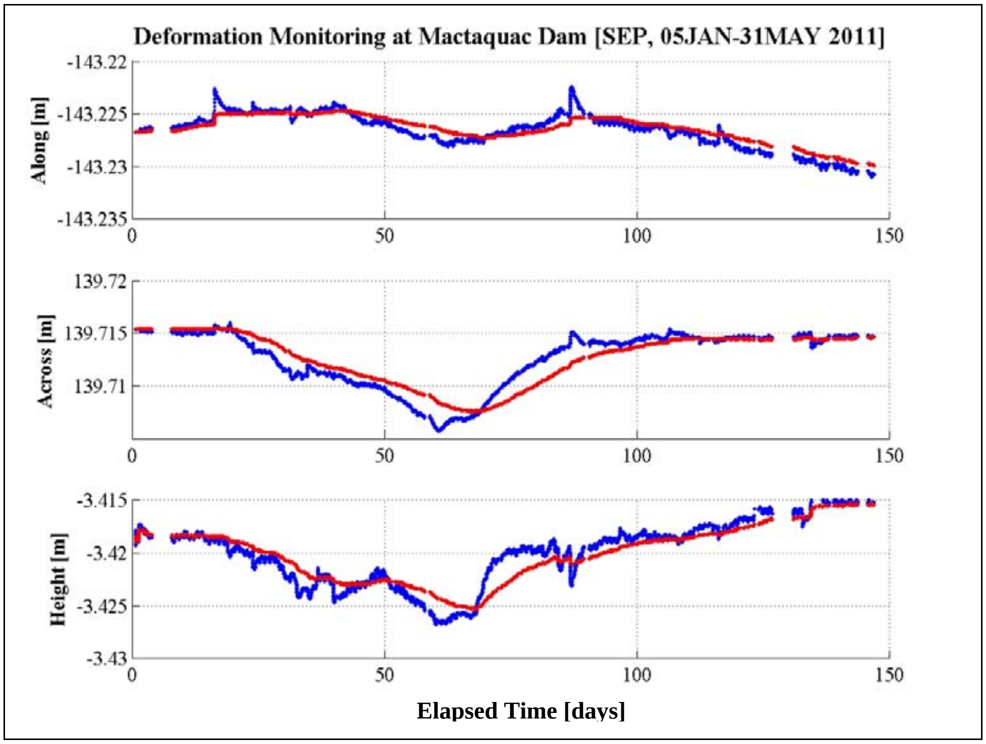

Figure 12: Station 100 to Station 4 (SEP) Baseline Solution Components

5 DISCUSSION

The slow, gradual displacement trend which culminates around the beginning of March and then returns to its original position resembles a freeze-thaw cycle. At present it is not possible to definitively say whether or not this is the case. As more data is collected, annual cycles will more clearly emerge and the displacement trends will be more easily identified.

When the achieved GPS monitoring results are compared with the displacement values determined from other instrumentation (Section 3.1), it can be seen that the measured values are larger than the expected values, particularly in the Y direction. Possible explanations are subsequently discussed.

5.1 Unstable GPS Reference Station

If the GPS reference station is moving when it is expected to be stationary, then its movement will appear as apparent displacement in the monitored stations. This phenomenon is suspected when all monitored stations exhibit the same displacement trends. Although it appears as if this is the case with these results, it must be pointed out that the coordinates presented have been transformed into the local coordinate systems. In this case, the fact that the results show similar movements in the Y direction after being rotated helps to solidify that the results are true (only if the coordinates showed similar trends before being transformed, would one suspect an unstable reference point). The installation of the second reference station will help eliminate any doubt.

5.2 Unstable Inverted Pendulum Reference

If the bedrock to which the Inverted Pendulums are anchored experiences a translation, then there is no way for the Inverted Pendulum to detect this movement. Figure 13 illustrates this concept. In the right panel, the basic components of an inverted pendulum are illustrated. A high tensile strength wire is anchored to a (stable) reference point. The wire is run vertically through the structure of interest (in this case a dam), usually through a precision drilled hole. The top of the wire is tensioned at the top by a float and tank assembly, which ensures that the wire is always plumb. A measuring device is installed directly below the float and a shuttle is lowered down the hole to centralize the wire at each measuring point. The position of the wire is read using an electronic sensor which can determine the location of the wire in orthogonal components to sub-millimetre level precision.

The inverted pendulum fails to recognize displacement when the entire body of the structure including the anchor point translates as an entity (left panel of Figure 13). There is no change in tilt and therefore no displacement can be detected. For this to occur and for GPS to detect the displacement, the bedrock under the Main Intake and Diversion would have to translate while the bedrock to which the GPS reference station is mounted remains stationary. Given the close proximity of the reference station to both structures, it is unlikely that this is the case.

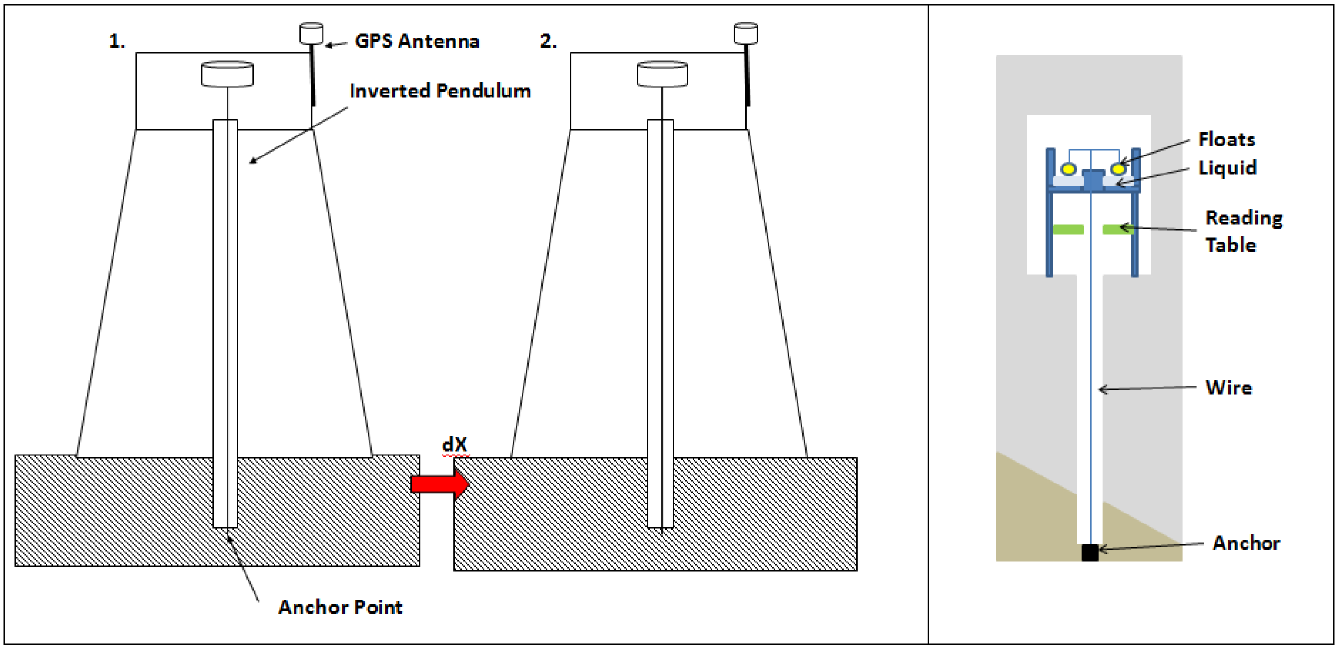

Figure 13: Inverted Pendulum Considerations. Left: Translation of Structure as an Entity goes Undetected. Right: Inverted Pendulum Components (right panel based upon Chrzanowski, 1993)

5.3 Differences in Thermal Effects

The different locations of the GPS antenna and inverted pendulum within the same structure mean that the measurements are effected differently by thermal heating. For illustration purposes, Figure 14 shows the isothermal profiles of a concrete dam located in Canada. It can be seen that the temperature variation on the concrete surface (30°C) is much larger than that near the interior of the structure (a few degrees). The implications of this difference in thermal effects in one dimension can be approximated using the coefficient of thermal expansion of concrete and the relationship:

$$\Delta L/L = \alpha \Delta T \qquad (1)$$

where L = original length, ΔL = change in length, α = coefficient of thermal expansion (12×10^{-6} for concrete at 20°C) and ΔT = change in temperature. The height of the main intake is about 40 m. For every 1°C temperature change, approximately 0.5 mm in height can be expected. The 3D effects are larger. It can easily be seen that differences of several millimetres can be expected in displacement values between locations.

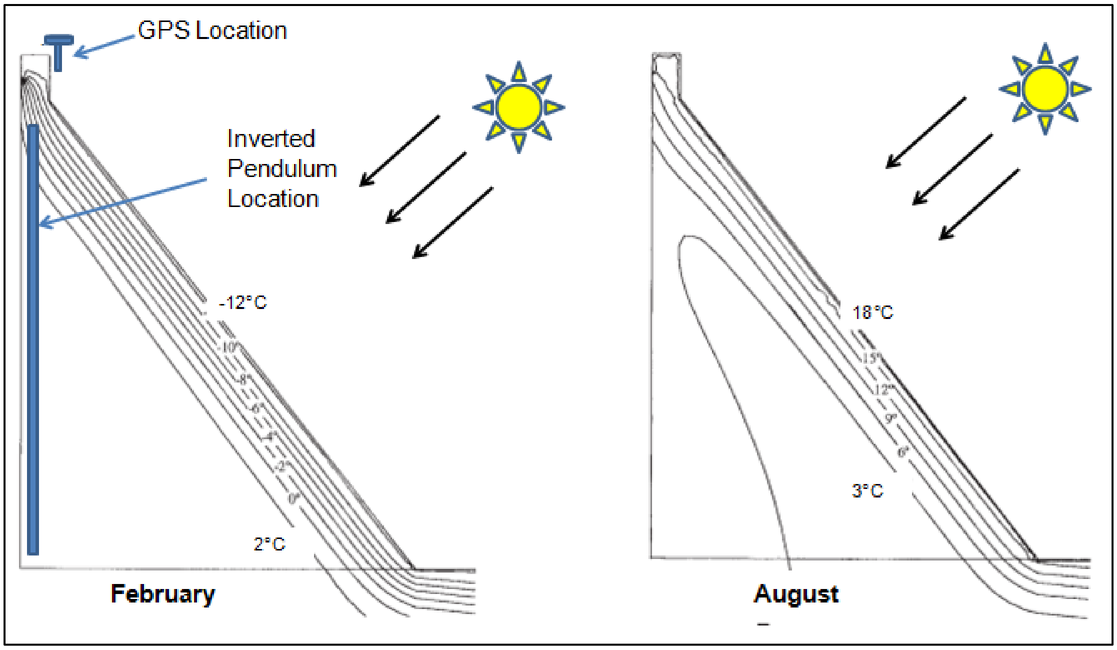

Figure 14: Isothermal Profiles of a Concrete Dam in February and August (based on Daoud et al. 1997)

5.4 *Deformation Mechanism*

The deformation behaviour of the structure and the locations of the instrumentation sampling the deformation behaviour can lead to seemingly incompatible results. To illustrate the point, Figure 15 presents the scenario in which a structure is rotating. An inverted pendulum and GPS setup are used to sample the deformation behaviour. Because of the different locations of the instrumentation on the structure, two entirely different pictures are presented by the technologies. For the inverted pendulum which is located at radial distance R1 from the rotation point, a displacement of D1 in the +Y direction is shown. For the GPS antenna which is located at radial distance R2 from the rotation point, a displacement of D3 in the +X direction is shown. The magnitudes of the displacements are directly proportional to the distance from the rotation point.

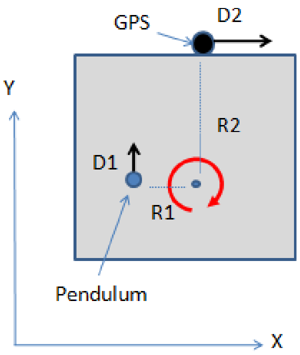

Figure 15: Sampling of the Same Deformation Behaviour with Different Displacement Results

Figure 16 illustrates the 3D path of Station 4 over this data collection period. It shows that the deformation behaviour is complex and that a scenario such as that seen in Figure 15 is not out of the question. As annual data becomes available, it will be possible to determine if the behaviour repeats.

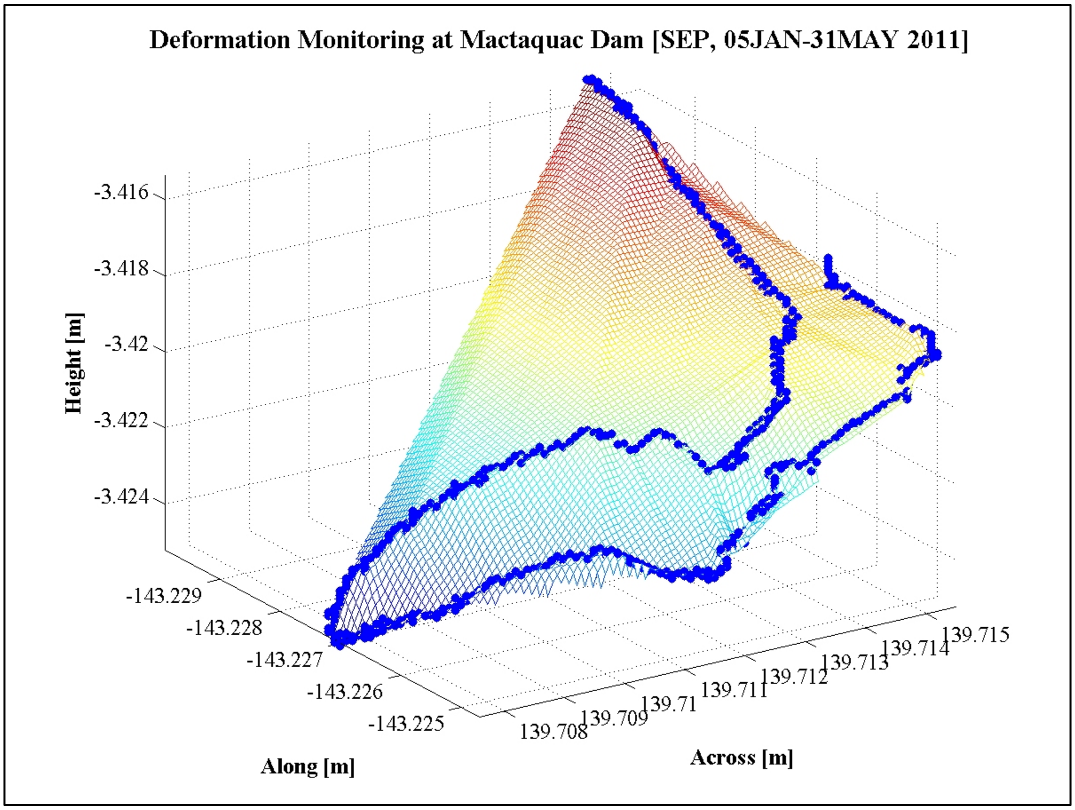

Figure 16: 3D path of Station 4 GPS Antenna

6 CONCLUSION

GPS positioning results for the first 5 months of data collection of four monitored stations at the Mactaquac Dam have been presented. This environment is very challenging for obtaining high precision GPS results due to nearby obstructions causing degradation in observation quality. Despite these environmental challenges, sub millimeter level resolution can be achieved using error profiling and long term filtering techniques.

All of the monitored stations experience the same gradual changes in both the across and height directions which peak near the beginning of March and come back to their original positions towards the end of that month. This pattern is different than that which is seen using inverted pendulum and plumb line instrumentation located near the GPS antenna locations. An explanation for the discrepancies is being pursued. Ideas being investigated include possible movement of either GPS or inverted pendulum reference points, thermal effects and the deformation mechanism itself. A second GPS reference station will be used in the future to validate system performance. Ultimately time will be the key in helping to determine the cause of the patterns being seen in the GPS results at the Mactaquac Dam. As thermal cycles and annual variations repeat, the same patterns should emerge.

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