# COMPARISON BETWEEN GEODETIC TECHNOLOGY AND PLUMB LINES IN MONITORING OF DISPLACEMENTS ON ITAIPU DAM

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**Abstract:** ITAIPU is the world largest dam regarding energy production and the second in installed power capacity. ITAIPU hydropower plant is located in the Southwest of Brazil on the Paraná River, which forms the border with Paraguay. The power generation began in 1981. One of the aspects for evaluating dams safety is the displacement of its structures, which has to be monitored and analyzed in different ways. In this case, different techniques and methods, adequate for the different types of structures, have to be applied. At ITAIPU Dam, the displacement measurements are performed by plumb lines and also by geodetic observations using a high precision Total Station based on a network of 7 stable pillars downstream the dam. A total of 20 object points are visualized. The Polytechnic School of the University of São Paulo (EPUSP) through its Laboratory of Topography and Geodesy (LTG), Department of Transportation Engineering - PTR, has recently focused attention on the use of GPS as an alternative for monitoring the pillars and the dam. The purpose of this paper is to describe the methodology used to process the GPS observations and to analyze the possibilities of displacements in one object point (F19) where GPS and plumb line readings are available.

## 1. INTRODUCTION

Control and monitoring of the most different engineering enterprises, during and after construction, are as important as planning, design, execution and “as built”.

Dam safety is one of the fundamental aspects during the whole service life of the structures designed for this end, as to them is associated a high accident risk potential of significant proportions not only for the structures themselves, but also for the population living in the region involved. Preventive actions are directly taken by means of installing devices that are able to monitor the behavior of the dam structures during the construction period and all along the operation time. These instruments should be capable of measuring the magnitudes involved, with the adequate precision, for further comparative analysis with the mathematical models provided in the design. The instruments are directly dependent on the type of structure to be monitored.

The types of monitoring devices used in dams are: civil instrumentation (extensometers, clinometers, plumb lines, among others) and geodetic instrumentation (GPS, total stations and levels). The two types are applied as a methodology for comparing the measurements among different periods of observation, determining the differences, that is, possible displacements.

Geodetic instrumentation has characteristics that complement the observations conducted with civil instrumentation, as the reference for the measurements is absolute (stable) and not related to the previous measurements. Thus, the displacements determined in function of the measurements carried out by a geodetic instrument always have the same absolute reference. However, civil instrumentation, a direct plumb line (PL), for example, stores displacement measurements related to its installation, which along time turns to be the reference for further measurements.

The Polytechnic School of the University of São Paulo, by means of the Laboratory of Topography and Geodesy – LTG, Department of Transportation Engineering – PTR, has carried out recent researches so as to define methodologies for adjusting displacement measurement techniques applied to the different structure types. These techniques include the use of several technologies and high precision equipment available for assessing the displacements.

The Itaipu hydropower plant is located on the Paraná River, on the border of Brazil and Paraguay, formed by five different dam types, identified below by numbers, and presented in Figure 1:

- 1 - Earthfill (right margin);
- 8 - Earthfill (left margin);
- 7 - Rockfill;
- 9 – Concrete – hollow gravity type (main);
- 3 - Concrete in buttress (lateral right dam).

Together they accomplish a total 7,700m in length with a maximum height of 196m.

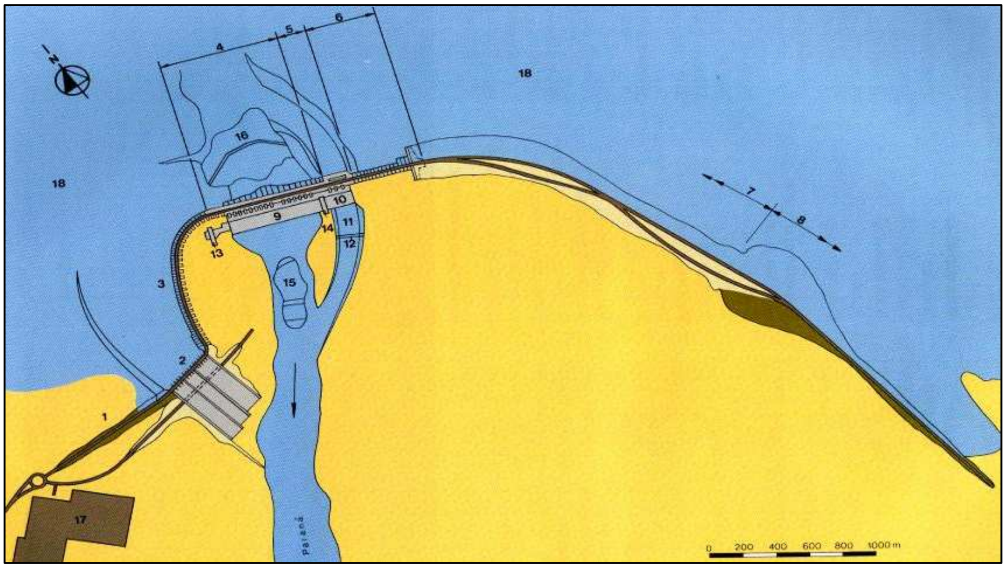


Figure 1 - Itaipu Dams
Source: Itaipu Binacional (2002)

In May 2007, the month in which Brazil and Paraguay celebrated the 33rd anniversary of the Itaipu agreement signature, the last two power-generating units from a total of 20, provided in the power plant design, started their operation.

Therefore, with all the units in action and with the Paraná River in favorable conditions, normal rainfall levels along the whole river basin, power generation may reach 100 billion kW/hour.

Objective

This work aims to show an assessment of the comparison between the results of observations with the GPS technology and those conducted by the PL in a key block of the main concrete dam, named F19.

The use of GPS technology demands the application of a methodology based on processed and adjusted observations, referred to a network with stable monumentation. The observations were conducted in two campaigns at different epochs.

The observations with the direct plumb line were conducted by the Itaipu automated system (ADAS) at the same epochs.

## 2. ITAIPU GEOLOGICAL INVESTIGATIONS

The Itaipu hydroplant region is formed by lava flows of the Alto Paraná Basin, belonging to the Serra Geral formation. The main geological characteristics of the place are:

- essentially horizontal lava flows, 20 to 70m thick;

- layers of basaltic breccia between the lava flows, with thicknesses varying between 1 and 30m, generally heterogeneous and less resistant and more deformable than basalt;

- horizontal permeability several times higher than vertical permeability.

The thickness, lithology and porosity of the breach layers are extremely variable and have to be analyzed. For this reason, since the initial phase, geological investigations were conducted by bore holes, inspections in situ and prospection with variable diameter wells of up to 4m and about 120m in depth. With this, the main layers and discontinuities located in the main dam foundation were crossed, which allowed the installation of 3 inverted plumb lines at different depths integrating the permanent monitoring system of the concrete structures.

The ITAIPU dam, owing to the magnitude of the concrete structures with blocks of up to 196m in height and of the geological discontinuities of the foundation, involved the execution of an intense concrete keys system at the blocks foundation and was given special attention with the foundation monitoring.

## 3. DAMS INSTRUMENTATION: HORIZONTAL CREST DISPLACEMENTS

According to Silveira (2003), the horizontal crest displacements of concrete dams are influenced by the following physical magnitudes:

- concrete structure deflection;

- structure base rotation, owing to foundation deformability;

- variation in ambient temperature.

Therefore, the horizontal crest displacements are influenced both by the concrete characteristics themselves, and by the properties of the foundation rock mass. These displacements are usually measured by direct and inverted plumb lines vertically installed between the dam crest and the foundation. This type of instrument is formed by a 1 mm-diameter stainless steel wire, fixed at the dam crest and kept stressed by a 30 to 40 kg weight, immersed in a reservoir with oil to keep the wire stability. Figure 2 illustrates the installation scheme of a direct PL in a concrete dam.

The readings of the plumb line horizontal displacements are conducted with the aid of optical (Figure 3) or electronic (Figure 4) coordinometers, according to the upstream–downstream directions and right–left margins. In the optical system, the displacements reading is conducted by a refracting telescope fixed to a micrometer that slides along a horizontal basis, until the wire position is determined. Despite there being verniers with ± 0.01mm accuracy, they allow readings with 0.5mm accuracy, owing to the difficulty of accurate visualization of the wire. More recently, the electronic coordinometers started to be used, as they allow automated readings with accuracy of the order of 0.05mm, that is, ten times greater than that of the optical coordinometer (Silveira, 2003).

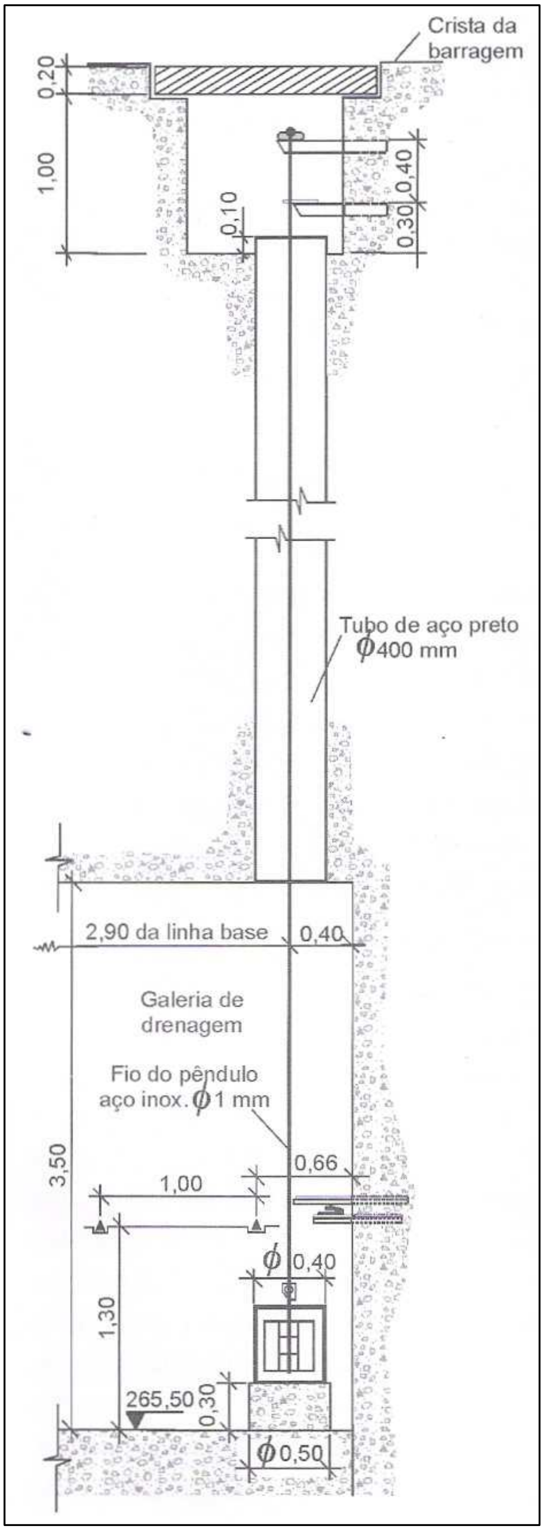



Figure 2 - Installation scheme of a plumb line in a concrete dam.
Source: Silveira (2003)


Figure 3 - Plumb line reading at ITAIPU dam with optical coordinometer

Figure 4 - Automated reading (ADAS) of the plumb line at ITAIPU dam

## HORIZONTAL DISPLACEMENTS OF ITAIPU MAIN DAM CREST

The horizontal displacements of the Itaipu dam crest have been measured at the instrumented key blocks (Figure 5), by direct plumb lines associated to inverted plumb lines, or multiple spider strain meter at the foundation. ITAIPU dam was the first concrete dam in Brazil in which inverted plumb lines were replaced by the spider strain meters of 3 extensometers at the foundation. However, four blocks were instrumented with inverted plumb lines taking advantage of the existence of vertical prospection wells at the foundation.

The theoretical displacements of the instrumented key blocks were foreseen by means of mathematical models. The crest horizontal displacement observed in the 18 initial years of operation, had a 60% increase in key block F19, that is, it went from 8.6mm in 1984 up to 13.8mm in 2002 (SILVEIRA, 2003).

The variation rate of the horizontal crest displacements was of the order of 0.2mm/year in 2002, which demonstrates a stabilization tendency along time. Nevertheless, between the summer and winter periods, Itaipu dam crest shows amplitudes of horizontal displacements of the order of 4 to 5mm at block F19 (SILVEIRA, 2003).

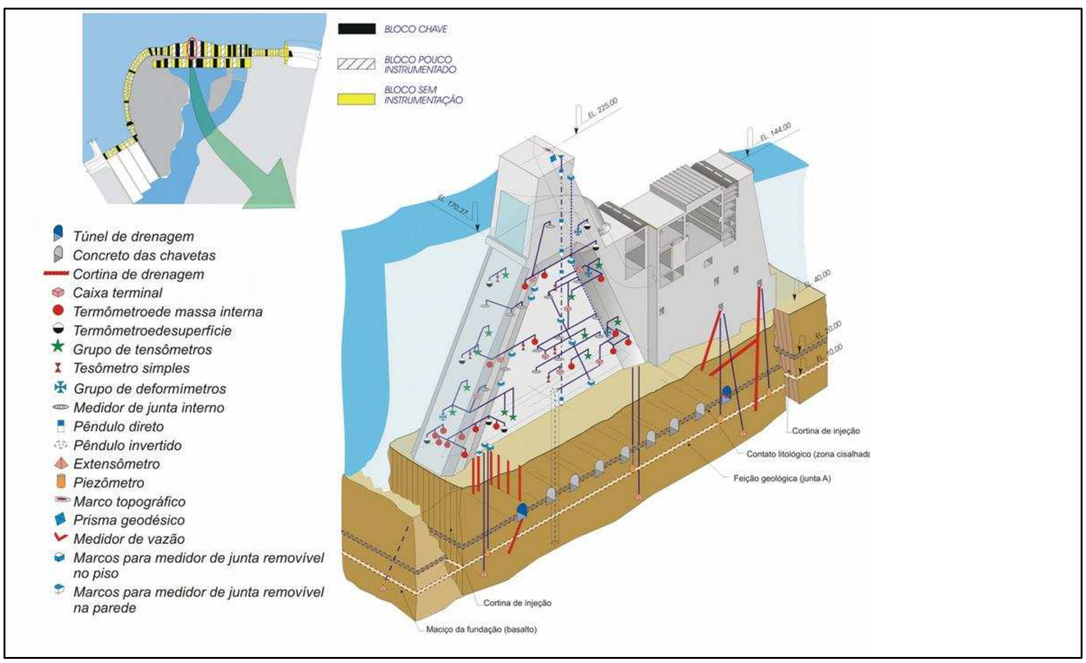



Figure 5 - Instrumented key block at ITAIPU dam

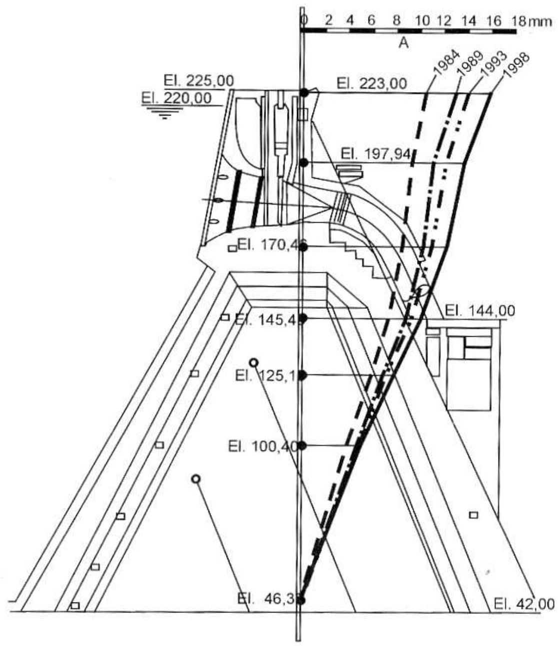



Figure 6 - Observations conducted by the Plumb line installed at the F19 point.

## 4. STABLE REFERENCE NETWORK FOR GPS OBSERVATIONS

Since the construction of Itaipu Binacional, there was special concern with the dam structure monitoring. For this purpose, 7 pillars considered stable were built, located downstream the dam. Furthermore, a continuous monitoring station was recently established, ITAI, located in the same area as the seven pillars, made official by IBGE. Finally, three more monumented points (EBPY≡ Tati Yupi, EBPI≡ PIR, EBBM≡SE01) were also recently implemented, located outside the dam influence area (Figure 7).

Two GPS observation campaigns were conducted in the periods: June 18 to 22 and October 15 to 19, 2007, in a total of five tracking sessions, of eight hours each, with a 5s rate. The following double-frequency receivers were used: Leica Geosystems, being two of them GX 1230 model - accuracy ±(5mm + 0.5ppm), two SR 520 model - accuracy ±(5mm + 1ppm), all of them with AX 1202 GG antennas, and two SR 530 model - accuracy ±(5mm + 1ppm) with AT 502 antennas. Two Javad receivers, Legacy model - accuracy ±(5mm + 1ppm) with choke ring type antennas. The positioning method adopted was the relative static one.

GPS observations were conducted in all the points shown in Figure 7, which included the reference points and seven points more on the structure, particularly F19, located in the same block where one of the direct plumb lines is installed. The point F19 coordinates were determined as from the three reference points considered stable, that is, EBPY≡Tati Yupi, EBPI≡PIR, EBBM≡SE01. The adjusted cartesian coordinates of these points, referred to WGS-84, are presented in Table 1.

The adjusted coordinates in the two campaigns and different sessions, calculated for F19 from the 3 reference points, are presented in Table 2.

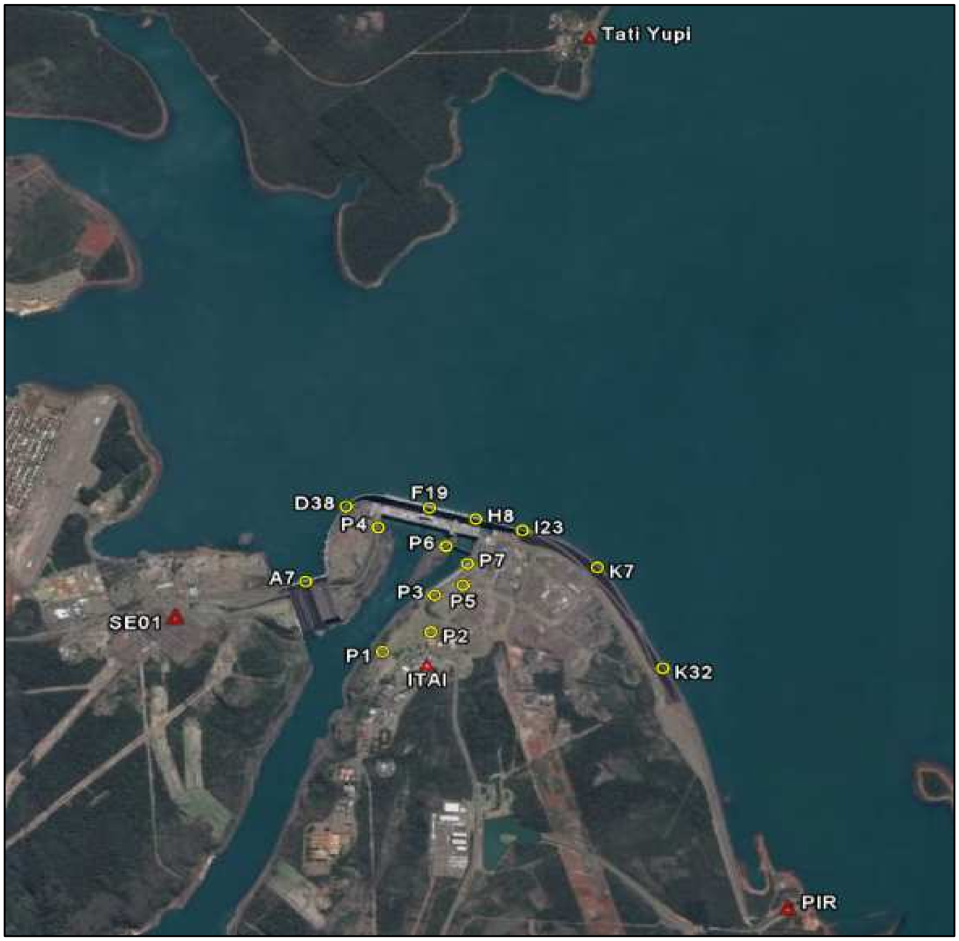



Figure 7 - Network of pillars and points on the dam, particularly, F19

Table 1 - Cartesian coordinates of the ITAI stations (fixed) and adjusted EBBM, EBPI and EBPY in WGS-84.

| Coordinates Station | X (m) | Standard Deviation X (m) | Y (m) | Standard Deviation Y (m) | Z (m) | Standard Deviation Z (m) |
|---|---|---|---|---|---|---|
| **ITAI (fixed)** | **3340128.1307** | **0.0031** | **- 4697983.6868** | **0.0031** | **- 2721315.4994** | **0.0027** |
| **EBBM** | **3338475.3022** | **0.0039** | **- 4699383.7674** | **0.0048** | **- 2721043.0867** | **0.0035** |
| **EBPI** | **3342198.7526** | **0.0065** | **- 4695456.5742** | **0.0079** | **- 2723221.0048** | **0.0053** |
| **EBPY** | **3342436.8252** | **0.0047** | **- 4699544.8085** | **0.0052** | **-2715925.8020** | **0.0037** |

Table 2 – Adjusted coordinates of point F19 in the UTM system and in the Dam axle system.

| Point | Campaign | Session | E (m) | N (m) | Standard Deviation E (m) | Standard Deviation N (m) | $X_B$ (m) | $Y_B$ (m) | Standard Deviation $X_B$ (m) | Standard Deviation $Y_B$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| F-19 | 1 | 1 | 742507,6932 | 7187746,1128 | 0,0052 | 0,0045 | 0,0002 | 0,0012 | 0,0052 | 0,0045 |
| F-19 | 1 | 2 | 742507,6931 | 7187746,1134 | 0,0056 | 0,0047 | 0,0005 | 0,0006 | 0,0056 | 0,0047 |
| F-19 | 1 | 3 | 742507,6915 | 7187746,1136 | 0,0053 | 0,0045 | 0,0021 | 0,0008 | 0,0053 | 0,0045 |
| F-19 | 1 | 4 | 742507,6929 | 7187746,1135 | 0,0037 | 0,0032 | 0,0007 | 0,0006 | 0,0037 | 0,0032 |
| F-19 | 2 | 1 | 742507,6959 | 7187746,1151 | 0,0033 | 0,0029 | -0,0019 | -0,0017 | 0,0033 | 0,0029 |
| F-19 | 2 | 2 | 742507,6937 | 7187746,1119 | 0,0069 | 0,0049 | -0,0004 | 0,0020 | 0,0068 | 0,0050 |
| F-19 | 2 | 3 | 742507,6939 | 7187746,1109 | 0,0050 | 0,0041 | -0,0009 | 0,0029 | 0,0050 | 0,0041 |

## 5. TRANSFORMATION OF UTM SYSTEM INTO DAM AXLE SYSTEM

A dextro Cartesian system was defined for this work, the direction of the normal axis (XB) longitudinal to the water flow, and the second axis transversal to the dam (YB), in the direction of the water flow, oriented downstream.

As the UTM system and the Dam Axis system are not parallel, and their origins were at different points, it was necessary to transform the UTM coordinates of point F-19 into Dam axis system. For this, a rotation and a translation had to be considered between the systems. Figure 8 illustrates this situation.

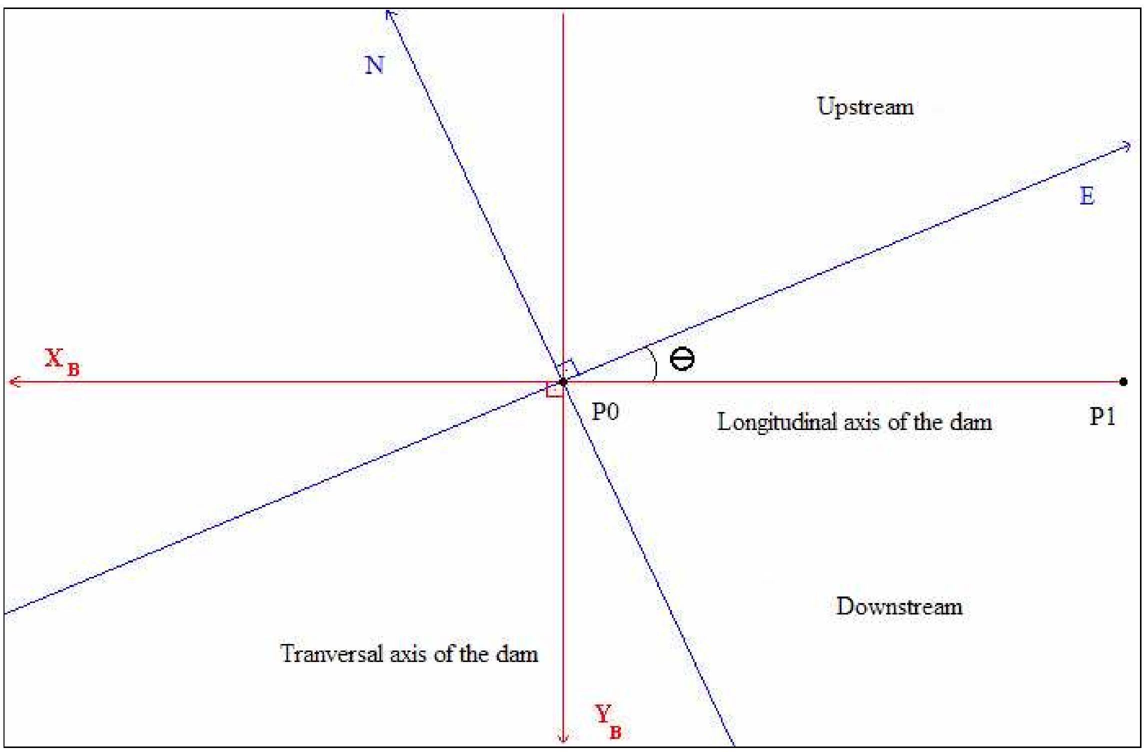



Figure 8 - Situation between the UTM system and the Dam Axis system.

To conduct the transformation between the systems, it was necessary to adopt a point P0 (E0,N0)=F19, as the origin of the dam cartesian system, and a point P1 (E1,N1)=H8 that defined the longitudinal axis alignment with the dam.

The rotation angle $\theta$ between the UTM system and the Dam Axis system may be calculated by the following expression:

$$\theta = arcsen\left(\frac{N_1 - N_0}{\sqrt{(E_1 - E_0)^2 + (N_1 - N_0)^2}}\right)$$

With these elements, it is possible to transform the coordinates of the UTM system into the Dam Axis system, using the following expression:

$$\begin{bmatrix} X_B^P \\ Y_B^P \end{bmatrix} = -R^{-1}\begin{bmatrix} E_P - E_0 \\ N_P - N_0 \end{bmatrix}$$

where:

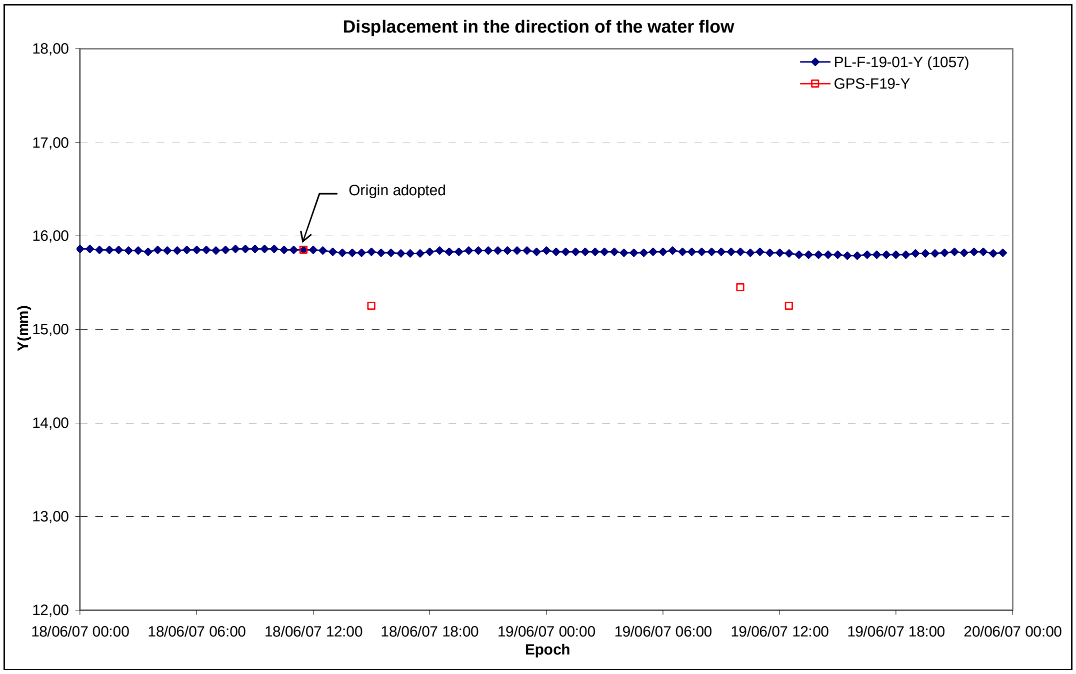
($X_B^P, Y_B^P$): coordinates of a point transformed into the Dam Axis system;

($E_P, N_P$): coordinates of a point in the UTM system; and

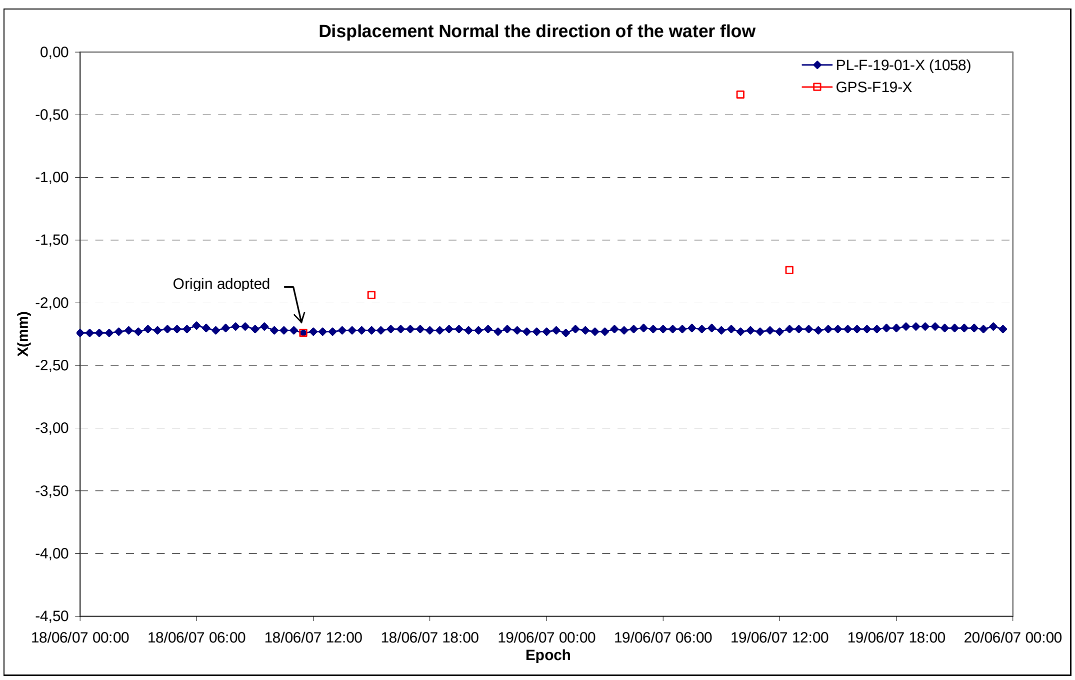
$$R = \begin{bmatrix} \cos\theta & -\mathrm{sen}\theta \\ \mathrm{sen}\theta & \cos\theta \end{bmatrix}$$

## 6. COMPARISON OF THE RESULTS OF THE PLUMB LINE VERSUS GPS OBSERVATIONS

For the purpose of comparing the results of the plumb line observations at point F19 and the GPS results in two campaigns, the same temporal origin was adopted, as there is not a single reference for these observations. Therefore, the result of the GPS observations in the first session in the first campaign was assumed to coincide with the plumb line result at the same epoch. These results are presented in Graphs 1, 2, 3 and 4, where a coincidence can be verified to exist at the June 18, 2007 11:30 (local time) epoch, adopted as origin.

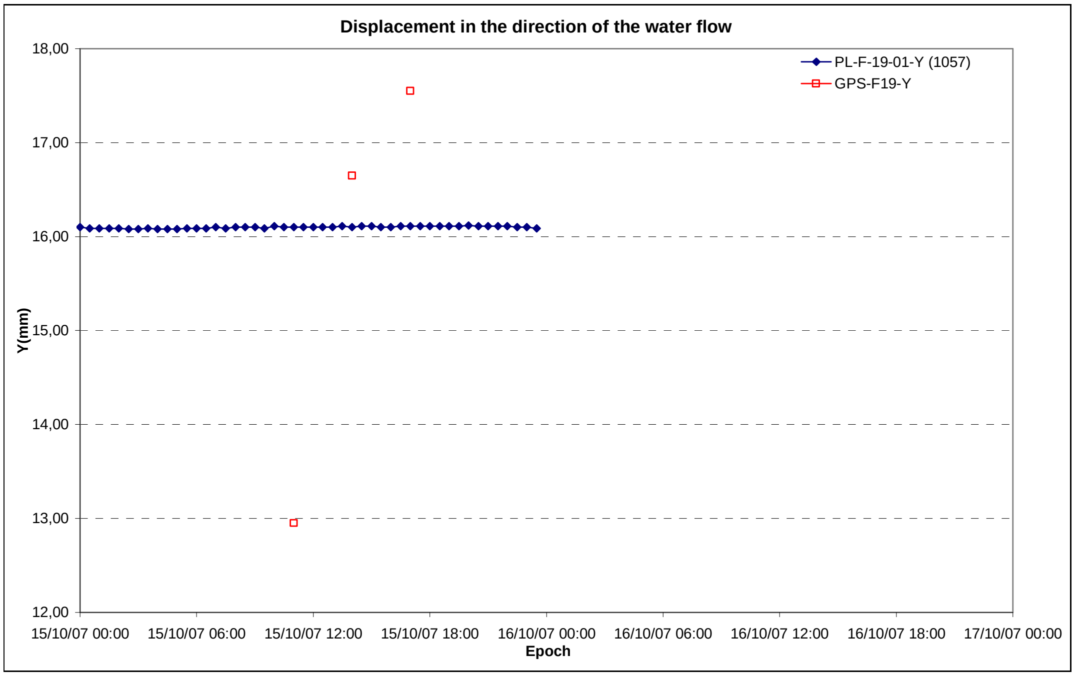



Graph 1 - Displacements in the water flow direction (Y) of point F19 determined by GPS (1$^{st}$ campaign) and by direct PL

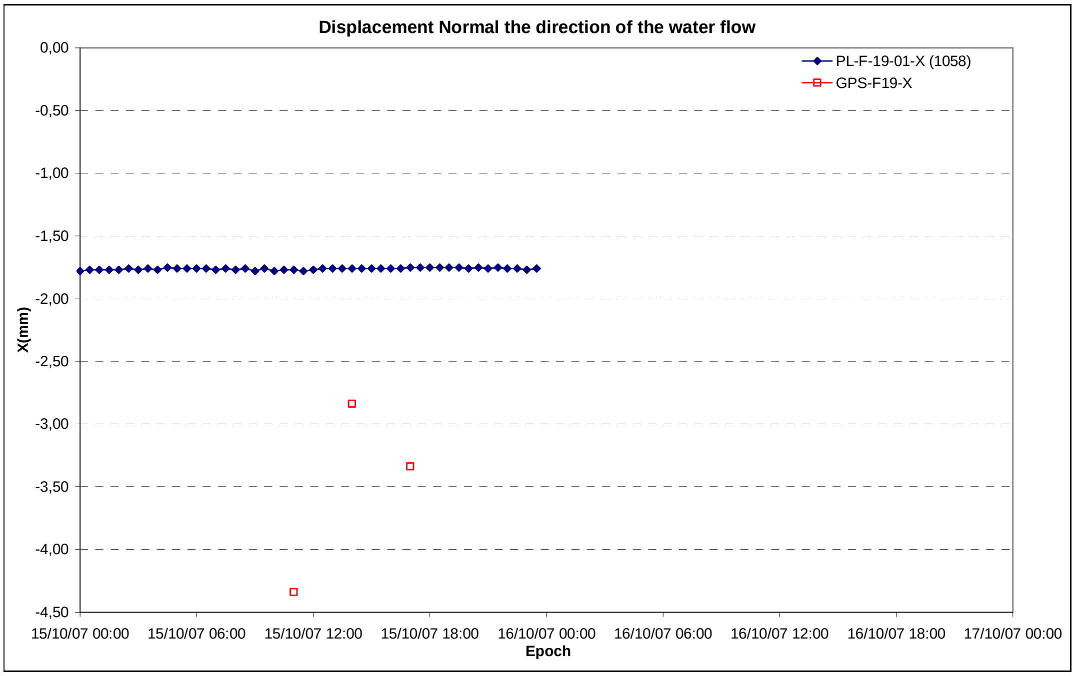



Graph 2 - Displacements in the normal direction of the water flow (X) of point F19 determined by GPS (1$^{st}$ campaign) and by PL

Analyzing Graph 1, the differences found between the PL values can be verified along with those determined by GPS are 0.58, 0.38 and 0.56 mm, in their respective epochs. In Graph 2, the differences found in their respective epochs are 0.28, 1.89 and 0.47 mm.




Graph 3 - Displacements in the direction of the water flow (Y) of point F19 determined by GPS (2nd campaign) and with direct PL




Graph 4 - Displacements in the normal direction of the water flow (X) of point F19 determined by GPS (2nd campaign) and by direct PL

Analyzing Graph 3, the differences found between the plumb line values and those determined by GPS are 3.15, 0.55 and 1.44 mm, in their respective epochs. In Graph 4, the differences found in their respective epochs are 2.57, 1.08 and 1.59 mm.

## 7. CONCLUSIONS AND RECOMMENDATIONS

This paper presents a first attempt for comparing two distinct technologies, the GPS and the pendulum, conscious that the nominal accuracy of the two equipments are different, the first being worse than the second. On the other hand, Itaipu has a continuous long historical data of the pendulum and the GPS, out to not be continuous, are recent. With this in mind, the differences are just a comparison of values. Nevertheless it is possible to guarantee that GPS is an efficient technology for obtaining results relative to a reference exterior of the structure, in the case, the three reference points away of the main influence of the dam. The GPS has a potential capacity to produce results in order to detect movements of the structure as far as long series of observations are available for comparison with PL.

The methodology used in this work shall be applied in new campaigns so as to generate a historical series of results by GPS, which will be able to provide a more representative comparison with the PL results. As an alternative for obtaining a historical series with GPS, so that its observation epochs coincide with those provided by the PL, is a proposal to install a GPS receiver that performs continuous observations at point F19 and/or in other points of the dam crest where direct PL are installed.

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