Interpretation of First Results from the Automated and Integrated Monitoring Scheme at Diamond Valley Lake in California

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ABSTRACT

In 2000, the Metropolitan Water District (MWD) of Southern California finished construction of Diamond Valley Lake (formerly the Eastside Reservoir), Southern California's largest water storage reservoir, with a capacity of nearly one billion cubic metres of water. This $2-billion project, located near Hemet, California (about 160 km southeast of Los Angeles), was designed to secure six months of emergency water for about 16 million inhabitants. It was created by enclosing a valley approximately 7.2 km long and 3.2 km wide with three large earth/rock filled dams of 2.9 km, 3.2 km and 0.8 km lengths and up to 85 m high. The filling of the reservoir began in December 1999 and is estimated to take between three and five years, depending on the availability of water throughout the western United States. At the time of writing this paper (December 2001), the filling was about 67 % complete.

Due to the dimensions of the project and its location within the earthquake prone area, an extensive monitoring program has been developed in order to provide a warning system and confirm that the dams and foundations are functioning as intended. The monitoring instrumentation includes an extended array of geotechnical instrumentation, strong motion accelerographs, active GPS stations, and a fully automated terrestrial geodetic system for Dam Deformation Monitoring (DDM). The latter has been operational since October 2000. This paper reviews the design and implementation of the DDM system and gives an evaluation of its performance over the first year of operation.

The automated DDM system was designed to detect displacements of targeted points on the downstream faces of the dams with an accuracy of 10 mm at the 95% confidence level. Eight Leica TCA1800 robotic total stations (RTS), permanently installed in specially designed shelters, perform automatic measurements to 232 targets (prisms) at pre-programmed time intervals. To randomise effects of atmospheric refraction, the observation cycles have been distributed at 8 hours time intervals at 4 am, 12 noon and 8 pm over the first 3 days of each week. An average of 10 cycles is taken as the final result for weekly reporting purposes. In emergency cases (e.g. an earthquake), the RTSs will automatically “wake-up” by the active GPS warning system.

All functions of RTSs, automatic data collection, and automatic data processing are controlled by DIMONS software developed at the University of New Brunswick. DIMONS performs an automatic data reduction (station adjustments, EDM corrections), identification of unstable reference or RTS points using the iterative similarity weighted transformation and automatically updates and displays the coordinates of the targets after each cycle of observations. The stations are remotely operated via a wireless LAN radio network and TCP/IP connections to the industrial "black box" computer at each station. The collected data and updated coordinates are available immediately for analysis at the MWD office located 120 kilometres away.

At the time of writing this paper (December 2001), all robotic total stations and the supporting DIMONS software have worked well above expectations since October 2000. They have supplied reliable weekly data without any major interruptions within the designed accuracy. Recently, occasional problems have occurred with the power supply (batteries rechargeable by solar energy). The problem has been solved by minimising the power draw by the industrial computers at RTS locations and slightly modifying the schedule of observations. The effects of refraction, as expected, proved to produce significant errors in individual cycles at some targets. They are, however, well randomised and minimised by taking an average of ten cycles every week as the final reporting result.

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1. INTRODUCTION

In 2000, the Metropolitan Water District of Southern California (Metropolitan) finished construction of Diamond Valley Lake (formerly known as the Eastside Reservoir), Southern California's largest water storage reservoir, with a capacity of nearly one billion cubic metres of water (986.8 million m^3). This $2-billion project, located near Hemet, California (about 160 km southeast of Los Angeles), was designed to secure six months of emergency water supply [Metropolitan, 1997] for about 16 million inhabitants. It was created by enclosing the Domenigoni and Diamond Valleys at an elevation of about 500 metres with the construction of three large earth/rock filled dams (Figure 1). The reservoir, about 7.2 km long and more than 3 km wide, covers over 4500 acres of land. The reservoir project consists of:

– the West Dam, 85 m high and 2.9 km long;
– the East Dam, 55 m high and 3.2 km long; and,
– the Saddle Dam, 40 m high and 0.8 km long.

The project also included construction of a storage forebay at the West Dam, a detention basin, and a pumping plant. The filling of the reservoir began in December 1999 and is estimated to take between three and five years, depending on the availability of water throughout the western United States. At the time of writing this paper (December 2001), the filling was about 67 % complete.

Due to the dimensions of the project and its location within the earthquake prone area, an extensive monitoring program has been developed in order to provide a warning system and confirm that the dams and foundations are functioning as intended. The monitoring instrumentation includes an extended array of geotechnical instrumentation for seepage and internal deformation measurements, strong motion accelerographs, active GPS stations connected to the California continuously operating reference system (CORS) and a fully automated terrestrial geodetic system for Dam Deformation Monitoring (DDM).

Details on the design and installation of the various components of the monitoring program were presented at the 10th FIG Symposium on Deformation Measurements in March 2001 [Duffy et al, 2001; Lutes et al, 2001]. This paper gives only a limited review of the automated geodetic DDM system followed by an evaluation of its performance since October 2000.

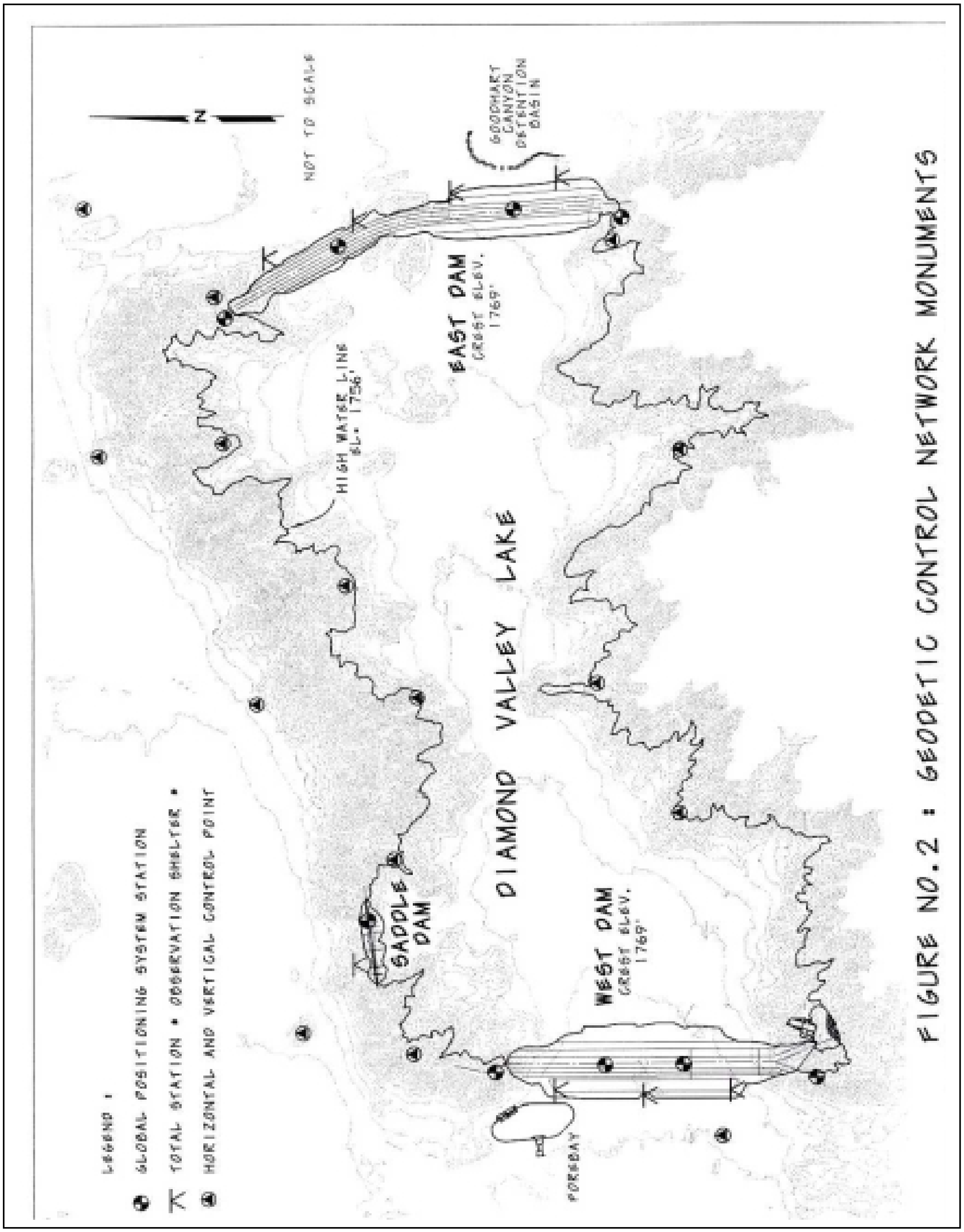

Figure 1. Diamond Valley Lake Layout and Monitoring Configuration.

2. REVIEW OF THE GEODETIC DAM DEFORMATION MONITORING SYSTEM

The geodetic dam deformation monitoring (DDM) plan [Duffy et al, 2001] was developed to monitor the response of the dams and foundations to the gravitational load of the dam and reservoir to ensure that any adverse conditions that develop during operation, and especially during initial filling, are detected as soon as possible. The fully automated DDM system became operational in October 2000. The monitoring results have been reported weekly or at any time when triggered by the warning system (continuous GPS and accelerograph indications).

Detection of horizontal and vertical displacements larger than 10 mm at the 95% confidence level, with respect to local reference points, was accepted as the accuracy criterion in designing the DDM scheme. After considering various solutions to satisfy the accuracy vs. minimal cost criteria, use of permanently installed robotic total stations (RTS) with automatic target recognition and with fully automated data collection and processing was accepted in the final design of the DDM scheme [Duffy et al, 2001]. Specially calibrated Leica TCA1800 total stations were selected as RTSs supported by DIMONS software developed at the University of New Brunswick [Lutes et al, 2001]. The software controls all functions of RTS and automatic data collection at pre-scheduled time intervals. It performs an automatic data reduction (station adjustments, EDM corrections), identification of unstable reference or RTS points using the iterative similarity weighted transformation [Chen et al, 1990], and automatically updates and displays the coordinates of the targets after each cycle of observations.

Error analysis and optimisation of the monitoring scheme led to a conclusion that in order to satisfy the 10 mm displacement detection criterion, maximum distances from RTS to object targets (prisms) should not exceed 500 m. Thus, in order to monitor all three dams, 8 permanent RTS had to be installed (Figure 1) to monitor movements of 232 prisms installed on survey pillars on the crowns and on the downstream faces of the dams. Three reference back sight targets were installed and included into the observation scheme at each RTS. One of the reference targets serves as the main orientation reference and the others are used as control points for monitoring the stability of the RTS station and the main reference target. Some of the reference points are common for two neighbouring RTS's.

It was realised that in the semi-arid and generally very hot climate conditions at Diamond Valley Lake, systematic errors of atmospheric refraction could produce unacceptably large positioning errors [Chrzanowski, 1989; Chrzanowski, 1999]. Therefore, in designing the survey procedures, minimisation and randomisation of the refraction effects was a major concern. The randomisation of refraction effects has been designed to collect 10 cycles of observations at 8 hour intervals over 4 days every week and average out the results for the weekly reporting of displacements. The observations were scheduled at 4AM, 12PM and 8PM.

Each total station requires a dedicated computer for the remote access capability, for controlling functions of the total station, and for data storage. Data communication and remote access between the on-site PCs running the total stations and the Metropolitan computer network has been accomplished using spread spectrum radios, creating a wireless LAN system covering over 15 square miles at the site. All RTS procedures can be controlled from a Metropolitan office (120 km from the project site) that is connected to the Metropolitan wide area network by a remote link through pcAnywhere. The remote controls include scheduling the remote power-up, giving commands for the measurements of selected angles and distances, and establishing the number of sets of measurements in a given cycle of observations. The data collection, downloading of raw data, backup of files, and processing of raw data is performed automatically within the DIMONS software.

Figure 3. RTS observation shelter.

Each RTS with its computer equipment, meteorological sensors, communication radio, and power supply are housed in an observation shelter (Figure 2). Due to the remote locations of the structures, all equipment is run by DC power from solar panels located adjacent to the shelters. The solar panels charge three 25 amp batteries that were designed to supply power to all the equipment for three days without recharging.

Though initial coordinates of all RTSs were determined in the coordinate system of the GPS area control network (Figure 1), each RTS survey point with its set of observed object and reference survey points are treated in the displacement monitoring process as an independent local network in its own local coordinate system. The displacements of any object target point are computed with respect to the RTS point and the reference target points. Because of the distorting effects of the shelters' glass windows on the lines of sight, a rigorous determination of the relationship between the local coordinate systems of individual RTS sub-networks is difficult. Nevertheless, the refraction effects of the glass panels are cancelled out when calculating displacements (differencing of positions) of the targets.

3. EVALUATION OF THE DDM SYSTEM PERFORMANCE

3.1 Performance of Instrumentation and Communication

The fully automated DDM system was installed in October 2000. At the time of writing this paper (December 2001), all RTS (Leica TCA1800) and the supporting DIMONS software have worked well above expectations, even during the very hot (over 40^0C) summer months. They have supplied reliable data without any major interruptions. DIMONS software has handled the data collection and analysis routinely without problems (assuming power is up). The stations come on when scheduled, perform their data collection cycles, check for tolerances, repeat cycles if needed, calculates updated coordinates and then shutdown, all without a problem. Geodetic data communication network has been very reliable and efficient. All DIMONS tasks required for the remote handling of the total station and programming/scheduling has been easily and reliably performed or changed from the office located 120 km. away.

The data supplied by the DDM system has shown that, so far, the deformations of the dams are within the design tolerances. The monitoring results of the geodetic DDM system, besides serving as a warning system, have also been used in verifying the designed geotechnical parameters [Szostak-Chrzanowski et al, 2001].

3.2 Evaluation of the Power Supply

The system worked as designed for almost a complete year before problems with batteries arose. Actually, some of the charge controllers started malfunctioning which caused the batteries to not charge and discharge correctly. This eventually led to problems with the re-booter program not being able to re-boot the computer because errors in Windows had occurred due to recurrent power failures. The remote computers had to be re-booted manually (a 240 km round trip) and then the corrupt files repaired. To solve this power problem, the suspect charge controllers have been replaced and then to recover the battery life, a program was started to turn off the system once a month during the four days when the readings were not taken. This allowed the batteries to fully recharge with no draw on them. The draw of the industrial type computers seems to be too great for the batteries to be able to maintain their charging capabilities over a long period of time. Currently, network cards are being installed that will allow for programming the computers to turn off when not in use, but leave them in a state that one can remotely turn them on if needed.

Till November 2001, the system has operated on the originally designed set time schedule, taking readings at 4AM, 12PM and 8PM. When power problems started occurring, the schedule has been changed to 9AM, 5PM and 12AM, to try to perform the majority of the measurements during sunny (wintertime) hours when the solar panels give the maximum output.

3.3 Evaluation of the Stability of Shelters, RTSs, and Reference Targets

The foundations of the shelters were designed according to the geology of each location to provide good structural stability. The pillar that each RTS is mounted on is monolithic with the foundation of the structure. The foundations of 6 shelters have proven to be stable well within the accuracy of the displacement detection. The two stations, which were installed in the dense alluvium at the south half of the East Dam both showed significant (several millimetres) displacements at the beginning of the monitoring program and have stabilised at the ±3-4 mm range. There are also two reference points in this same area that indicate larger instability than obtained at other reference points close by. At the time of writing this paper, the annual GPS area control survey is being performed to verify the stability of the RTS and reference points with respect to their initial positions and compare with the results of the continuous automated surveys data.

3.4 Accuracy of the DDM System

3.4.1 Evaluation of Double Observed Points

The accuracy evaluation of the DDM system has been based on comparing displacements of those points that are observed simultaneously from two neighbouring RTSs. There are 5 double-observed targets at the West Dam and 6 at the East Dam. Figure 3 shows an example of a double point (labelled as pt. 1079 and 7079) at the West Dam observed from RTS3 and RTS2.

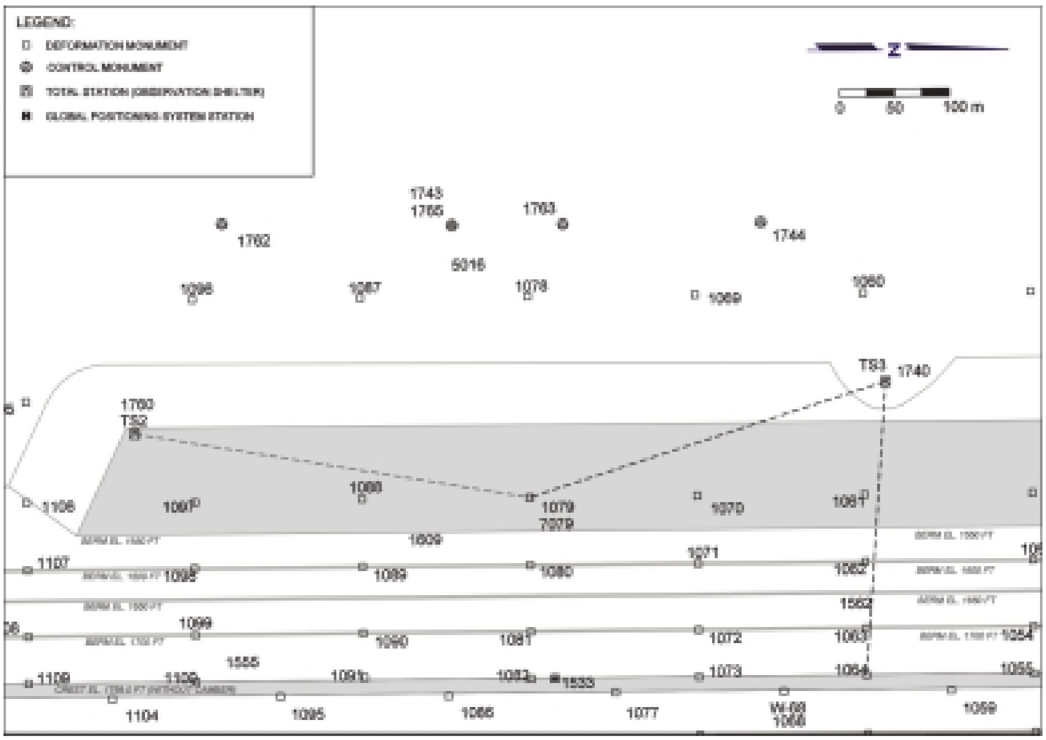

Figure 3. Example of a double-observed point.

The differences of double-observed displacements may be treated as true errors. By taking a sufficiently large sample of the true errors of differences, one may estimate standard deviations of the components of the weekly averaged displacements.

The accuracy evaluation was performed separately for the winter and summer seasons in order to compare the performance during the hot summer (over 40^{0}C at noon) conditions and during the cool season (down to 5^{0}C at 4 am). Eight weeks of observation data (December 4-January 29) were analysed in the winter and 12 weeks (June 11–August 31) in the summer. Analysis of the eleven double observed points has given the following errors (at 95% confidence levels) of individual components of displacements:

For winter months:
e_{dN} = 2.4 mm; e_{dE} = 4.8 mm; and e_{dH} = 6.6 mm.
For summer months:
e_{dN} = 2.0 mm; e_{dE} = 3.4 mm; and e_{dH} = 5.4 mm.

All the errors are well within the designed tolerance of 10 mm at 95%. This is an excellent result, considering that the double observed points are located at the marginal distances (340 m to 500 m from RTSs) of the networks. Since the double targets are located either at the toes or at the crests of the dams, the lines of sight to those points are either close to the ground or along the faces of the dams, thus being maximally exposed to large gradients of temperature. One may expect, therefore, that the overall accuracy of displacements of all other points should be better than the accuracy of the double-observed points. It is interesting to note that the summer months gave better results than the winter observations. One can explain it that either there is a better randomisation of refraction errors in the summer (more turbulent air), or the observation conditions during the dry summer months are better (less fog, no rain drops on the prisms, etc.) More investigation is needed.

3.4.2 Effects of Atmospheric Refraction

The above discussion on the overall accuracy of displacement determination has proven that the required tolerance of 10 mm in detecting the displacements is being satisfied if 10 cycles of observations, spread over 3 days, are averaged to supply weekly results. However, time plots of individual cycles (Figure 4) show that the accuracy of individual cycles may be strongly affected by systematic errors caused by varying temperature gradients.

As expected, the strongest refraction effects occur along the lines of sight that are low above the ground or along the dam face. The smallest effect is on the lines of sight from RTSs to the points on the crest of the dams. The lines from RTS3 to 1079 and from RTS3 to1064 (see Figure 3) have been used as an illustration of the two extreme cases. The line RTS3-1079, of a total length of 340 m, runs almost horizontally about 1.5 m above ground. The line RTS3-1064, of a total length of 276 m, goes steeply up to the top of the dam with a height difference of 70 m, thus having the average vertical clearance above the face of the dam of several metres. Figures 4 and 5 show a portion of the time series (October 2000 – January 2001) of daily changes of height at 4 am and 12 noon for points 1079 and 1064 respectively. During that period of time, the temperatures at noon ranged from 25°C in October to 13°C in January, and the temperatures at 4 am ranged from 12°C in October to 5°C in January. The two examples indicate that:

1. In both cases, the noon observations seem to give more consistent results than the observations at 4 am (a rather unexpected result);
2. The height changes of point 1079 may reach 50 mm over a few days time interval (assuming that no actual deformation takes place) when observing at 4 am and 20 mm

when observing at noon, while the maximum height changes at point 1064 may reach 20 mm during the 4 am observations and 8 mm during the noon observations.

3. The weekly averages of 4 am vs. 12 noon observations to point 1079 show a systematic bias of about 30 mm. There is no significant bias between 4 am and 12 noon results at pt. 1064.

Surprisingly, not much larger effects have been shown during the hot (up to 46^0C) summer months (not illustrated here due to the space restriction), giving the average systematic bias of 40 mm vs. 30 mm between the noon and 4 am observations to pt. 1079.

One may conclude from Figure 4 that, in extreme conditions, the atmospheric refraction may introduce errors of up to 50 mm in the determination of displacements from a single cycle of observations taken always at the same time of the day, and up to 70 mm difference between displacements determined at noon and at 4 am. In the case of point 1079, the systematic bias of 30 mm over the distance of 340 m corresponds to a change in the vertical gradient of temperature (dT/dH) of 0.6°C/m between 4 am and 12 noon. This is a realistic value and agrees very well with results of investigations conducted some years ago at UNB [Chrzanowski, 1989].

4. CONCLUSIONS

After over a year of implementation (since October 2000), the fully automated system for monitoring structural dam deformations at Diamond Valley Lake has run successfully and supplies reliable weekly information on the displacements of targeted points within the required tolerance of 10 mm at the 95% confidence level. Despite the recent power supply problems, this system has met and exceeded the monitoring requirements of the State of California and has proved to be a cost effective method of surveying this large facility.

The selected instrumentation (Leica TCA1800), DIMONS software, and data communication system have met all the requirements and expectations of the project. The problems with

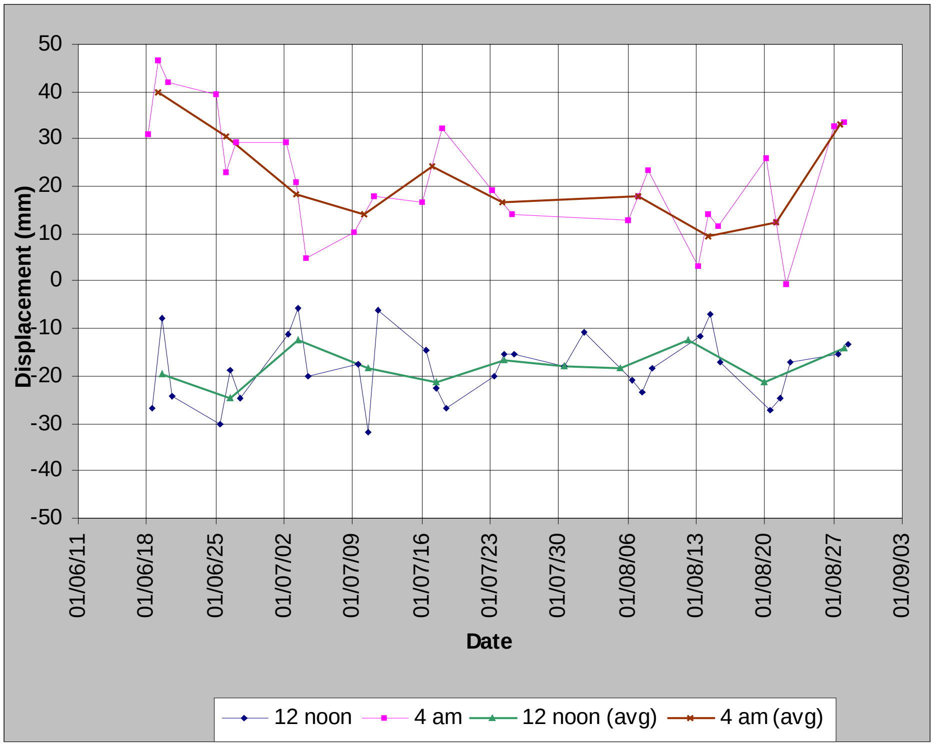

Figure 4. Comparison of 4 am and 12 noon height determinations for point 1079.

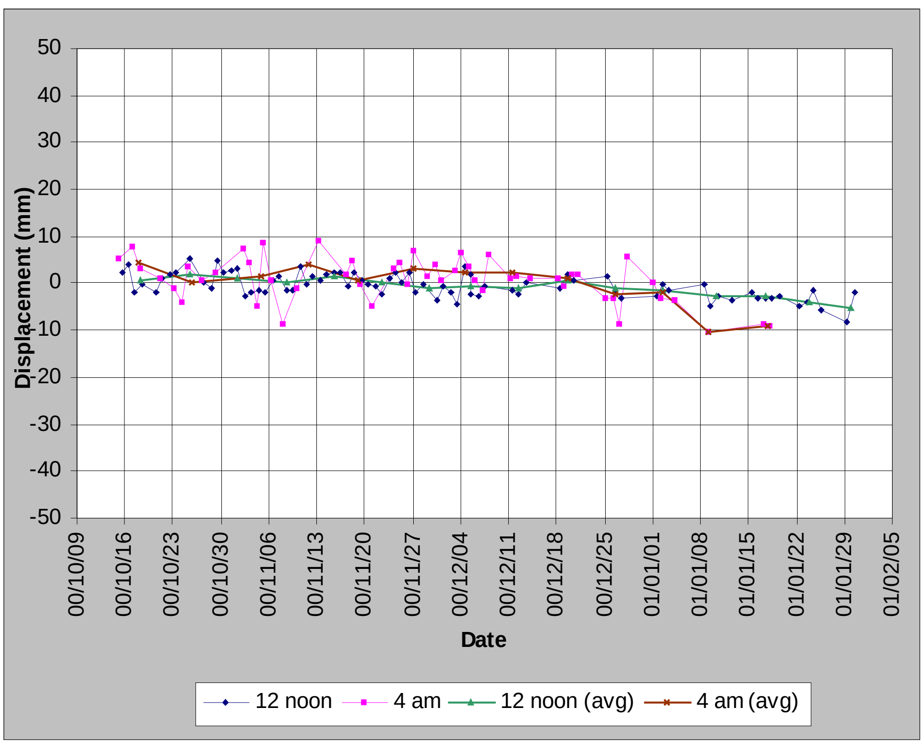

Figure 5. Comparison of 4 am and 12 noon height determinations for point 1064.

batteries, which have occurred after one year of operation, will not cause the power supply interruption after upgrading the recharging schedule and slightly modifying the schedule of the maximum power draw.

Effects of atmospheric refraction, as expected, are of a major concern along the lines running close to the ground but they are being randomised and well controlled by taking observations spread over different time of the day and by averaging 10 cycles of weekly observations for the final determination of displacements.

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