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Technical Note

Geomatics applied to dam safety DGPS real time monitoring

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Abstract

New advances in geomatics and communications technologies are enabling the development of Automated Auscultation System for structure monitoring. In particular, Differential GPS (DGPS) technique allows real-time monitoring of structures with millimetre accuracy after an appropriate mathematical treatment. The results of real-time DGPS monitoring of a pilot dam over 15 months are presented and compared with the results of pendulums and angular collimation. DGPS monitoring was established to control two points at the top of the dam with reference to an external and stable station. Communications were critical, evolving from initial GPRS connections to more reliable ASDL line in the last months. Real-time DGPS positions were filtered to reach millimetric accuracy through Kalman filter. Two configurations of the filter were tested, one more adapted to predictable and uniform velocity deformations (low frequency) and another more suitable for sudden and large movements (high frequency). Root mean square errors were calculated taking pendulums as a reference. Results show that both DGPS and angular collimation allow monitoring with millimetric accuracy. In the last period, where communications with processing server were stable, a global accuracy of 1.44 and 1.86 mm was reached for real-time DGPS monitoring. RINEX post-processing yielded millimetric results, validating real-time observations. We can affirm that the DGPS system is very useful for dam auscultation and safety as it detects adequately absolute deformations, being a complement to existing methods which should be considered in new safety plans.

Keywords: *Dam monitoring, Geomatics, DGPS, Structures, Real time.*

1. Introduction

Dams and other large structures require safety programs that monitor ongoing processes, in accordance with the required specifications of each country. Dam monitoring typically includes measurement of hydraulic behavior, ground water pressures, tilts, strains and displacements (movement control). Among movement control methods are measurements using geotechnical instruments (e.g., direct and inverted pendulum, inclinometers, tiltmeters, jointmeters) and geodetic-surveying methods (e.g., leveling, trilateration, triangulation, angular collimation). Geotechnical methods are very reliable and achieve high precisions, even the cents of millimeter.

As technology develops, new methods of movement control are emerging. Among them we can highlight: fiber optics, robotic total stations and Differential Global Positioning System . DGPS technology allows continuous measurements to be made in absolute coordinates and introduces the possibility of alarms in real time. The unique limitation is that the GPS antennae have to be placed in a clear space without nearby elements that can cause multipath problems (i.e., reflections of GPS satellite signals off nearby objects).

DGPS has previously been applied in slope stability studies, where the required accuracy is centimeters. In recent years the parallel development of this technology and wireless communications has allowed measurements to achieve millimeter accuracy, enlarging the application of DGPS to the movement control of large structures.

In dams, the amplitude of movements depends on several parameters, such as dam height, shape, type of concrete, joints topology, hydrostatic load and temperature. Technical articles show some previous cases of DGPS-based monitoring in dams, for example, Pacoima dam in California [1], Libby Dam in Montana [2] and Tolt Dam in Seattle (www.trimble.com), all of them in USA. In Europe Kops Dam (Austria) is being monitored by the "GPS-based Online Control and Alarm System" project [3].

In this paper we analyze the feasibility of using DGPS for

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movement control of concrete dams. Additionally, we compare the results from two different measurement systems – pendulums and angular collimation - and correlate them with the results from the DGPS program. Finally, we draw conclusions about the application of DGPS to dam movement control and safety.

The case history described in this paper is that of La Aceña dam, owned by Canal de Isabel II (CYII) the main water supplier for Madrid (Spain) (Figure 1). This work is part of the DGPS research program of the Topography and Geomatics Laboratory at Technical University of Madrid.

2. Experimental procedure

2.1. Area of study

The La Aceña dam is located at the Aceña river watershed. This is a tributary of the Tagus river, located at the Peguerinos town council in the Ávila province (Central Spain) (Figure 2). This arch-gravity dam is made of concrete, being 68 m high over foundation. The upstream facing is vertical and the downstream facing has a 0.4 slope. The dam top is 1319 m above sea level and it is 340 m long, 6 m wide, with 2 lanes of 2.25 m each and 2 sidewalks of 0.75 m each.

The dam has four pendulums (P-1, P-2, P-3, P-4), all of them direct (hanging), giving information about the displacements of the dam crest in relation to the inspection gallery where the lower reading devices are located (Figure 3). There are reading bases in the intersection of each pendulum and the gallery. In all bases of the inspection gallery and at the base of the pendulum 2 (horizontal gallery), automatic reading devices are installed besides the manual reading devices (Figure 3).

The great slenderness of this dam makes more notable the amplitude of radial movements of annual cycle, due to the external solicitations (water load and temperature). These

Fig. 1 La Aceña dam (Central Spain). General view

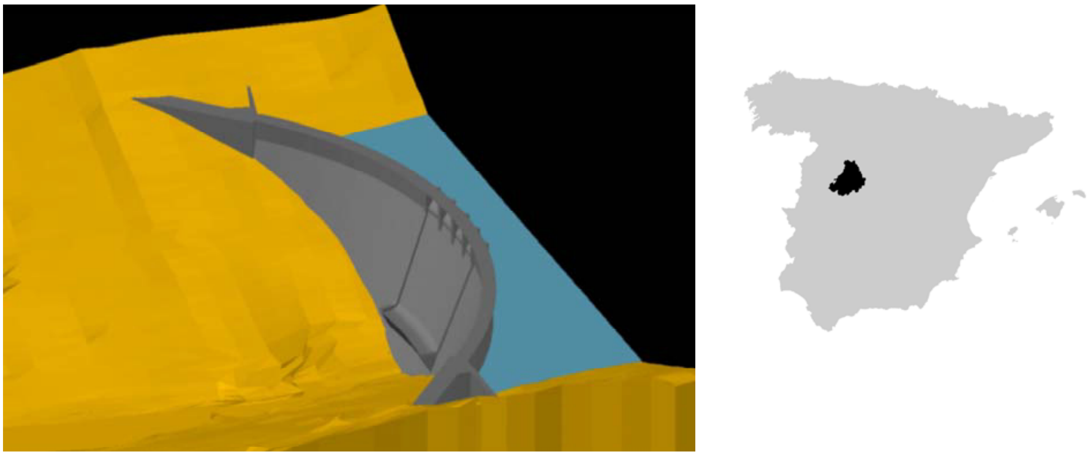

Fig. 2 La Aceña dam. 3D model and general location map, Avila Province (Spain)

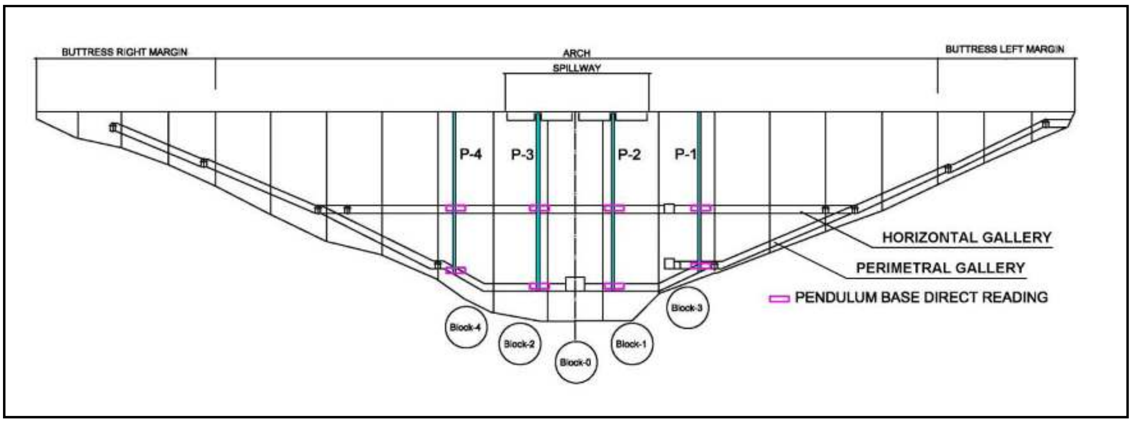

Fig. 3 Location of direct pendulums. Front view

movements are about 35-40 mm [4] (Figure 4).

Nowadays, La Aceña dam is being monitoring using three different radial movement auscultation technologies: direct pendulums, DGPS and precise angular collimation.

2.2. Description of dgps system and configuration

The DGPS network consists of three main components: antennas and receptors, communication system and IT system to process data. Two points on top of the dam (AC1 and AC2) were chosen to install DGPS mobile stations, close enough to the direct pendulums (P3 and P2 respectively), with the aim of comparing displacements with both technologies. Antennas and receptors were installed on top of the dam keeping the symmetry about the axis of the dam (Figure 5). The reference station was located downstream of the dam on the left margin, away from it to ensure stability (Figure 6).

Fig. 6 DGPS spatial arrangement in La Aceña Dam

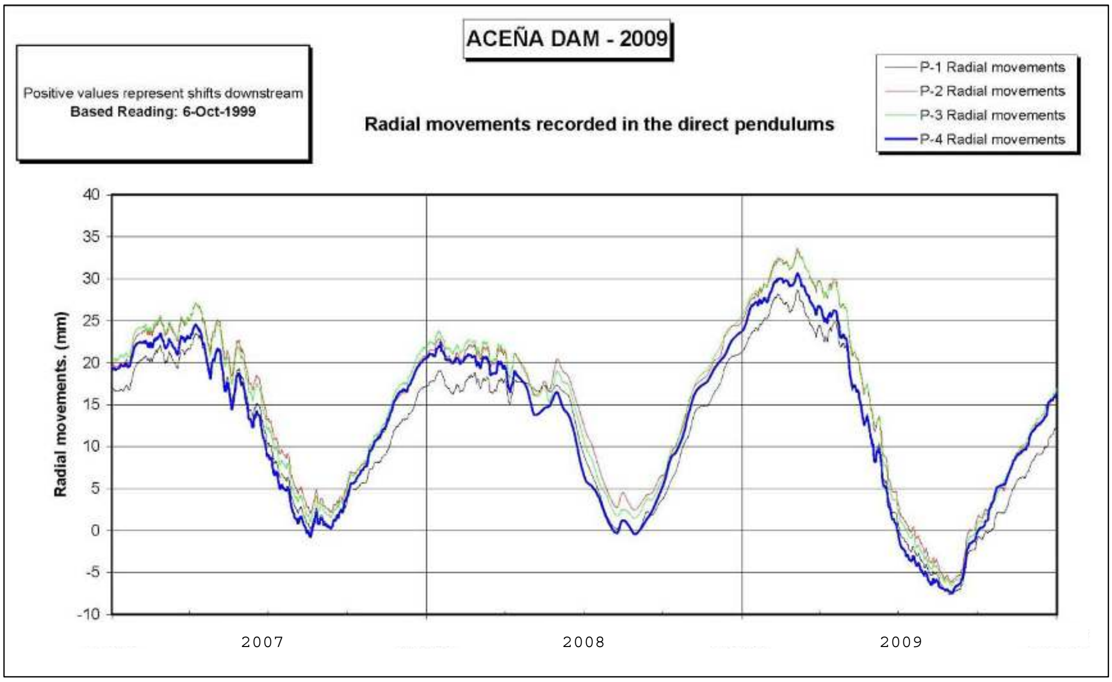

Fig. 4 Radial movements recorded in the direct pendulums

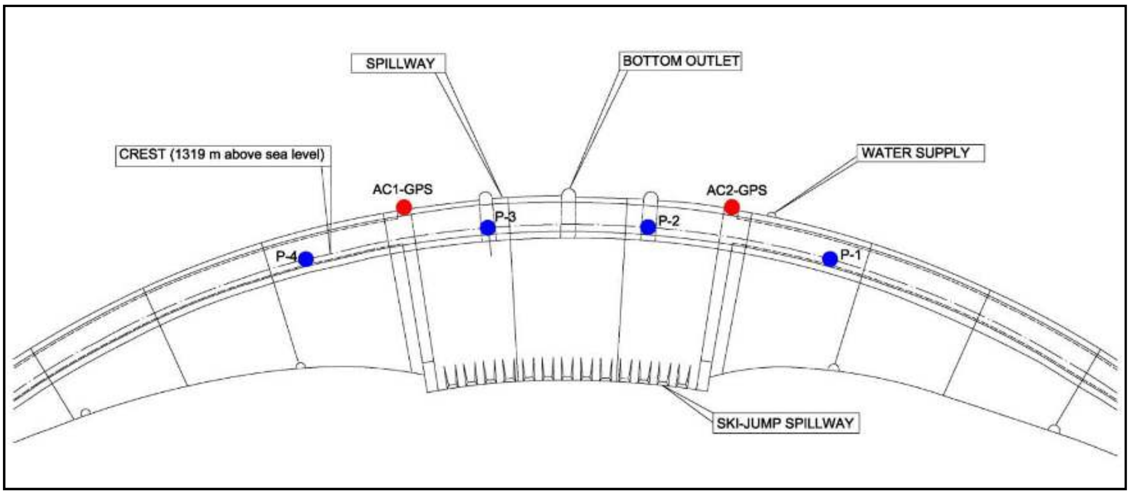

Fig. 5 Location of direct pendulums. Front view

Data transmission between GPS receivers and the server was initially via GPRS, until the ADSL line was installed at the dam. ADSL has produced a considerable improvement in the quality of communications (Figure 6).

Data were processed with a real time application based on DGPS technology, designed for movement control, with high accuracy in real time. Real-time solutions were filtered to improve accuracy. A well-known filter in this field is the Kalman filter [5]. This filter consists of a set of mathematical equations, some of them predictive and others based on iterative adjustment that provides a recursive estimation of the error [6]. The filter allows adjusting the positions to the observed movement change rate in function of the previous positions, making possible to achieve millimetric accuracy in low frequency oscillations. The first predictive filter equations have the following structure (Eq. 1 & 2) [7]:

$$\hat{X}^*_t = A.\hat{X}_{t-1} \tag{1}$$

$$\hat{P}^*_t = A.\hat{P}_{t-1}.A^T + Q \tag{2}$$

: Estimation of the system status
$\hat{X}^*_t$: System status at a certain time
$\hat{X}_{t-1}$: Matrix of changes between status
A : Covariance of the residue in a certain time
$\hat{P}_{t-1}$: Estimation of the covariance
$\hat{P}^*_t$: Covariance of the random perturbation of the
Q *process that tries to estimate the status*

The Kalman filter can be calibrated to answer in a slow way but more accurate, for example to adapt it to the daily control of the deformations in a longer period of time or in a faster way but less accurate if we expect large movements in shorts periods of time. This adjustment is achieved by changing the values of Q, which allows fitting the filter to the predicted changes rate with more o less sensitivity depending on the objectives of the auscultation. Large values of Q mean fast response - but less smoothing of the measurement noise. A small value of Q means slow response - but good smoothing of the measurement noise. In the current case study, two different values of Q have been used, a lower value (Q=1E-13) for the filter configuration called AC and a greater value (Q=1E-11) for the configuration called ACB, where the adjustment effect is perfectly visible. The AC configuration is adapted to slow movements while the ACB allows capturing faster movements of the structure. Both configurations have been simultaneously executed as if they were two different auscultations with the same input data.

We have also post-processed RINEX (Receiver Independent Exchange) files for a year. RINEX files were recorded daily with an interval of 10 seconds, containing phase observables in the first frequency (L1). It was also estimated the uncertainty associated with each observation.

2.3. Angular collimation

A topographic control system with 21 control points on the downstream facing of the dam was installed (Figure 7). Based on that network angular collimation, monitoring was developed monthly during 2009. The main objective was to control the radial plant movements of the dam. Data acquisition was made using a total station and following the polar radiation methodology with, at least, two readings for each point from different bases.

The observation system was a Leica TCA2003 total station that included TPS System 1000 technology. The integrated distanciometer provided ±(1 mm + 1 ppm) precision and it was completely robotized with automatic target recognition (ATR) including a CCD sensor. The angular precision was ±0.15 mgon.

2.4. Analysis of errors

In order to analyze the accuracy the implemented auscultation systems, against the results obtained with the pendulums (considered as real movements), Root Mean Square Errors (RMS) were calculated as follows (Eq. 3):

$$\varepsilon = \sqrt{\frac{\sum (l_{Pendulum} - l_{GPS\ Real\ Time})^2}{n}} \qquad \varepsilon = \sqrt{\frac{\sum (l_{Pendulum} - l_{Collimation})^2}{n}}$$

$$\varepsilon = \sqrt{\frac{\sum (l_{Pendulum} - l_{GPS\ Postprocess})^2}{n}} \tag{3}$$

Table 1 shows the pairs of control points that were chosen for comparison using proximity criteria:

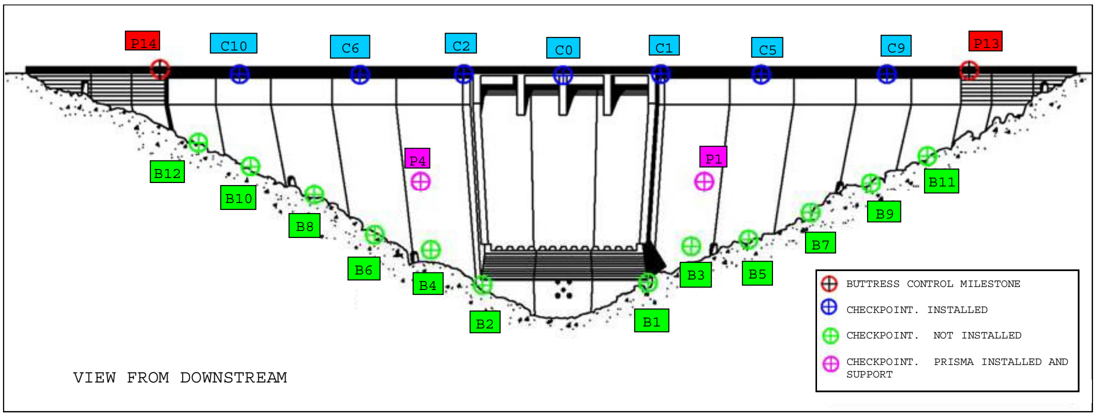

Fig. 7 Collimation system configuration. Control points on the downstream facing

3. Results

The root mean square error of DGPS radial movements was calculated for two periods: a) from January 2009 to March 2010 (complete period) and b) from December 2009 to March 2010 (without communications problems - ADSL working fine) and the results are shown on Table 2.

Period b), when ADSL communication was working fine, shows a lesser error than in the whole period and in both cases the dimension of errors is millimetric. The RMS of the 13 collimation readings, from January 2010 to March 2010, was calculated and the results are shown on Table 3.

The following figures show the evolution of the three displacement data sets (DGPS, pendulums and angular collimation), all of them along the radial direction (Figure 8).

Figure 9 shows the evolution of measurements of DGPS and pendulums during the final period, characterized by the stability and continuity of the communications. It shows the good correlation between both series during the analyzed months.

Two different configurations of the Kalman filter (AC and ACB) were carried out in order to asses their effect on the results. AC configuration provides more filtered solutions, that is, with more "inertia", relative to previous positions, being a good configuration with great accuracy suitable for slow, progressive and predictable movements, like this dam case during almost year. Moreover, the ACB configuration provides a less filtered solution, less accurate in phases where the movement is progressive and predictable, but allowing to capture trends of change and sudden movements which are useful in dam safety (Figure 10).

A post-process calculus, from the daily RINEX files, was made in order to obtain the baselines between the three GPS stations, for each observing day. For each base line, the ambiguities of cycle were solved using double-differences of phase in L1. With the values of these vectors and their matrix of variance-covariance a Least Square Adjustment was made, where the unique fix point, in this adjustment, is the base station (AC). Moreover, daily coordinates of the other two stations, standard deviation and ellipses of error were obtained. The mean standard deviation of the adjustment is about 0.4 mm in plant and 0.5 mm in elevation, which guarantees the millimetric accuracy of the process. As additional information, we recorded 8640 observation periods for each day, being the longest base line of 251 m. Post-process results of period from July 2009 to October 2010 and the uncertainty associated to each position are shown in Figure 11:

Table 1 Equivalents control points compared in the three methods

Direct pendulums	DGPS Points	Collimation prisms
P-3	AC-1	C2
P-2	AC-2	C1

Table 2 Errors in radial movements measured with DGPS

Radial movements	RMS (ε) period a)	RMS (ε) period b)
P-2 - AC2 GPS	2.33 mm	1.44 mm
P-3 - AC1 GPS	3.09 mm	1.86 mm

Table 3 Errors in radial movements measured with DGPS

Radial Movements	RMS (ε)
P2B2 - PRISM C1	1.79 mm
P3B2 - PRISM C2	2.21 mm

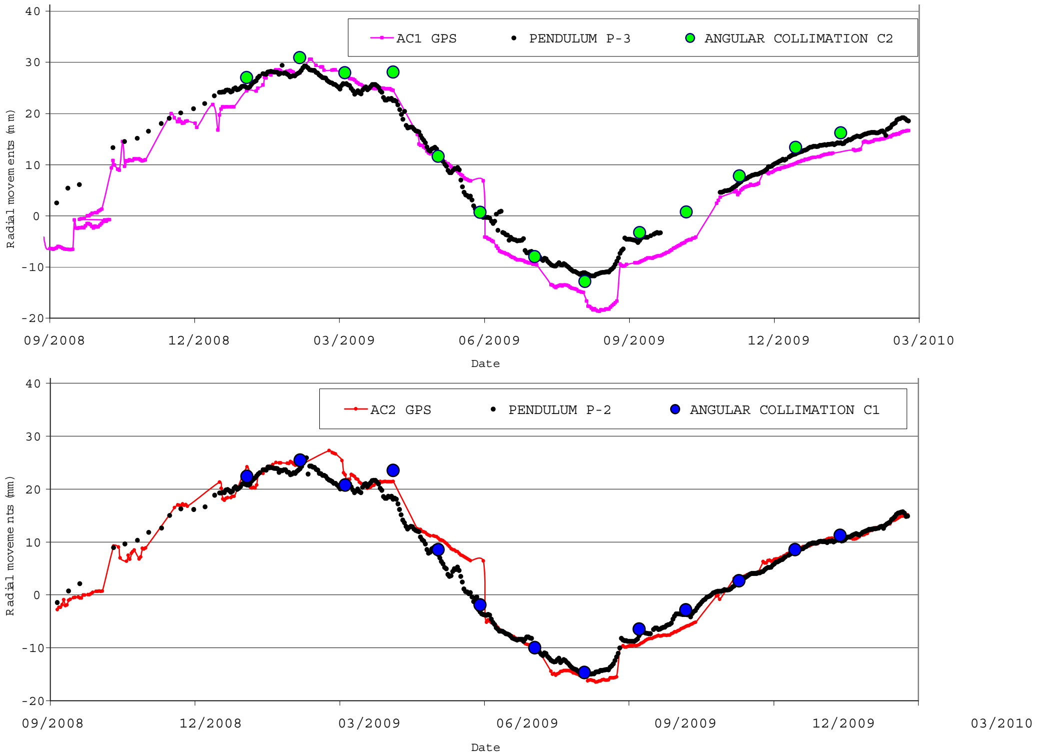

Fig. 8 Comparison of monitoring results: DGPS, pendulums and angular collimation

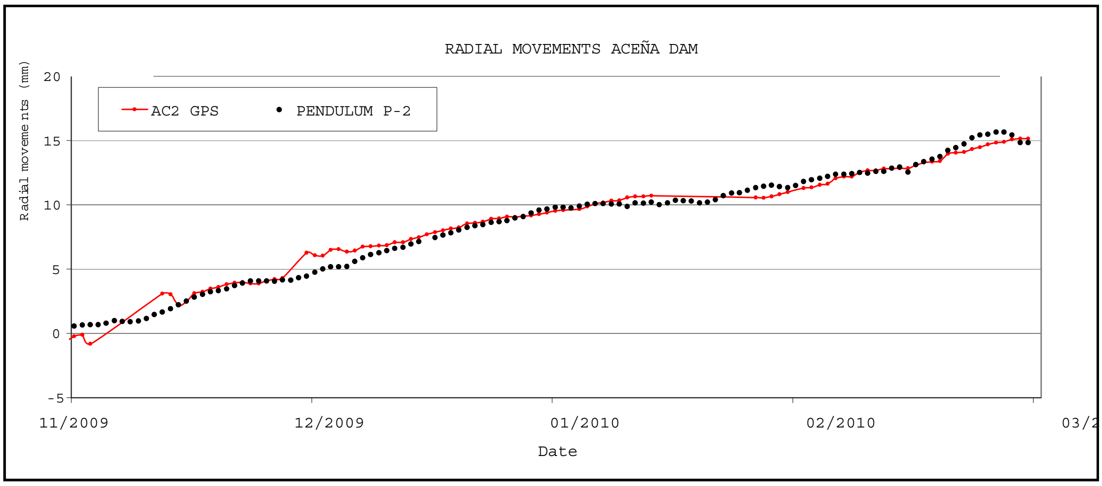

Fig. 9 Comparison of monitoring results between DGPS and direct pendulum (AC2 GPS and P-2)

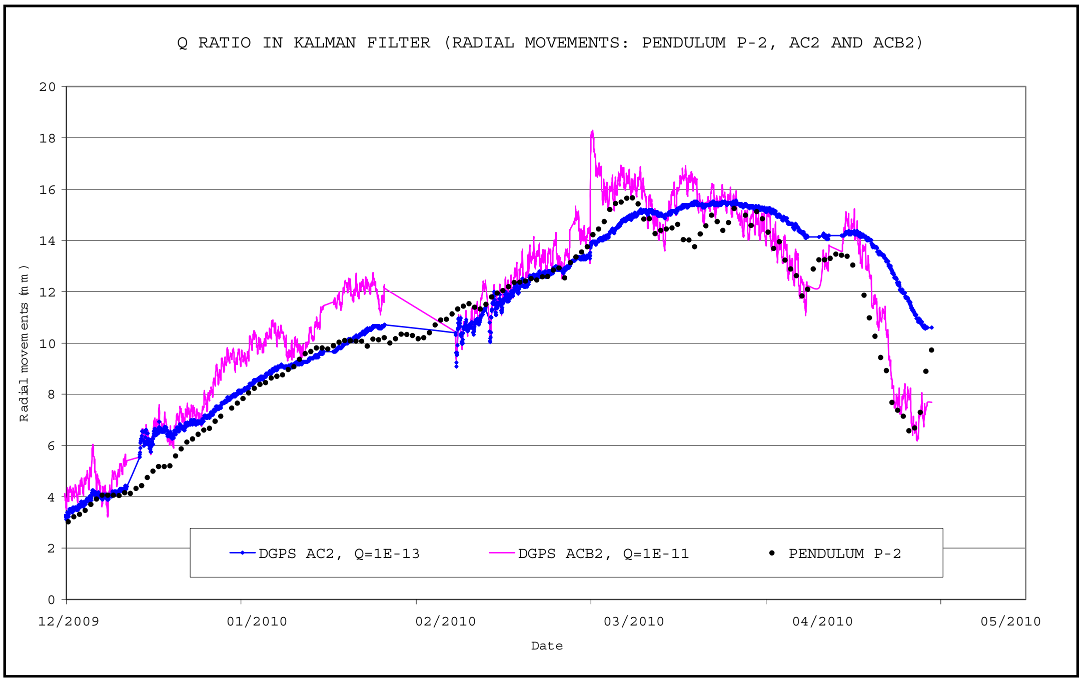

Fig. 10 Effects of Kalman filter configurations in radial movements measured at AC2 GPS

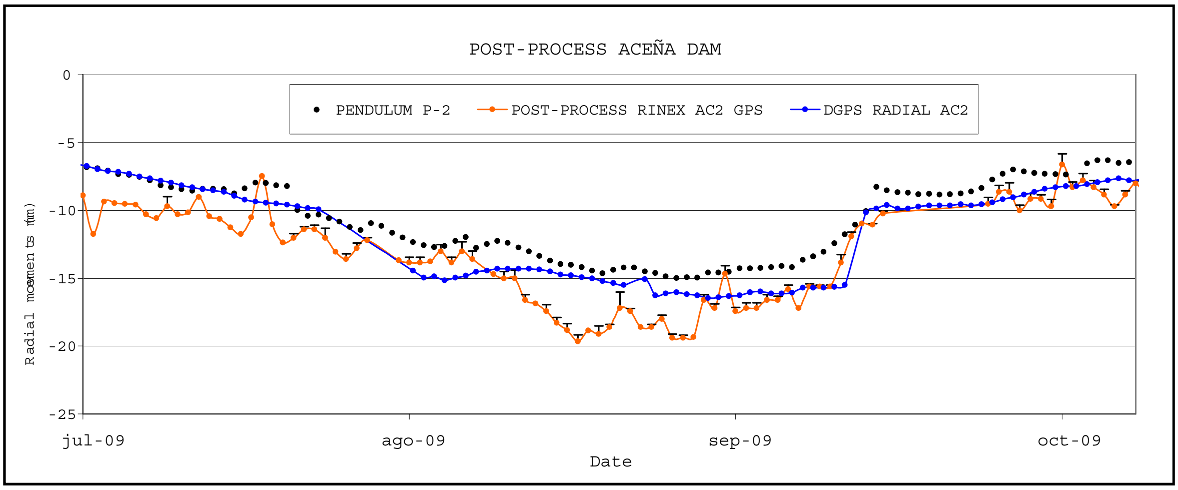

Fig. 11 Detail of post-processed and real-time DGPS measurements, including standard deviation for DGPS adjustment

It was calculated the root mean square error between the range of radial displacements recorded by the pendulum (considered as real movements) and the series of results obtained in "real time" and in "post-process" during the post-processing period (January 2009-January 2010). Besides, it was also calculated the RMS for a specific period (May 15-June 17, 2009) during which Kalman filter was altered to respond slowly with high inertia (Eq. 4). This analysis showed a significant deviation of the results in real time and confirmed that post-processing yielded more accurate solutions under this scenario (Tables 4 and 5; Figure 12).

$$\varepsilon = \sqrt{\frac{\sum \left(l_{Pendulum} - l_{GPS\ Postprocess}\right)^2}{n}} \qquad \varepsilon = \sqrt{\frac{\sum \left(l_{Pendulum} - l_{GPS\ Real Time}\right)^2}{n}} \tag{4}$$

4. Conclusions

The comparison of the obtained results between direct pendulums (reference values) and the DGPS system values is satisfactory for dam auscultation. Mean accuracy in real time DGPS, was between 2.33 and 3.09 mm in the first case (total period) and 1.44 - 1.86 mm in the period with stable communications. Precise angular collimation yielded also high accuracy solutions (1.79 – 2.21 mm) but in a monthly basis. These results coincide with the high level of agreement found by Rutledge and Meyerholz (2005) between DGPS and pendulum data in Libby Dam, which confirms that DGPS is well suited for long-term performance monitoring of dams.

The annual amplitude of observed movements (40.86 mm) is also well measured by both the DGPS (43.74 mm) and the precise angular collimation (40.18 mm). Behr et al. (2000) demonstrated that DPGS represented with precision radial displacements of Pacoima dam, and correlated this movement with the thermoelastic behavior of the structure. The low RMS values obtained for La Aceña support the fact that DGPS System is accurate with millimetric precision when the Kalman filter is applied, allowing the reduction of high frequency observation noise, as reported by Behr et al. (2000).

During the recorded period, many communications shutdowns occurred, affecting data quality and processing, as DGPS system needed to setup after each event. Dam location, in a remote and mountainous zone with frequent electrical

Table 4 Errors in radial movements with real-time and post-processed data (January 2009-January 2010)

Radial Movements	RMS (ε)
REAL TIME AC2 GPS – PENDULUM P-2	2.15 mm
POST-PROCESS RINEX AC2 GPS – PENDULUM P-2	2.36 mm

Table 5 Errors of radial movements with real-time and post-processed data (15 May-17 June 2009)

Radial Movements	RMS (ε)
REAL TIME AC2 GPS – PENDULUM P-2	4.09 mm
POST-PROCESS RINEX AC2 GPS – PENDULUM P-2	1.13 mm

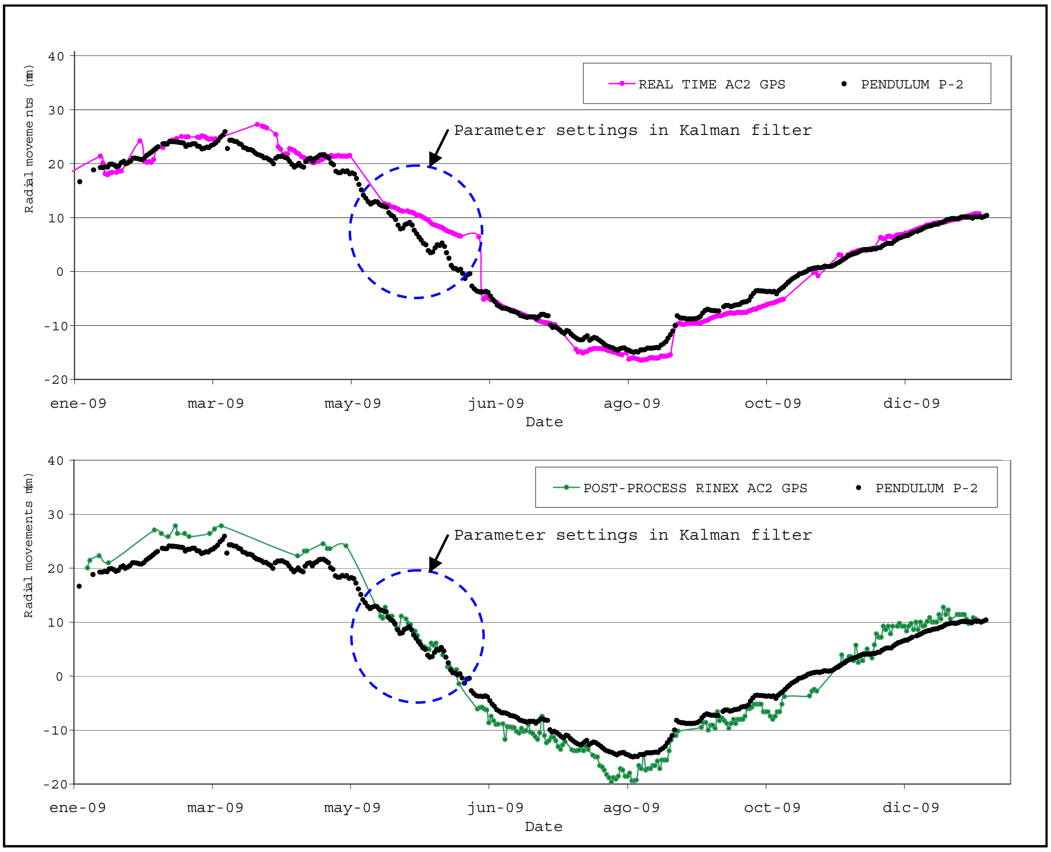

Fig. 12 Effect ofKalman filter configuration on real-time solutions ($Q=10^{-13}$except for highlighted period from May 15 to June 17 2009 where $Q=10^{-15}$) and post-processed solutions versus pendulum P-2

storms, affected the initial GPRS system communication. Once the ADSL was installed, data quality and accuracy were better. We can affirm that data discontinuity, due to communications problems, has negative influence over the DGPS system accuracy.

The configuration constants of the Kalman filter should be chosen according to the expected or observed movement velocity of the structure to be controlled. When calibrated constants, for specific movement velocity, are used and movement velocity is higher than expected, the filtered solution deviates from reality and takes some time to converge to the exact measurement. Moreover, if we analyze the period when communications were stable, the observed error is between 1.44 and 1.86 mm, showing that well adjusted Kalman filter allows reaching high accuracy when the structure movement is as predicted.

It is important to remark that both this technique and the precise angular collimation provide absolute coordinates while the direct pendulum system is based on a relative coordinate system, being complementary auscultation systems that allow ruling out possible movements in the foundation. When there is an uncertainty on the foundation movements and there is not an alternative auscultation system, DGPS or precise angular collimation can be used since both are based on absolute coordinate systems. Rutledge and Meyerholz [2] pointed out that the DGPS system offers the upside of being able to: 1) precisely monitor vertical displacement, 2) monitor monoliths without pendulums, and 3) track pure horizontal and vertical translation. These qualities of DGPS are well suited to performance monitoring and have important implications for dam safety. These authors support that, when pendulums are absent, DGPS networks should include at least two reference stations for safety reasons

Post-processed results showed also a high accuracy, with an error close to 2 mm with respect to the pendulums. Post-processing is useful in shifting periods, during which the calibration parameters of the Kalman filter may induce deviations of real time results. As an alternative, post-processing allows keeping high accuracy during those periods of time.

An interesting alternative to keep real time accuracy in the long term is to run different auscultation processes with different "Kalman filter" calibration. This allows representing low frequency dynamics as well as shifting periods with the same accuracy.

As a general conclusion we can affirm that the DGPS system is very useful in dam auscultation and safety as it detects adequately absolute deformations, being a complement to the existing methods which should be considered in new safety plans.

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