

GNSS AND ACCELEROMETERS DATA FUSION IN LARGE STRUCTURES MONITORING



TECHNICAL REPORT

FINAL DRAFT

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INDEX

1	Definition of the monitoring system demands	1
1.1	Introduction	1
1.2	Specifications for the monitoring system	2
1.3	Software for GNSS processing data	2
1.4	References	3
2	Computational models for high-quality GNSS positions	4
2.1	Introduction	4
2.2	Analysis of multi-sensors fusion	5
2.3	Kalm filtering	5
2.4	Synchronization, decimating, and filtering procedures	5
2.5	Development of a positioning system with GPSToolkit	6
2.6	References	6
3	Laboratory characterization	7
3.1	Introduction	7
3.2	A test of three-storey building model developed at LNEC	7
3.3	Experimental model developed at FEUP	9
3.4	Linear displacement axis at FEUP	10
3.5	References	11
4	Application to bridges and Viaducts	11
4.1	Introduction	11
4.2	Corgo Viaduct	12
4.3	Footbridge at FEUP	13
4.4	Road Bridge of Lanheses	15
4.5	References	16
5	Application to large dams	17
5.1	Introduction	17
5.2	Activities	18

5.3	References	20
6	Final Workshop	20

1 Definition of the monitoring system demands

1.1 Introduction

The monitoring systems have two main objectives: (i) to evaluate the safety conditions and durability of the infrastructures and to develop a better understanding about their day-to-day behaviour; (ii) to detect the occurrence of special events that might jeopardize the safety of the structure. To reach the first objective it is mandatory to create a database as most extensive as possible to support an analysis of the structural behaviour. Regarding the second objective near real-time automatic systems must be created in order to analyse the recorded data and establish limits of alert with alarm warnings when those limits are exceeded.

This R&D project aims to develop a measurement system, based on GNSS (Global Navigation Satellite Systems), suitable to monitor large scale civil engineering structures and infrastructures, particularly bridges and dams. This monitoring system final objective is to measure the displacements of some selected points of the structures. These points should be the most important ones to characterize the general behaviour of the monitored structure. The advantages of using a GNSS system are undeniable: this equipment is robust, operates under all weather conditions, does not require intervisibility between the monitored points and the reference points, uses an external tridimensional reference systems, and provides an extremely accurate time-reference frame.

The GNSS positioning is affected by a numerous set of errors due to natural and artificial phenomena. These errors should be reduced as much as possible, in order to obtain good estimated distances between the observed satellites and the antenna of the receivers. There are well known observation and observation combination techniques (phase differences measurements, relative positioning and Precise Point Positioning - PPP) that allow to strongly reduce, or sometimes even eliminate, most of the errors. Using carefully selected observation and processing techniques it is possible to obtain high-precision GNSS positioning.

The RTK (Real Time Kinematics) is the more recent high-precision positioning GNSS technique. It allows us to obtain high quality coordinates in almost real-time. When used in conjunction with top grade receivers (able to do observations at high frequencies) the RTK seems to be able to monitor high frequencies displacements of structures. Unfortunately the positioning precision is only at the centimetre level. To reduce this uncertainty it will be used short baselines and processing techniques based on the use of various filters and methodologies for multi-sensor observations fusion.

It is precisely in the development of these techniques that the actual research project is focused. After the monitoring system specification, several techniques will be developed and tested in order to be included in a reliable measurement system that will meet the specified requirements.

To define the monitoring system demands the following items have been addressed:

- Requirements of the monitoring system in view of the behaviour of the selected structures;
- Acquisition of know-how on data acquisition systems and in-site monitoring equipment;
- Identification, characterization and analysis of software available for data processing.

1.2 Specifications for the monitoring system

We have done a bibliographic review of academic research publications on civil engineering structures monitoring systems. Special attention was given to monitoring systems using GNSS sensors. The main goal of this review was to evaluate the required specifications for these monitoring systems. This review, along with the results of technical and scientific work previously made by research team members, allowed us to identify the most relevant quantities to measure and these measurements' specifications regarding: a) sensitivities; b) acceptable errors bounds; c) dynamic ranges. We were also able to define the technical specifications of the hardware needed for data acquisition and transmission.

Extensive open field tests were done in order to evaluate the use of GNSS relative positioning technics for measuring the distance between two points. Lab experiments using small scale prototypes allowed us to assess and exploit various issues regarding the use of electronic measuring devices (sensors) for structural monitoring. The need to precisely measure very small time intervals on a time scale precisely defined and common to all the sensors was identified and addressed. These activities are the subject of the Technical Report:

- "Estado da arte de sistemas de monitorização GNSS": [TechRep_05_ABarrias.pdf](https://www.dropbox.com/s/w3kjpmpdp5dob3b/TechRep_05_ABarrias.pdf?dl=0)
(https://www.dropbox.com/s/w3kjpmpdp5dob3b/TechRep_05_ABarrias.pdf?dl=0)

1.3 Software for GNSS processing data

Two lines of action were identified, the first is to use commercial and scientific software already well known to process GNSS observations, registered in the laboratory and on site, and then try to improve the resulting temporal processing series with applying filters

and integration other time series from other sensors, for example accelerometers. The second proposed develop software specifically for the monitoring of civil engineering structures, from free software license (eventually freecode) existing one.

The project team LNEC, benefiting from the previously purchased software such as BERNESE 5.0, scientific software developed by the University of Bern, and the PINNACLE, commercial software developed by Topcon, and, finally, the great experience of the use of GNSS and accelerometers, opted for the first line of action. In the first line of action, it developed a FORTRAN program, using the algorithm presented by Bock et al. 2011 and Smyth and Wu, 2007 for the fusion a time series of displacements observed with GNSS with a time series of accelerations observed by accelerometers that are referred to in Tasks 2 and 3.

The FEUP team has used Leica Spider to store RINEX GNSS data on site. For processing these data the use of FOSS software was tested. The team tested first GPS Toolkit (Applied Research Laboratories of the University of Texas at Austin – ARL:UT). Unfortunately the lack of technical support, both from ARL:UT staff and from informal FOSS support groups, forced the FEUP team to abandon GPS Toolkit. As an alternative the team has chosen RTKLib, another FOSS software. RTKLib proved to be a very valuable and sophisticated piece of software. Informal technical support through FOSS-GPS mail list helped the team to surpass the few difficulties that had arisen.

Detailed information is available in the following technical report:

- “Reading RINEX 2.11 Observations Data Files”:
[TechRep_03_APS_ReadingRINEXObsFile_20150430.pdf](https://www.dropbox.com/s/hts6r3q3gbzvate/TechRep_03_APS_ReadingRINEXObsFile_20150430.pdf)
(https://www.dropbox.com/s/hts6r3q3gbzvate/TechRep_03_APS_ReadingRINEXObsFile_20150430.pdf?dl=0)
- “Clock Corrections and Orbit’s Computations for GPS using RINEX 2.11 GPS Navigation Message Files”:
[TechRep_04_APS_ClockCorrectionsAndOrbits_20150604.pdf](https://www.dropbox.com/s/plt11onfnvns1pg/TechRep_04_APS_ClockCorrectionsAndOrbits_20150604.pdf)
(https://www.dropbox.com/s/plt11onfnvns1pg/TechRep_04_APS_ClockCorrectionsAndOrbits_20150604.pdf?dl=0)

1.4 References

Bock, Y., D. Melgar and B.W. Crowell (2011): “Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers”. Bulletin of the Seismological Society of America, Vol. 101, N^o 6, pp. 2904-2925, Dezembro 2011, doi: 10.1785/0120110007.

Smyth, A. e M. Wu, (2007): "Multi-rate Kalman filtering for the data fusion of displacements and acceleration response measurements in dynamic system monitoring", *Mech. Syst Signal Process.*, 21, 706-723.

Lima, José Nuno, Sérgio Oliveira e Maria João Henriques (2014): "Fusão de deslocamentos medidos com o GNSS e de dados de acelerómetros medidos com elevada frequência de amostragem utilizando um filtro de Kalman", *Actas da 8ª Assembleia Luso-espanhola de Geodesia e Geofísica, Universidade de Évora, Évora, 29 a 31 de Janeiro de 2014.*

António Pestana (2015): "Reading RINEX 2.11 Observations Data Files", Technical Report. ISEP, April 2015.

António Pestana (2015): "Clock Corrections and Orbit's Computations for GPS using RINEX 2.11 GPS Navigation Message Files", Technical Report. ISEP, June 2015.

2 Computational models for high-quality GNSS positions

2.1 Introduction

Due to its characteristics, the same GNSS equipment can be used to monitoring notable point displacement of large civil engineering structures with different frequencies, from very low frequencies to high frequencies.

The monitoring of low frequency displacements with GNSS, it is usually to use the relative positioning in static mode that requires observation sessions lasting more than one hour. With this positioning mode it is easy to measure displacements with millimeter precision.

The monitoring of high frequency displacements with GNSS it is necessary to use the positioning in kinematic mode, and it may be real-time kinematic (RTK) or post-processing kinematic, but the frequency of displacements is limited to the sampling frequency of the GNSS observations (typically 50 Hz). However, the kinematic positioning mode has more uncertainty (a few centimetres) than the static mode, essentially due to errors originated by signal reflections from the satellites (multipath) and tropospheric refraction. The use of the positioning mode to monitor high frequency shifts with millimeter precision is challenging, and therefore, the main problem of this project. One of the possibilities to improve the accuracy of kinematic positioning, is the fusion of sensors that will be given in regard 2.2.

2.2 Analysis of multi-sensors fusion

Analysis of multi-sensors fusion (using accelerometers and multi-rate Kalman filtering) potential as a mean to increase GNSS positions precision:

The fusion displacements with accelerations, the first measured with the GNSS and the second measured with accelerometers, strip GNSS accuracy advantage in low frequencies and the high sensitivity of the accelerometers at high frequencies, resulting in a time series of long displacements and large resolution. From the algorithm presented by Bock et al., 2011 and Smyth and Wu, 2007 we developed a FORTRAN program for integrating on a time series of displacement in one of the components resulting from GNSS measurements, a time series of accelerations in the same component simultaneously measured with an accelerometer. This program has been successfully tested in a laboratory test performed on the campus of the LNEC, which will be described in Task 3.1 and also in communication Lima et al. 2014: [EncInt_01.pdf \(https://www.dropbox.com/s/j69zac2sf53aqueu/EncInt_01.pdf?dl=0\)](https://www.dropbox.com/s/j69zac2sf53aqueu/EncInt_01.pdf?dl=0).

2.3 Kalm filtering

In the context of this task the team studied various methods for signals processing with special focus on Kalman filtering. The Technical Report "Estimadores Sequenciais de Mínimos Quadrados para Equações de Observações" is a result of this study. These methods were used for fusing inertial sensors (accelerometers and gyroscopes) and GNSS positioning systems.

Detailed information is available in the following technical report:

- "Estimadores Recursivos de Mínimos Quadrados para Equações de Observações": [TechRep_01_APS_Kalman_20150923.pdf \(https://www.dropbox.com/s/p14vuswyc4ytqfs/TechRep_01_APS_Kalman_20150923.pdf?dl=0\)](https://www.dropbox.com/s/p14vuswyc4ytqfs/TechRep_01_APS_Kalman_20150923.pdf)

2.4 Synchronization, decimating, and filtering procedures

Synchronization, decimating, and filtering procedures were studied and applied to adjust and to improve the measured signal. Double integration techniques using the accelerometers data were implemented to transform the measures accelerometers into dynamic displacements. The multi-sensor fusion allowed to combine the best of each sensor and of each monitoring system. Using data from laboratory tests and multi-sensor fusion techniques, the final results demonstrated measured errors of 1mm or less into a confidence interval of 95%.

Detailed information is available in the following technical report:

- "Experimental model with GNSS and multiple sensors – design, instrumentation and data analysis": [TechRep_12_CRodrigues_ExpModel.pdf](https://www.dropbox.com/s/ey4awgbajyrz80v/TechRep_12_CRodrigues_ExpModel.pdf) (https://www.dropbox.com/s/ey4awgbajyrz80v/TechRep_12_CRodrigues_ExpModel.pdf?dl=0)

2.5 Development of a positioning system with GPSToolkit

GPSTk consists of an open source package of libraries that aims to support the creation of GNSS applications by common users. Based in the principle of object-oriented programming, GPSTk supplies an extended collection of functions to process typical GNSS files and solve navigation and positioning problems.

GPSTk is sponsored by the Space and Geophysics Laboratory, which is part of the Applied Research Laboratories from Texas University, Austin (ARL:UT). This software is the result of several decades of research at ART:UT, whose source code was release to the public in the beginning of the this century.

The development of GPSTk has been made gradually, and it is currently in its version 2.5.

In this task a relative positioning program "from scratch" using the GPSToolkit libraries was developed. Despite GPSTk being a great development resource for GNSS applications, it requires a high level of programming skill to face the challenges of solving some of the more complex problems about GNSS data processing. Also, it was found that the GPSTk web based user support, during the development of this work, was apparently undergoing some profound changes since the technical discussion forums were not very active or supportive. Nevertheless, GPSTk is surely a very useful and robust GNSS development resource that still maintains a high reputation among the specialized open source GNSS application developers. Therefore it should always be considered in the future applications.

Detailed information is available in the following technical report:

- "Bridge Monitoring System Approaches using GNSS and Accelerometers Data Integration": [TechRep_13_SSantos_GNSS_Acel.pdf](https://www.dropbox.com/s/w617zcvexwh2aw7/TechRep_13_SSantos_GNSS_Acel.pdf) (https://www.dropbox.com/s/w617zcvexwh2aw7/TechRep_13_SSantos_GNSS_Acel.pdf?dl=0)

2.6 References

Bock, Y., D. Melgar and B.W. Crowell (2011): "Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers". Bulletin of the Seismological

Society of America, Vol. 101, Nº 6, pp. 2904-2925, Dezembro 2011, doi: 10.1785/0120110007.

Smyth, A. e M. Wu, (2007): "Multi-rate Kalman filtering for the data fusion of displacements and acceleration response measurements in dynamic system monitoring", *Mech. Syst Signal Process.*, 21, 706-723.

Lima, José Nuno, Sérgio Oliveira e Maria João Henriques, 2014: "Fusão de deslocamentos medidos com o GNSS e de dados de acelerómetros medidos com elevada frequência de amostragem utilizando um filtro de Kalman", *Actas da 8ª Assembleia Luso-espanhola de Geodesia e Geofísica, Universidade de Évora, Évora, 29 a 31 de Janeiro de 2014.*

António Pestana (2014): "Estimadores Recursivos de Mínimos Quadrados para Equações de Observações". Technical Report. ISEP, July 2014.

Carlos Rodrigues (2015): "Experimental Model with GNSS and Multiple Sensors". Technical Report. FEUP, September 2015.

Sérgio Santos (2015): "Bridge Monitoring System Approaches using GNSS and Accelerometers Data Integration". Technical Report. FEUP, November 2015.

3 Laboratory characterization

3.1 Introduction

The numerical models developed in the previous task were integrated in order to make a preliminary demonstrator capable of providing a first experimental evaluation of the measurement system capabilities.

Towards this goal field tests were made outside on a location with a clear view of the sky using both GNSS receivers (with and without multi-sensors techniques) and conventional displacement transducers.

In the aim of this task three physical models were developed and used: a linear displacement axis at FEUP, a three-storey building model developed at LNEC and a metallic tower developed at FEUP.

3.2 A test of three-storey building model developed at LNEC

On the campus of LNEC, it has been installed on a level steel beam, a high precision linear motion system, developed by Rexroth, and, on the latter, a physical model of a building of three floors, with 1 meter high (see Figure 3.1). This model was instrumented with two GNSS receivers and their antennas (although one of the equipment has become as reference station, about 300 meters of this structure), one triaxial Nanometrics, model

Titan SMA and three uniaxial accelerometers of Kinematics model ES-Episor U2. The three-storey building slides on the linear motion system at a constant speed of 1 cm per minute.

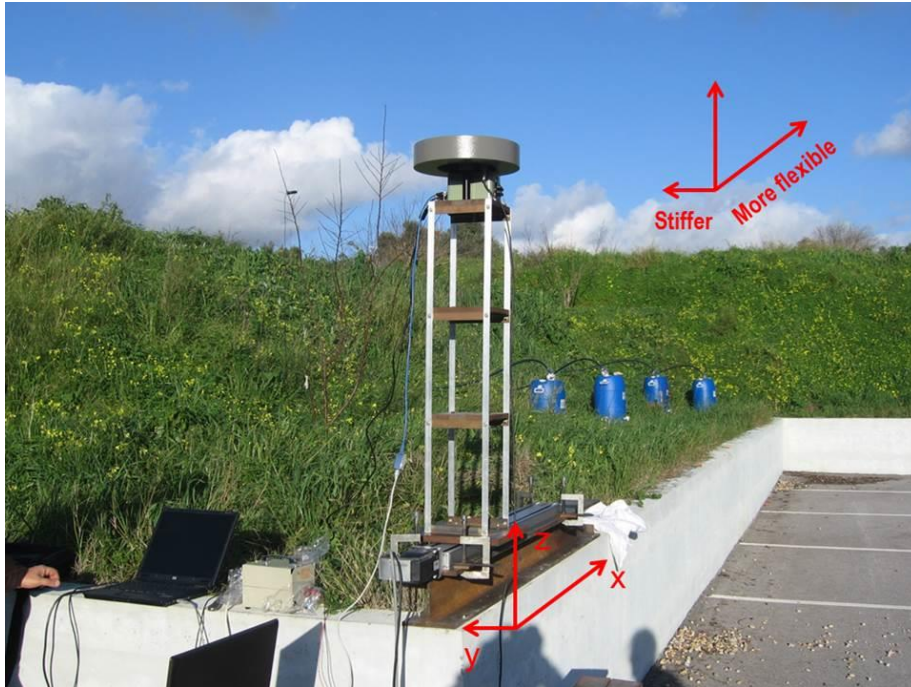


Figure 3.1 — Three-storey building model developed at LNEC.

GNSS observations were recorded with a sampling frequency of 20 Hz. These observations were processed in kinematic mode, with the Pinnacle Topcon software and open source software RTKLIB using a reference station located about 300 meters. The accelerometer of Nanometrics recorded with a sampling frequency of 50 Hz with a 24-bit resolution to a range of 1 g. The x-axis of this accelerometer was oriented in the direction of the longitudinal axis of the linear motion system (coincident with the more flexible building side), the Y axis was oriented in the transverse direction of the linear motion system, and z-axis was oriented in the direction of the vertical of the place. The accelerometers of Kinematics also oriented in the longitudinal direction of the linear motion system, and they recorded at a sampling frequency of 250 Hz with a resolution of 16 bits for a range of $\frac{1}{4}$ g.

During the test it was introduced in building a forced vibration, through gentle strokes in the building pillars in order to excite the three main modes of vibration. The accelerometers identified with high precision the first three modes of vibration whose frequency were 1.13 Hz, 4.45 Hz and 7.27 Hz, respectively. The GNSS observation only identified the first two vibration modes, whose frequencies were estimated at 1.13 Hz and 4.58 Hz, respectively. The 3rd mode of vibration, due its submillimeter amplitude, was not identified by GNSS.

Integrating twice the time series of accelerations, correcting each integrating the resulting drift, it was possible to compare it to the time series of displacements obtained from GNSS observations after filtering linear motion with constant speed of 1 cm per minute introduced. The agreement between the two series is very good, the standard deviation is only 2.4 mm and a correlation is 0.994.

The speed of the linear motion system was applied ($1\text{cm /minute} = 0.000167\text{ m /s}$) to the temporal series of accelerations integrated twice to yield a time series very close to the actual movement, designated by "real movement". It ran up the program developed for fusing the two time series observed with GNSS and an accelerometer, obtaining a time series of displacements. The latter series was compared with the time series of the "real movement" and obtained a standard deviation of 1.04 mm and a correlation of 0.999.

The conclusion of the test is that the fusion of the two by independent technical observed time series improves GNSS precision in kinematic mode, managing to filter an important part of the noise that is characteristic of GNSS observation.

Detailed information is available in the following paper:

- Lima, José Nuno, Sérgio Oliveira e Maria João Henriques, 2014: "Fusão de deslocamentos medidos com o GNSS e de dados de acelerómetros medidos com elevada frequência de amostragem utilizando um filtro de Kalman", Actas da 8ª Assembleia Luso-espanhola de Geodesia e Geofísica, Universidade de Évora, Évora, 29 a 31 de Janeiro de 2014: [EncInt_01.pdf \(https://www.dropbox.com/s/j69zac2sf53aqueu/EncInt_01.pdf?dl=0\)](https://www.dropbox.com/s/j69zac2sf53aqueu/EncInt_01.pdf?dl=0)

3.3 Experimental model developed at FEUP

An experimental model (see Figure 3.2) was designed with the main objective to carry out controlled laboratory tests with different sensors and diverse treatment technics, namely the multi-sensor fusion techniques. This model aims to simulate the behavior of real structures exhibiting proper natural frequencies, stiffness and strength for the proposed studies.

The laboratory model integrated diverse instrumentation, making a total of 16 sensors. In this context, a GNSS antenna was installed on top of the structure. Strain gauges, inclinometers, accelerometers, and LVDTs carefully positioned to measure other relevant structural parameters.



Figure 3.2 — Experimental model developed at FEUP.

Several static and dynamic loading tests were performed allowing to gather extensive data. The collected results were, at same time, exploited into various signal processing procedures and multi-sensor fusion techniques. The developed model can also be used into future tests and exhibitions.

Detailed information is available in the following technical report:

- *"Experimental model with GNSS and multiple sensors – design, instrumentation and data analysis"*:
[TechRep_12_CRodrigues_ExpModel.pdf](#)
(https://www.dropbox.com/s/ey4awgbajyrz80v/TechRep_12_CRodrigues_ExpModel.pdf?dl=0)

3.4 Linear displacement axis at FEUP

A linear displacement encoder that directly monitors the position of the axis slide was developed to calibrate and validate GNSS antenna (see Figure 3.3).

Detailed information is available in the following technical report:

- *"Ensaios conduzidos no demonstrador da FESTO"*:
[TechRep_09_ABarrias.pdf](#)
(https://www.dropbox.com/s/vdknmpp7g0pqcdl/TechRep_09_ABarrias.pdf?dl=0)



Figure 3.3 — Linear displacement axis at FEUP.

3.5 References

Bock, Y., D. Melgar and B.W. Crowell (2011): "Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers". *Bulletin of the Seismological Society of America*, Vol. 101, N° 6, pp. 2904-2925, Dezembro 2011, doi: 10.1785/0120110007.

Smyth, A. e M. Wu, (2007): "Multi-rate Kalman filtering for the data fusion of displacements and acceleration response measurements in dynamic system monitoring", *Mech. Syst Signal Process.*, 21, 706-723.

Lima, José Nuno, Sérgio Oliveira e Maria João Henriques, 2014: "Fusão de deslocamentos medidos com o GNSS e de dados de acelerómetros medidos com elevada frequência de amostragem utilizando um filtro de Kalman", *Actas da 8ª Assembleia Luso-espanhola de Geodesia e Geofísica*, Universidade de Évora, Évora, 29 a 31 de Janeiro de 2014.

Sérgio Magalhães, "Conceção e análise de um demonstrador para a monitorização estrutural" (2015). MSc. Thesis. ISEP, November, 2015.

Carlos Rodrigues (2015): "Experimental Model with GNSS and Multiple Sensors". Technical Report. FEUP, September 2015.

António Barrias (2015): "Ensaios conduzidos no demonstrador da FESTO". Technical Report. FEUP. FEUP, June 2015.

4 Application to bridges and Viaducts

4.1 Introduction

In order to meet the objectives of this task the research team undertook an extensive analysis of the structural behavior of three bridges: the Corgo Viaduct, the Footbridge (at the Campus of the FEUP) and the Bridge of Lanheses (over Lima River).

In our initial proposal it was planned to install a GNSS monitoring system in the cable stayed viaduct of Corgo in order to monitor the effect of the temperature changes on the top of the masts. However, due to the late start of this R&D project, only the final load test of the viaduct was possible to monitor. Further observations were not possible regarding the lack of conditions to operate on site. Nevertheless, the GNSS data collected during the load test and the data obtained from a permanent structural health monitoring system previously installed on site, made it possible to develop and validate a very complete numerical model. This model is able to fully characterize the structure behavior. The expertise acquired within the deployment, assembly and exploitation of the GNSS equipment was used to carry out another two real-scale demonstrators. In both of these two applications the following activities were developed:

- Development of the numerical model of the bridge
- In-site implementation of the proposed GNSS-based measurement system
- Simultaneously collect and analyze relevant data from the GNSS-based system and the conventional monitoring system
- Extensive analysis of the bridge behavior

4.2 Corgo Viaduct

The Corgo Viaduct in the A4 highway, cross the Corgo River near Vila Real, in northern Portugal. The total length of the viaduct is 2800m, divided into three substructures: the main viaduct, a stay cable bridge with a middle span of 300m, and the north and south approach viaducts (see Figure 4.1).



Figure 4.1 — Corgo Viaduct: general view.

This structure was fully instrumented with electrical and optical sensors and a structural health monitoring system was implemented. At the end of the construction a loading test was carried out, using a total of 16 heavy trucks at different load positions, and data from

the sensors was collected. The deflection along the bridge deck was measured with a levelling measuring system.

Numerical models of structural analysis were developed and calibrated using these experimental results, allowing the study of the behaviour of this important structure and establishing a reference for further studies or inspections campaigns.

A preliminary test of the use of the GNSS was also carried out on this bridge. At the mid-span of the central span three antennas/receivers GNSS were installed: one in the central reservation and the other two in the both sides of the deck. Unfortunately some measurements problems (mostly due to GNSS signals reflections on the moving columns of the very large trucks used for the loading tests) did not allowed to achieve the expected quality of the measurements made.

Full information about this work can be found in the following documents:

- Gonçalo Carvalho, "Modelação do viaduto do corgo durante o ensaio de carga estático" (2015). MSc. Thesis. ISEL, January, 2015:
[Tese3_MEC_GoncaloCarvalho_Corgo](https://www.dropbox.com/s/nrgi2bny94h83dv/Tese3_MEC_GoncaloCarvalho_Corgo.pdf?dl=0)
(https://www.dropbox.com/s/nrgi2bny94h83dv/Tese3_MEC_GoncaloCarvalho_Corgo.pdf?dl=0)
- Diogo Rebelo, "Observação e modelação do comportamento dinâmico do viaduto do corgo. Utilização integrada de modelos de identificação modal e modelos de elementos finitos de barra" (2015). MSc. Thesis. ISEL, March, 2015:
[Tese1_MEC_DigoRebelo_Corgo. Pdf](https://www.dropbox.com/s/fm4yloispuz5wno/Tese1_MEC_DigoRebelo_Corgo.pdf?dl=0)
(https://www.dropbox.com/s/fm4yloispuz5wno/Tese1_MEC_DigoRebelo_Corgo.pdf?dl=0)
- Sérgio Oliveira et. al, "Observação e modelação do comportamento dinâmico de um viaduto atirantado. Utilização integrada de modelos de identificação modal e modelos de EF" (2014). 5as Jornadas Portuguesas de Engenharia de Estruturas. LNEC, 2014: [EncNac_06.pdf](https://www.dropbox.com/s/c2nv8nvkpk1d5oi/EncNac_06.pdf?dl=0)
(https://www.dropbox.com/s/c2nv8nvkpk1d5oi/EncNac_06.pdf?dl=0)

4.3 Footbridge at FEUP

The footbridge located at the campus of the FEUP crosses a road and enables the access to the canteen (see Figure 4.2). It is formed by two spans of 28m and 30m. The deck is composed by pre-fabricated slabs with 1m length each and comprises four prestressing cables embedded in reinforced concrete. The profile of the structure is made of two

catenary-type shapes joined by a circular curve over the inter-mediate support. The design rectangular cross section is $3.80 \times 0.15 \text{m}^2$.



Figure 4.2 — Footbridge at campus da FEUP.

In order to explore GNSS technology as an alternative response to the structural monitoring problem, this bridge was fully equipped with a monitoring system using conventional transducers (e.g. temperature sensors, displacement transducers, accelerometers, inclinometers and crackmeters) and a load test was carried out. During this load test the vertical displacements at middle span was measured with GNSS and displacement transducers (LVDT).

The experimental GNSS outcomes were then compared with the numerical modelling results.

Despite the overall success of the data acquisition on the majority of the sensors it was concluded that the reception conditions of the GNSS signals at the test site were far from being good. The test site, although in an urban area, does not have a very high building density. However there are tall buildings and a sports hall in the vicinity. The library building is a massive structure nearby the footbridge and blocks a large region of the sky. The sports hall has a metallic roof top and large pieces of the metal ion the side walls. These two buildings seriously degrade the reception of the GNSS signals, either by blocking them (the library) or by reflecting them promoting multipath (the sports hall).

In this way, it is possible to conclude from this work that although the GNSS system is a promising tool on the monitoring of civil engineering structures, the process of choosing which structures are able to take advantage of this system based on its location is of great importance since the presence of major buildings and other obstacles in the nearby region of the monitored structure can invalidate the acquisition of good measurements by the GNSS system.

Full information about this work can be found in the following documents:

- António Barrias et al, "Multi-sensor monitoring applied to a stress-ribbon footbridge" (2015). IABMAS, 2016: [EncInt_02.pdf](https://www.dropbox.com/s/enzqqj7lzmst3v/EncInt_02.pdf?dl=0)
(https://www.dropbox.com/s/enzqqj7lzmst3v/EncInt_02.pdf?dl=0)
- António Barrias, "GNSS and accelerometers data fusion in large structures monitoring: Application to a real work site scenario". Technical Report. FEUP, 2015: [TechRep_10_ABarrias.pdf](https://www.dropbox.com/s/umljttjql5nrdfe/TechRep_10_ABarrias.pdf?dl=0)
(https://www.dropbox.com/s/umljttjql5nrdfe/TechRep_10_ABarrias.pdf?dl=0)

4.4 Road Bridge of Lanheses

Lanheses bridge crosses Lima River near Viana do Castelo (see Figure 4.3). It consists in a multi span single girder deck built in reinforced and prestressed concrete with a total length of 1218m, simple supported in 40 columns and two abutments. South side abutment is a fixed end support, while all the rest have installed slide bearing supports.



Figure 4.3 — Lanheses bridge over Lima River.

Lanheses bridge is permanently monitored by a system that includes displacements transducers (LVDTs) for measuring the relative movements at the top of the columns and at the north abutment.

As a complement to the permanent monitoring system three pairs of GNSS antenna+receiver were put in place: one pair on the deck near to the north abutment and the other two on sites considered fixed (not moving). The GNSS equipment was kept in continuous operation and the data collected has allowed the research team to measure the movements of expansion joint for more than 48 hours.

The movements measured using GNSS technics were found in accordance to the same movements measured using LVDTs. So GNSS has proven to be able to measure the bridge horizontal displacements.

Full information about this work can be found in the following documents:

- Sérgio Santos, "Bridge monitoring system approaches using GNSS and accelerometers data integration" (2015). Technical Report. FEUP, 2015: [TechRep_13_SSantos_GNSS_Acel.pdf](https://www.dropbox.com/s/w617zcvexwh2aw7/TechRep_13_SSantos_GNSS_Acel.pdf) (https://www.dropbox.com/s/w617zcvexwh2aw7/TechRep_13_SSantos_GNSS_Acel.pdf?dl=0)
- Samuel Neves, "Monitorização e análise do comportamento da ponte de Lanheses" (2015). Technical Report. FEUP, 2015: [TechRep_11_Samuel_Lanheses.pdf](https://www.dropbox.com/s/s67ttrm18tj58o2/TechRep_11_Samuel_Lanheses.pdf) (https://www.dropbox.com/s/s67ttrm18tj58o2/TechRep_11_Samuel_Lanheses.pdf?dl=0)

4.5 References

Gonçalo Carvalho, "Modelação do viaduto do corgo durante o ensaio de carga estático" (2015). MSc. Thesis. ISEL, January, 2015.

Diogo Rebelo, "Observação e modelação do comportamento dinâmico do viaduto do corgo. Utilização integrada de modelos de identificação modal e modelos de elementos finitos de barra" (2015). MSc. Thesis. ISEL, March, 2015.

Sérgio Oliveira et. al, "Observação e modelação do comportamento dinâmico de um viaduto atirantado. Utilização integrada de modelos de identificação modal e modelos de EF" (2014). 5as Jornadas Portuguesas de Engenharia de Estruturas. LNEC, 2014.

António Barrias et al, "Multi-sensor monitoring applied to a stress-ribbon footbridge" (2015). IABMAS, 2016.

António Barrias, "GNSS and accelerometers data fusion in large structures monitoring: Application to a real work site scenario". Technical Report. FEUP, 2015.

Sérgio Santos, "Bridge monitoring system approaches using GNSS and accelerometers data integration" (2015). Technical Report. FEUP, 2015.

Samuel Neves, "Monitorização e análise do comportamento da ponte de Lanheses" (2015). Technical Report. FEUP, 2015.

5 Application to large dams

5.1 Introduction

In this task we intend to improve the monitoring system of Cabril dam (Zêzere river), a sixty years old dam, that is the highest Portuguese arch dam (132 m). In this dam significant horizontal cracking occurred near the crest since the first filling of the reservoir, and a concrete swelling process was recently detected; the water level presents important variations along the year. In what concerns the monitoring system, although it is quite complete, it should be noticed that only the dynamic monitoring component is automated, since 2008. This component includes the accelerations measurement (1000 Hz) in the upper zone of the dam and insertion, with 16 uniaxial accelerometers and three triaxial (equipment installed by the Project Team, thanks to previous funding from FCT, REEQ/815/ECM/2005).



Figure 5.1 — Cabril dam: general view.

The measurement of the static response is not automated. Namely, the static displacements at the central cantilever are only measured by geodetic methods twice a thousandths of a year (due to the great curvature of the dam a plumbline was not installed at the central cantilever).

So, the displacement history at the top of the central cantilever is proposed to be measured by GNSS. It is also proposed the development of software for integrating GNSS and other monitoring data.

Since the dynamic response of large dams to ambient and operational excitation is characterized by extremely low amplitude vibrations (accelerations amplitude of about $g/1000$) the use of GNSS in dams should be directed to acquire accurate static displacement histories, which is essential to characterize the long-term dam behavior (the Project team already performed GNSS tests on Cabril dam). The goal is to get accurate hourly (or even daily) displacement histories – with a precision of about 1 mm – to be obtained automatically by processing the original GNSS series, which can be measured at high frequency rates (up to 100 Hz).

As in bridges, also in the study of dams the fusion of GNSS and accelerometers data is viable in order to obtain displacement series with high frequency rates. However, due to the low amplitude of dynamic dams response under ambient/operational excitation (for seismic loads higher amplitude vibrations may occur) the main interest of these series is mostly on its spectral contents which can be directly analysed from the acceleration series – the spectral analysis of displacements and/or accelerations allows one to obtain the modal parameters of the structure (modal identification) which is of great interest for the dam safety control.

5.2 Activities

This task includes:

5.2.1 Installation of two GNSS antennas in Cabril dam: one at the top of the central cantilever and the other as a reference antenna, located at a fixed point near the dam; the GNSS data will be transmitted to a local computer via wireless.

The project provides funding for acquisition of two GNSS Leica receivers (GMX902 GNSS model), two Leica GNSS antennas (model AS10), the software for management of GNSS observed data and its processing Leica (model Leica GNSS Spider). Unfortunately, financial constraints in LNEC delayed the acquisition of this equipment to the end of the project. However, pending the owner of the Cabril dam, EDP, prepare the logistics for the installation of GNSS equipment: the establishment of a post of steel coated for thermal protection, solar radiation and wind in the centre of the dam crest. On top of this post will be installed one GNSS antenna.

Near the dam, downstream and on the left bank, the EDP will use one post in concrete, with solid foundations, from an ancient medium voltage electrical network already

disabled. This post will be cut to a height of 7 meters from the ground, and the remaining top will put the second GNSS antenna.

The project also provides funding for acquisition one PC server, where the Leica GNSS Spider was installed, and the software for management the accelerometer network installed on Cabril dam.

The GNSS equipment purchased has been tested on the campus of the LNEC. The two antennas Leica GNSS AS10 were installed on the roof of the Department of concrete dams (Figure 1), distant one another of about 25 m, each connected to a Leica GMX902 GNSS receiver. Using the Leica Spider software, the observations of these devices were processed in a kinematic manner and in real time with a sampling frequency of 1 Hz, and processed in a static mode at the end of each time records with the same sampling frequency. In Lima, 2015 only were analysed the time series generated by the hourly solutions of this small baseline tests.

5.2.2 The installation of a radar unit for measuring automatically the reservoir water level and installation of a thermometer for measuring the ambient temperature wasn't necessary, because the dam owner allowed us the access to their data base where this information is available;

Still within the scope of this task we continued the research at LNEC in order to create an innovative software for automatic online processing of data collected continuously by GNSS and Accelerometers. This software:

- allow both the tracking of the time evolution of displacements from GNSS and the tracking of the main modal parameters evolution;
- Automatically analyse the correlation with the water level and annual temperature variations;
- be able to generate and send automatically (via internet) the most relevant structural information concerning the dams' structural health condition.

Full information about this work can be found in the following documents:

- "Seismic Safety Evaluation of Luzzone Dam. Use of a 3DFEM State Formulation in Pressures and Displacements": [EncInt_03.pdf](https://www.dropbox.com/s/977cblly5vx031/EncInt_03.pdf?dl=0)
(https://www.dropbox.com/s/977cblly5vx031/EncInt_03.pdf?dl=0)
- "Monitoring the dynamic behavior of Cabril Dam": [EncInt_04.pdf](https://www.dropbox.com/s/miascsx0x7ugzxa/EncInt_04.pdf?dl=0)
(https://www.dropbox.com/s/miascsx0x7ugzxa/EncInt_04.pdf?dl=0)

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Oliveira S., Alegre A., Silvestre A., Espada M., Câmara R. (2015) "Seismic Safety Evaluation of Luzzone Dam. Use of a 3DFEM State Formulation in Pressures and Displacements". 13th Int. Benchmark on the Numerical Analysis of Dams, EPFL Sep.9-11, Lausanne, Switzerland.

Oliveira S., Silvestre A., Espada M., Salvado P., Câmara R. (2015) "Monitoring the dynamic behavior of Cabril Dam". 2nd Int. Dam World Conference. LNEC, April 21-24. Lisbon, Portugal.

Oliveira, S.; Salvado, P.; Silvestre, A.; Espada, M.; Câmara, R. (2014) - Monitorização e modelação do comportamento dinâmico de barragens de betão. Estudo da interação dinâmica água-estrutura. JPÉE2014, LNEC, Lisboa.

6 Final Workshop

A final workshop was organized on 25th September, at FEUP where we had the attendance of all research team drawing also the technical and scientific community for discussion and dissemination of the R&D project results. During the meeting it was possible to draw guidelines for the use of the GNSS-based system to monitor large scale structures and to evaluate of the GNSS-based system as a main component of a maintenance and surveillance monitoring system for advanced civil engineering structures (smart structures).

Full slide presentation and final programme available in: [Seminario_FEUP_Set2015.pdf](https://www.dropbox.com/s/duygjrh5b3tr6q9/Seminario_FEUP_Set2015.pdf?dl=0) (https://www.dropbox.com/s/duygjrh5b3tr6q9/Seminario_FEUP_Set2015.pdf?dl=0)