Proposal for Verification of the Stability of Observation Pillars for Monitoring of Structures by GPS – The Case of ITAIPU Dam

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SUMMARY

The ITAIPU hydro-electrical power plant is situated in the Southwest of Brazil on the Parana River, which forms the border with Paraguay. The generation of electrical energy began in 1981. ITAIPU Dam still the World's largest with regarding to electrical power installation and the second largest in water volume.

One of the aspects for the evaluation of security is the displacement of structures, which has to be monitored and analyzed in different ways. For this reason, different techniques and methods, appropriate for the different types of the structures, have to be applied.

At the ITAIPU Dam the measurement of displacements is performed by plumb lines and also by geodetic observations based on a network of 7 observations pillars downstream the dam.

The purpose of this paper is to describe new procedures to verify the stability of the observation pillars of the base control network by GPS.

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1. INTRODUCTION

The control and monitoring of engineering projects during and after construction are as important as planning, execution and also as-built.
The behavior of engineering works is directly related to the security of concrete structures. It is of extreme importance, because high-level risks are involved. An accident could have significant consequences not only for the structures themselves but also for the community, as a whole.
The Polytechnic School - University of Sao Paulo - EPUSP through its Laboratory of Topography and Geodesy - LTG of the Transportation Engineering Department - PTR, has carried out studies recently, to define adequate methods and techniques for the measurement of displacements by use of high precision instruments, such as Total Stations and GPS receivers, and also by conventional instruments.
The ITAIPU dam is composed of concrete, earth fill and rock fill dams with a total length of 7700m and a maximum height of 196m.

Figure: The ITAIPU dam

The measurements of displacements of structures are accomplished by direct and inverted plumb lines and also by geodetic observations (Silveira 2003).
For the purpose of monitoring the structures displacements, were defined so-called Object Points, distributed near the crest of the dam, as follows:

- Spillway - A7 and A15
- Right wing dam - D8, D20, D38, D54 and D57
- Main dam - E6, F5/6, F13/14, F19/20, F35/36, H8, H8A and I10
- Rock fill dam – I23, MR-K-1, MR-K-7, MR-K-12, MR-K-32

The network for the geodetic control measurements is formed by seven observation pillars constructed downstream from the dams.
Geodetic observations campaigns began in 1982, before the water reservoir started to be filled. The distances between the observation pillars of the control network (P1, P2, P3, P4, P5, P6 e P7) and the Object Points as shown in FIGURE 1, were measured using a Kern Mekometer ME-3000 - in the initial stage – and nowadays using a Leica Total Station TC 2002.

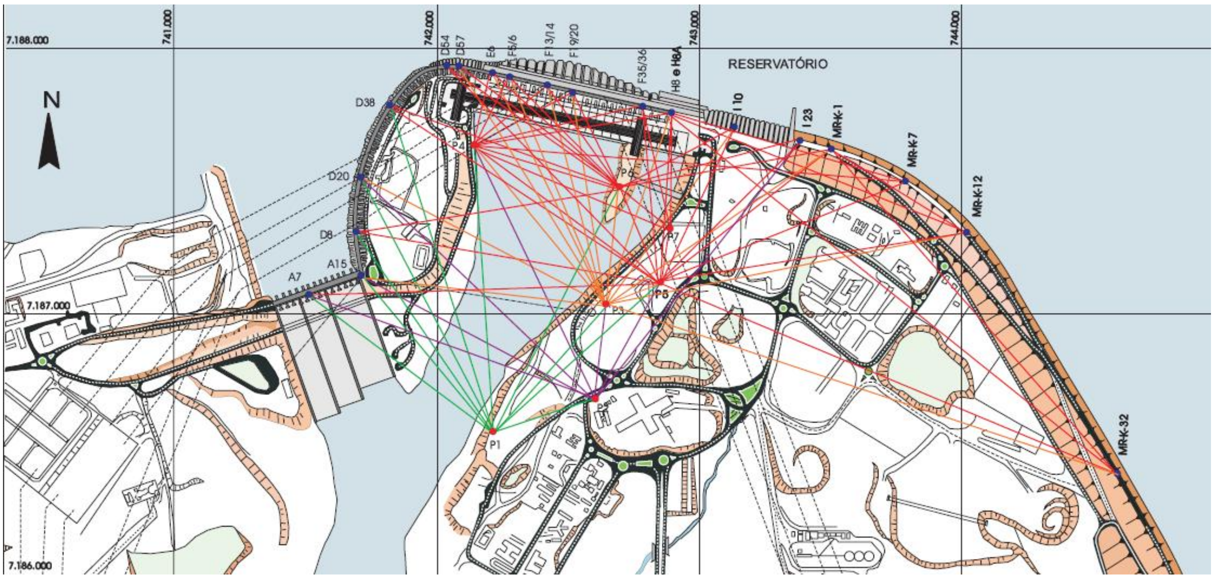

Figure 1: Observation pillars and Object Points (ITAIPU DT 2005)

2. THE OBJECTIVIES

The geodetic observations of displacements vectors of the so-called “key structures” (structures of main interest) led to results, which could not be easily analyzed by the engineers of ITAIPU. However, the University of Sao Paulo is well experienced in these matters.
For these reasons, technical cooperation between the Polytechnic School - University of Sao Paulo - EPUSP and ITAIPU Binacional, which operates the hydro-electrical power plant, came into existence.
The purposes of this cooperation are:

First: to analyze the geodetic control system presently in use at ITAIPU dam;

Second: consolidate the discrepancies revealed after processing the data collection from several observation campaigns;

Third: to study the case, define and propose alternative methodologies to monitor the structures displacements of the dam using GPS observations.

Taking into consideration that the basic condition for monitoring structures by geodetic or GPS measurements is the stability of the observations pillars, an initial GPS campaign was executed in April 2006 using GPS receivers at all the observation pillars of the control network, in order to obtain stable geocentric reference for the monitoring campaigns by geodetic instruments (Total Stations) normally used by ITAIPU.
The next GPS campaign is scheduled for October 2006 in order to get new data for comparison with the data shown in this paper.
The stability of the reference pillars will be analyzed after processing and adjustment of the observations obtained during the campaigns.

3. PLANNING OF THE DATA COLLECTION

The execution of the first GPS campaign was prepared in function of the local logistical support before and during the data collection.

3.1 Definition of the methodology

The applied methodology for the two GPS campaigns (April and October 2006) is defined as follows:

- All of the above mentioned observation pillars of the reference system should be occupied simultaneously, with Double-frequency receivers for data collecting, data processing and adjustment.
- A fixed reference station, named ITAIPU-CHI-FOZ was chosen as the reference station, and its coordinates determined and adjusted from two stations of the so-called

RBMC (Rede Brasileira de Monitoramento Contínuo – Brazilian Network of Continuous GPS
Operating). These two stations named UEPP, in Presidente Prudente – state of Sao Paulo, and SMAR, in Santa Maria - state of Rio Grande do Sul, were chosen because their convenient distances from the area of this study. The coordinates of the RBMC stations are related to the so-called "Sistema de Reference Geocentrico para as Américas (SIRGAS 2000) – Geocentric Reference system to the Americas", which is practically identical to the WGS 84 (World Geodetic System).

3.2 The site infrastructure

Some measures were taken as support to the first campaign:

- Utilization of the data of the active Reference Station ITAIPU-CHI-FOZ, constructed by ITAIPU Administration, recently approved by IBGE (Instituto Brasileiro de Geografia e Estatística) to be integrated in the RBMC.
- Removal of the observation pillars covers to avoid GPS signals obstructions and multipath.
- Adapters were developed to fix GPS antennas on existing forced centering systems, model Kern.

4. SITE DATA COLLECTING

The data collection of the first GPS campaign took place during the period between April 3rd and 6th of 2006 by using a total of eight GPS receivers (including ITAIPU-CHI-FOZ station). The equipment used is specified as follows:

- 5 Double-frequency receiver of Leica Geosystems, 4 model GX 1220 (precision 5mm+0.5ppm) and 1 model SR 520 (precision 5mm+1ppm), all with AT 1202 antennas.
- 2 Double-frequency of Leica Geosystems model SR 530 (precision 5mm+1ppm) with antenna AT 502.

All antennas with these receivers were mounted at the pillars P1, P2, P3, P4, P5, P6 and P7, as shown in FIGURE 2, and operated for a period of 4 days. For computing of positions the relative-static method was chosen with logging interval of 5 seconds during 8 continuous hours of observation time at least.

Fig 2: Installation of GPS Antennas on top of pillars P1 to P7 and the fix Station ITAIPU-CHI-FOZ respectively

5. PROCESSING AND ADJUSTMENT OF DATA

5.1 ITAIPU-CHI-FOZ Station

After completing 12 hours of data collection at the main stations UEPP and SMAR of the RBMC network and also at the ITAIPU-CHI-FOZ station on April 6th, the data were processed by means of the software LEICA GEO Office version 3.0.
In order to get better precision for the positions to be computed, the precise ephemerides for GPS week number 1369, downloaded from IGS (International GNSS Service) website, which comprises a world wide network of more than 400 stations, were used (Mônico 2000).
The vectors UEPP→ITAIPU-CHI-FOZ and SMAR→ITAIPU-CHI-FOZ to be processed are shown in FIGURE 3:

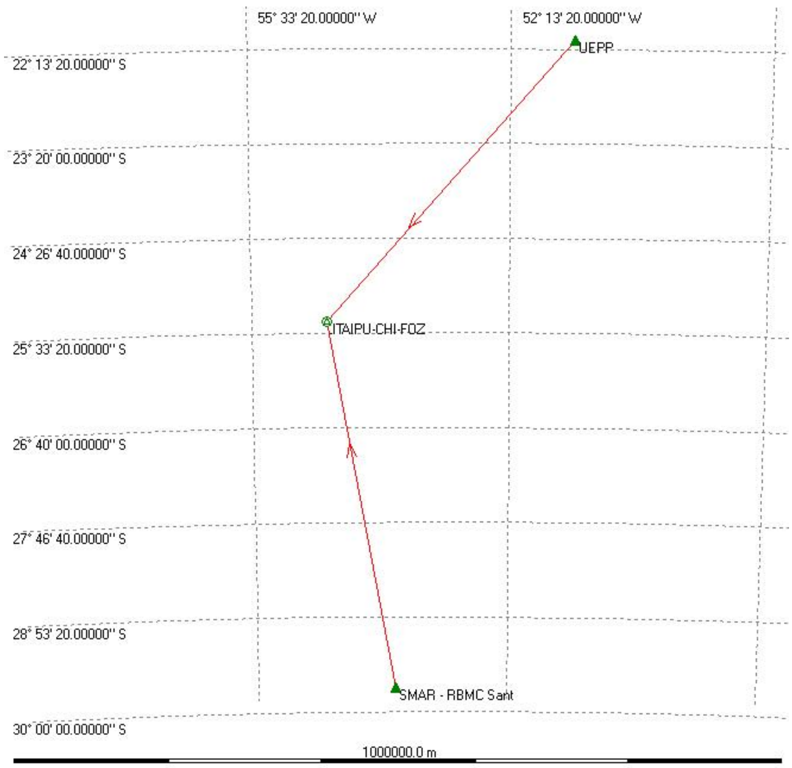

Fig 3: Vectors to be processed and adjusted for ITAIPU-CHI-FOZ station

The two vectors UEPP→ITAIPU-CHI-FOZ and SMAR→ITAIPU-CHI-FOZ are about 480km in length and form a triangle. In other words, the station ITAIPU-CHI-FOZ can be determined from the two stations UEPP and SMAR by adjusting the redundancy of observations. In the case of redundancy of observations, to obtain a unique solution with the best results normally the Least Squares method has to be applied.

The transmitted signals suffer influences of atmosphere, mostly by the ionosphere, which can be easily eliminated for short distances (baselines up to 50km). However, for long distances the ionosphere effects can easily be eliminated by a linear combination of frequencies L1 and L2, generating the so-called L3 or IonoFree frequency.
During the static processing of the two vectors, the ambiguity solution was performed by the IonoFree (L3) frequency as shown in TABLE 1.

	Reference: UEPP	**Rover: ITAIPU-CHI-FOZ**	
Coordinates WGS84:			
Latitude:	22° 07' 11.65710" S	25° 25' 14.44421" S	
Longitude:	51° 24' 30.72220" W	54° 35' 17.85545" W	
Ellip. Hgt:	430.9500 m	183.2500 m	
Solution:	Fase		
Frequency:	IonoFree (L3)		
Ambiguity:	Yes		
Quality:	Sd Lat: 0.0008 m Posn. Qlty.: 0.0012 m	Sd Lon: 0.0009 m	Sd Alt: 0.0022 m

	Reference: SMAR	**Rover: ITAIPU-CHI-FOZ**	
Coordinates WGS84 :			
Latitude:	29° 43' 08.12600" S	25° 25' 14.44476" S	
Longitude:	53° 42' 59.73530" W	54° 35' 17.85586" W	
Ellip. Hgt:	113.1100 m	183.1701 m	
Solution:	Fase		
Frequency:	IonoFree (L3)		
Ambiguity:	Yes		
Quality:	Sd Lat: 0.0059 m Posn. Qlty.: 0.0077 m	Sd Lon: 0.0049 m	Sd Alt: 0.0131 m

TABLE 1: Coordinates of ITAIPU-CHI-FOZ station processed with reference to UEPP and SMAR

The results of the coordinates adjusted are shown in TABLE 2:

Station		Coordinate	Corr.	Sd	
ITAIPU-CHI-FOZ	Latitude	25° 25' 14.44422" S	-0.0578 m	0.0033 m	
	Longitude	54° 35' 17.85546" W	0.0440 m	0.0034 m	
	Alt. Elip	183.2479 m	-0.2666 m	0.0085 m	
SMAR - RBMC Sant	Latitude	29° 43' 08.12600" S	0.0000 m	-	fixed
	Longitude	53° 42' 59.73530" W	0.0000 m	-	fixed
	Ellip. Hgt	113.1100 m	0.0000 m	-	fixed
UEPP	Latitude	22° 07' 11.65710" S	0.0000 m	-	fixed
	Longitude	51° 24' 30.72220" W	0.0000 m	-	fixed
	Ellip. Hgt	430.9500 m	0.0000 m	-	fixed

TABLE 2: Adjusted coordinates of ITAIPU-CHI-FOZ station

5.2 The Network formed by pillars P1 to P7

The procedures for data processing and adjustment of the position of the network observation pillars are similar to the procedures described above.
Precise ephemerides were also used and the data collecting was performed during 4 hours on April 3rd and during 8 hours on April 4th, 5th and 6th.
As a result, independent vectors for 4 days period were obtained. The distances in that network vary from 300m to 1300m.
For data processing and adjustment of the network, 4 reference stations were selected, namely: ITAIPU-CHI-FOZ, P4, P1 and P5. From these stations the remaining stations P2, P3, P6 e P7 were processed as shown in TABLES 3, 4, 5 and 6.

Reference: ITAIPU-CHI-FOZ			**Rover: P1 to P7**		**06/04/06**	
ID	**Ambig.**	**Sol.**	**Freq.**	**Latitude**	**Longitude**	**Ellip. Hgt**
P1	Yes	Fase	L1 + L2	25° 25' 11.43358" S	54° 35' 31.35052" W	168.9844
P2	Yes	Fase	L1 + L2	25° 25' 04.73242" S	54° 35' 17.29385" W	181.8517
P3	Yes	Fase	L1 + L2	25° 24' 52.37914" S	54° 35' 16.59244" W	183.4935
P6	Yes	Fase	L1 + L2	25° 24' 38.18337" S	54° 35' 14.65325" W	152.8979
P4	Yes	Fase	L1 + L2	25° 24' 33.50139" S	54° 35' 35.37787" W	147.1729
P5	Yes	Fase	L1 + L2	25° 24' 49.95606" S	54° 35' 08.68429" W	186.5787
P7	Yes	Fase	L1 + L2	25° 24' 43.30517" S	54° 35' 07.79190" W	176.3042

TABLE 3: Processed coordinates for P1 to P7, with reference to ITAIPU-CHI-FOZ station

Reference: P4			Rover: ITAIPU-CHI-FOZ, P7, P6, P1 and P3		03/04/06	
ID	**Ambig.**	**Sol.**	**Freq.**	**Latitude**	**Longitude**	**Ellip. Hgt**
ITAIPU-CHI-FOZ	Yes	Fase	L1 + L2	25° 25' 14.44422" S	54° 35' 17.85554" W	183.2412
P7	Yes	Fase	L1 + L2	25° 24' 43.30518" S	54° 35' 07.79194" W	176.3042
P6	Yes	Fase	L1 + L2	25° 24' 38.18337" S	54° 35' 14.65330" W	152.8827
P1	Yes	Fase	L1 + L2	25° 25' 11.43347" S	54° 35' 31.35066" W	168.9633
P3	Yes	Fase	L1 + L2	25° 24' 52.37906" S	54° 35' 16.59242" W	183.5033

TABLE 4: Processed coordinates for ITAIPU-CHI-FOZ P7, P6, P1 and P3 with reference to P4

Reference: P1			Rover: ITAIPU-CHI-FOZ, P2 to P7		04/04/06	
ID	**Ambig.**	**Sol.**	**Freq.**	**Latitude**	**Longitude**	**Ellip. Hgt**
ITAIPU-CHI-FOZ	Yes	Fase	L1 + L2	25° 25' 14.44211" S	54° 35' 17.85578" W	183.6164
P3	Yes	Fase	L1 + L2	25° 24' 52.37700" S	54° 35' 16.59272" W	183.8765
P5	Yes	Fase	L1 + L2	25° 24' 49.95399" S	54° 35' 08.68460" W	186.9502
P7	Yes	Fase	L1 + L2	25° 24' 43.30313" S	54° 35' 07.79218" W	176.6752
P6	Yes	Fase	L1 + L2	25° 24' 38.18130" S	54° 35' 14.65356" W	153.2679
P4	Yes	Fase	L1 + L2	25° 24' 33.49932" S	54° 35' 35.37817" W	147.5450
P2	Yes	Fase	L1 + L2	25° 25' 04.73028" S	54° 35' 17.29409" W	182.2859

TABLE 5: Processed coordinates for ITAIPU-CHI-FOZ P2 to P7 with reference to P1

Reference: P5			Rover: ITAIPU-CHI-FOZ, P1 to P4, P6 and P7		05/04/06	
ID	**Ambig.**	**Sol.**	**Freq.**	**Latitude**	**Longitude**	**Ellip. Hgt**
ITAIPU-CHI-FOZ	Yes	Fase	L1 + L2	25° 25' 14.44420" S	54° 35' 17.85537" W	183.2581
P1	Yes	Fase	L1 + L2	25° 25' 11.43356" S	54° 35' 31.35043" W	168.9950
P2	Yes	Fase	L1 + L2	25° 25' 04.73241" S	54° 35' 17.29376" W	181.8745
P3	Yes	Fase	L1 + L2	25° 24' 52.37915" S	54° 35' 16.59233" W	183.5026
P7	Yes	Fase	L1 + L2	25° 24' 43.30522" S	54° 35' 07.79181" W	176.3151
P6	Yes	Fase	L1 + L2	25° 24' 38.18339" S	54° 35' 14.65319" W	152.9084
P4	Yes	Fase	L1 + L2	25° 24' 33.50140" S	54° 35' 35.37782" W	147.1830

TABLE 6: Processed coordinates for ITAIPU-CHI-FOZ P1 to P4 with reference to P5

The configuration of the adjustment network with all its vectors is presented in FIGURE 4:

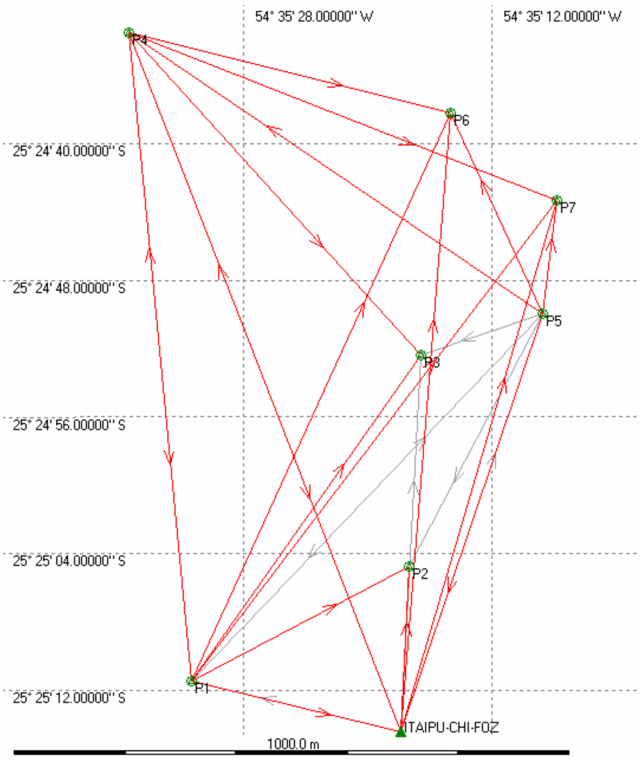

Fig 4: Configuration of adjustment network of the pillars P1 to P7 with ITAIPU-CHI-FOZ as a control station

Some vectors such as ITAIPU-CHI-FOZ→P1, ITAIPU-CHI-FOZ→P5, P1→P5, P2→P3, P5→P1, P5 →P2, P5→ P3, had shown larges residuals (outliers) after passing statistical tests and had to be eliminated before re-computing the adjustment.
TABLE 7 presents the adjusted final coordinates of the network of observation pillars together with the respective corrections and standard deviations.

Station		Coordinate	Corr.	Sd	
ITAIPU-CHI-FOZ	**Latitude**	**25° 25' 14.44422" S**	0.0000 m	-	fixed
	Longitude	**54° 35' 17.85546" W**	0.0000 m	-	fixed
	Ellip. Hgt	**183.2479 m**	0.0000 m	-	fixed
P1	**Latitude**	**25° 25' 11.43354" S**	0.0003 m	0.0005 m	
	Longitude	**54° 35' 31.35061" W**	0.0002 m	0.0004 m	
	Ellip. Hgt	**168.9706 m**	0.0018 m	0.0012 m	
P2	**Latitude**	**25° 25' 04.73241" S**	0.0001 m	0.0006 m	
	Longitude	**54° 35' 17.29388" W**	0.0001 m	0.0006 m	
	Ellip. Hgt	**181.8506 m**	0.0009 m	0.0016 m	
P3	**Latitude**	**25° 24' 52.37908" S**	0.0008 m	0.0007 m	
	Longitude	**54° 35' 16.59240" W**	0.0007 m	0.0007 m	
	Ellip. Hgt	**183.5065 m**	0.0063 m	0.0020 m	
P4	**Latitude**	**25° 24' 33.50140" S**	0.0002 m	0.0005 m	
	Longitude	**54° 35' 35.37786" W**	0.0001 m	0.0004 m	
	Ellip. Hgt	**147.1760 m**	0.0014 m	0.0012 m	
P5	**Latitude**	**25° 24' 49.95606" S**	0.0001 m	0.0004 m	
	Longitude	**54° 35' 08.68436" W**	0.0001 m	0.0004 m	
	Ellip. Hgt	**186.5680 m**	0.0008 m	0.0012 m	
P6	**Latitude**	**25° 24' 38.18338" S**	0.0001 m	0.0005 m	
	Longitude	**54° 35' 14.65325" W**	0.0001 m	0.0004 m	
	Ellip. Hgt	**152.8969 m**	0.0008 m	0.0012 m	
P7	**Latitude**	**25° 24' 43.30520" S**	0.0001 m	0.0005 m	
	Longitude	**54° 35' 07.79188" W**	0.0001 m	0.0004 m	
	Ellip. Hgt	**176.3051 m**	0.0008 m	0.0012 m	

TABLE 7: Adjusted coordinates of the network of pillars P1 to P7

6. ANALYSIS OF THE RESULTS OF THE FIRST CAMPAIGN

The adjusted final coordinates of the basic network for the observation pillars P1 to P7, computed after the first campaign, show standard deviations better than GPS receivers nominal values of +/- 6mm.

7. CONCLUSIONS

The adjusted coordinates for the observation pillars, calculated after the first campaign, could be considered as a reference for comparison with the results of further campaigns which should make use the same methodology.
Therefore, it could be possible to propose the components for displacement vectors and their precision between several campaigns.

8. ACKNOWLEDGEMENTS

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