Monitoring Oscillations of Slender Structures with GPS and Accelerometers

Noemi Emanuela CAZZANIGA, Livio PINTO, Gianfranco FORLANI and Paolo ABRUZZI, Italy

Key words: GPS, deformations, monitoring, hypothesis testing, high rise buildings

SUMMARY

Slender structures (such as the chimney of thermo-electrical power plants) oscillate due to dynamic loading by wind, temperature differentials and earthquakes. The Italian Centre for Experimental Electric Science (CESI) started a project, in cooperation with the Polytechnic of Milan, to monitor the structural integrity of an industrial chimney and to identify at any time signs of stiffness changes, perhaps due to breaches, enervations or material fatigue. To this aim, an integrated system combining GPS and accelerometers measurements, from very low frequencies up to 100 Hz, is being set up. The goals are first to identify the principal modes of oscillation to characterize the response of the chimney and later to monitor structure behaviour to detect critical situations in nearly real time. The prediction capability of the system will stand principally on tracking the evolution of the eigenfrequencies and of the maximum amplitude of oscillation of the chimney connected to the intensity of the loads.

The system will be installed on a chimney of the power plant of Piacenza (Italy), 120 m high. It will acquire data at a frequency of 10 Hz from 3 GPS (one rover on the chimney, connected to the acquisition and processing unit by a WI-FI system, and two masters) and at 100 Hz from 2 tri-axial accelerometers on the chimney. Simultaneous acquisition of anemometer data is also foreseen.

Data analysis rests on an initial DFT computation, followed by a l.s. interpolation of the rover movement which allows to estimate the accuracy of the frequency determinations. This in turn enables a time series analysis procedure based on statistical test, to highlight changes or trends in the principal mode of vibration coming from breaches or material fatigue.

After the system description, the data analysis procedure will be explained in detail and results on a series of tests prior to system installation will be described, showing the high sensitivity of the system to frequency changes.

Monitoring Oscillations of Slender Structures with GPS and Accelerometers

Noemi Emanuela CAZZANIGA, Livio PINTO, Gianfranco FORLANI and Paolo ABRUZZI, Italy

1. INTRODUCTION

Industrial plants need to maintain the integrity of their main structures as long as possible, often because of lack of proper areas for new constructions and high building costs. Damages may not only lead to production cuts and delays, but also involve risks for the safety of nearby installations and personnel. Depending on risk analysis and on the actual costs to be faced in case of failure, it may be sensible to install a monitoring system to guarantee, with proper maintenance and early notice of failures, a long building life.
In recent years, the interest grew towards using GPS, mostly in combination with accelerometers, to monitor high rise buildings oscillations and movements. For instance, the Hearthquake Hazard Team, U.S. Geological Survey (California), implemented a real-time seismic monitoring system for high rise buildings (Çelebi et al., 2003).
The Italian Centre for Experimental Electric Science (CESI), in cooperation with the Polytechnic of Milan (Italy), started a project to monitor the structural integrity of chimneys of thermo-electrical power plants and to identify at any time signs of breaches, enervations or yielding. Slender structures like this are susceptible to oscillations, due to dynamic loading from wind, thermal effects and earthquakes. While earthquakes will occasionally hit with the most severe loads, wind may produce material fatigue. Wind-induced response consists of a static component, i.e. a mean value, and a dynamic component. Generally, accelerometers are used to measure the structure vibrations and, by double integration, the displacements. This, however, only capture the dynamic components of the response. In tall buildings, the quasi-static component of wind loads may be significant, although not a cause of fatigue in itself: failure to account for it may cause incorrect evaluation of the load on the structure. In recent years the use of GPS for the measurement of displacements has been put forward, to also capture this static component in full. By supplementing accelerometers with GPS receivers measuring at high frequencies, both the static and dynamic components of along-wind and across-wind displacements can be obtained.
Considering the static component and the predominance of the first mode of oscillation for wind-induced responses, the current GPS technology looks well suited for such application; measurement rates up to 20 Hz are now common in GPS receivers and newest models are capable of even higher rates.
In most cases such kind of structures can be modelled as clamped beam with a natural frequency around 1 Hz; therefore the GPS sampling rate is fully adequate and a single receiver on the top will have good satellite visibility as well as maximum sensitivity to loading.
Should the load on the structure induce higher modes, a single measurement point will not suffice to identify the change in the behaviour, because of the more complex structure motion: more would be needed, distributed along the chimney span. Apart from cost considerations, installation of another pair of GPS receivers was ruled out since it proved

unfeasible: the shape and size of the chimney is such that satellite visibility is unfavourable over large time windows.
So, it was decided to implement a GPS/accelerometers integrated system, capable to measure vibrations on a range of frequencies up to 100 Hz. In the first period after its installation, the system is supposed to gather the data necessary to identify the principal modes of oscillation, in order to allow the characterization of the chimney response and determine the critical values for frequencies and displacements which may lead to failure. Then, the goal is to monitor structure behaviour, to detect critical situations (such as large displacements or sudden changes in the natural frequency) in near real time as well as to spot early signs of drift in the natural frequency, highlighting a loss of stiffness due to material fatigue.
The prediction capability of the system will therefore stand on tracking the evolution of the eigenfrequencies and of the maximum amplitude of oscillation of the chimney connected to the intensity of the loads.
The first goal (structural identification) is achieved measuring displacements and frequency components under known loads, to calibrate the parameters of the mathematical model. GPS positions are obtained in post-processing kinematic (PPK) and filtered by means of a Kalman smoother. A time series analysis, by means of the Discrete Fourier Transform (DFT), allows to identify frequency components of the oscillations. The collected data will be input to the structural identification software "Histride" developed at CESI.
As far as the second goal is concerned, we need either accurate frequency determination as well as confidence intervals, allowing to mark as significant or not a frequency difference with respect to the reference value. To this aim, we combined a Fourier analysis, which identifies the frequencies, with an explicit l.s. modeling of the displacement of the chimney top, which provides estimates of the frequency contents of the displacements.
(Çelebi et al., 2002) studied GPS performance for dynamic monitoring of structures without data filtering because of the high noise-to-signal ratio and the very small displacements. Very often GPS is used in combination with accelerometers, applying low-pass filtering to remove noise (Kijewski et al., 2003). In some cases, the two measurement systems are not integrated, but just used to compare their results (Yoshida et al., 2003; Cefalo et al., 1998). As a tool for data analysis, the Fourier Transform is extensively used. (Ogaja et al.) after pre-processing data by means of a Finite Impulse response Median Hybrid Filter, estimate instantaneous frequencies using the time-frequency wavelet transform and then detect changes by using a cumulative sum scheme. Although we also use DFT, our data analysis is performed on the results of l.s. estimation, taking advantage of the comprehensive parametric tests body provided by the l.s. to test the hypothesis of a frequency change in a probabilistic framework.
In the following, section 2 describes the system components; section 3 describes data processing and data analysis of GPS data for structure monitoring; section 4 reports the results of preliminary tests.

2. SYSTEM COMPONENTS

The system integrates high-precision GPS with a set of traditional sensors in a comprehensive and robust sensor array. Besides a GPS receiver, the chimney will be equipped with two tri-axial accelerometers, mounted on the top and in the middle of the chimney span (see figure 1). Ideally, there should be some overlap in the range of frequencies gathered by both types of instruments, so a comparison or a combination of the data in a single filtering procedure is possible. At present, though, the accelerometers are not yet available so in the following we will concentrate on the GPS side only.

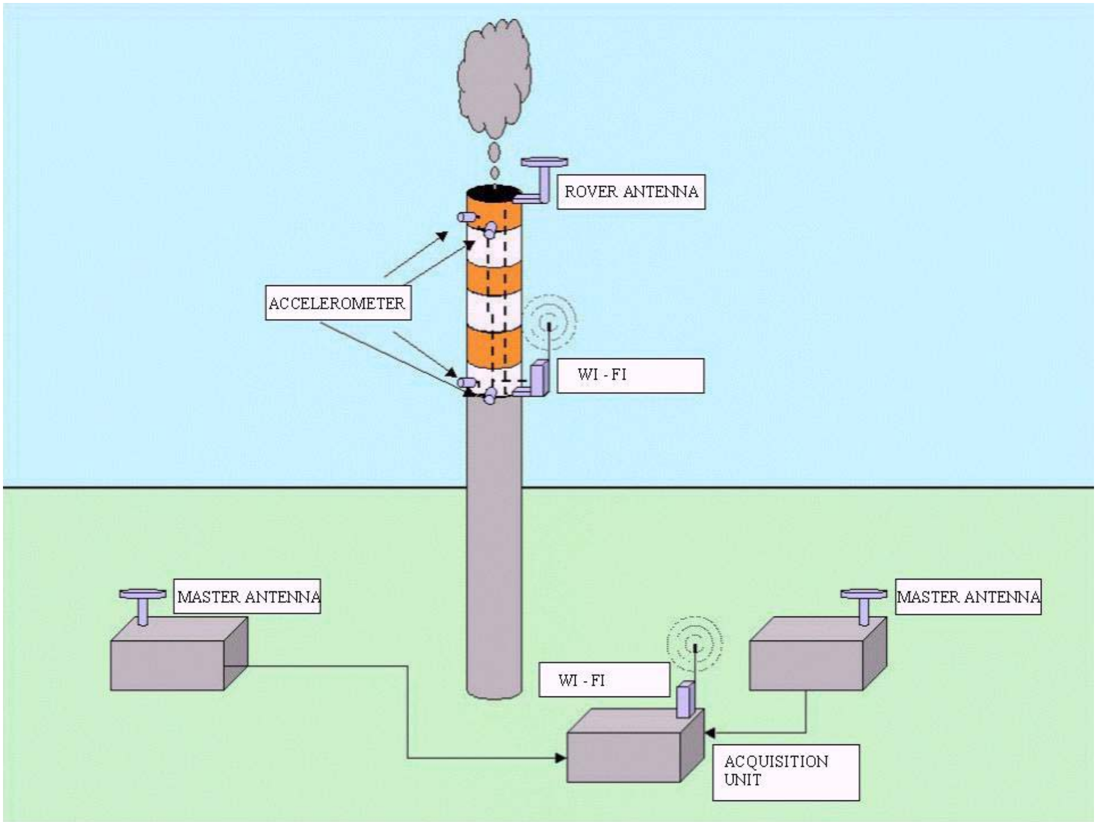

Figure 1 - Sketch of the monitoring system.

2.1 GPS network configuration

Given the height and stiffness of the structure, the expected displacements at the top are in the order of 10 cm, with natural frequency less than 1Hz. Because of its geometric and mechanical characteristics, it's possible to model the chimney dynamic like that of a clamped beam, so torque responses are negligible and are not considered. Therefore, the motion of the chimney top is contained in a horizontal plane.
Expected displacements are in the accuracy level of kinematic GPS with phase measurements. Since at least in the testing of the system we wanted some degree of

redundancy, more than two receivers are supposed to be used. We selected GPS dual-frequency geodetic receivers (LEICA GRX1200), designed suitably for permanent stations, providing sub-centimeter resolution with a 20 Hz sampling rate, with Leica AX1202 geodetic antennas.
Simulations of a few GPS network configurations were performed with the software NETGPS (Crespi et al, 1996) to decide the number and the relative locations of the GPS receivers. As a result, we decided to install one receiver on the chimney as the rover station and two on the ground as master stations. In fact, putting more receiver on the chimney is not necessary to model the motion: as mentioned above, the whole top ring of the chimney shifts in a horizontal plane. Using two master receivers allows a reliability check of the GPS observations against receiver-dependent outliers (admittedly an expensive one); on the other hand, it does not rule out systematic drifts of the solution (see section 4) which may affect all receivers.
Since the objective is to spot the (possible) raise of damages due to material fatigue, the monitoring system does not require real-time capability.

2.2 Accelerometers

Two Crossbow CXL02LF3 tri-axial accelerometers will be installed, one on the top of the chimney and another in the middle of the chimney span, to complement GPS data and monitor higher order modes of vibration. These accelerometers will acquire data with a 100 Hz rate. As data logging system we use a CRONOS-C1, with integrated buffer battery. Although it is not our case, this system can operate with a PC at a high frequency of updating, computing the FFT and applying digital filters in real-time. Also, a software to set-up acquisition, visualise and save data in ASCII format will be installed.

2.3 System configuration and data acquisition

Rather than a real time network solution (NRTK) we choose a less expensive and more conservative post-processing option, a near real-time solution being enough. Data are therefore processed in post-processing kinematic (PPK). The acquisition rate is set at 10 Hz and data are saved in the internal memory card of each receiver. This solution is a safeguard against temporary losses of connection between receivers and PC. Every 5 minutes, raw data are downloaded from the receivers and stored in the PC hard disc by the software Spider by LEICA. Downloading takes currently about 3 to 4 minutes; in the remaining time before the next download, the data are processed, triggering the alarm if this is the case, otherwise the results are stored for the long term analysis. Spider takes care of the interaction between data download and data processing. Using this procedure, the system status can be continually checked at 5’ intervals. A full cycle (data acquisition, download from the three receivers, data processing and short term analysis) is performed in less than 10 minutes.

Currently the system is operating in a test mode, with all receiver on the ground. We are checking the communications, the sustainability of the data transfer and the smooth pipelining of the various processing steps.

As far as data transmission is concerned, we are using a serial connection, via cable. In the full-scale development, a cable connection up to the top of the chimney is not feasible; on the other hand, the bandwidth of a radio modem is too small to comply with the data flow: downloading would last more than 5', so preventing a continuous monitoring. Even if our receivers can sustain a 20 Hz acquisition rate, we must therefore currently work at 10 Hz. A Wi-Fi a wireless connection with two access points for Ethernet, which can handle up to 400 meters outdoor, will be used in the full scale system implementation. Being faster than serial connection, we hope it will make it possible to work at the maximum GPS acquisition rate.

3. DATA PROCESSING AND DATA ANALYSIS

The system will be operated in two ways: just after installation, to gather data for the characterization of the dynamic response of the structure; later, in proper monitoring mode. A rough preliminary structural analysis of the chimney will point out the location and the number of accelerometers to be installed to properly monitor the higher modes of oscillation. Afterwards, a measurement campaign will be executed to provide the structural identification software with calibration data. From these measurements and from the finite element modelling of the structure, the reference values for the maximum allowed displacement will be derived and the principal modes of oscillations will be identified. Besides, the unperturbed position of the rover antenna will be determined with high confidence, so that absolute displacements will be measured in the monitoring phase.

The monitoring stage will feature a short-term analysis as well as a long term one. The former should be capable to spot sudden changes in the response to loads; the latter should highlight a (possibly slow) trend towards critical conditions.
Two main signals of fatigue damages can be spotted from the measurement of displacement: a change in the oscillation frequency of the first mode and a change of the displacement under a known load. The wind being the principal source of stress, the measured value of the displacement is of little value in itself to highlight stiffness changes, unless anemometer data are available. Although comparatively smaller in percentage, changes in the frequency response can be detected from a time series analysis of the displacement of the rover on the chimney top.
For the system to provide an early warning of a frequency drift towards failure, we need to enhance the sensitivity of the long-term analysis. This can be achieved trough an accurate evaluation of the first mode frequency and providing a means to find out whether the change with respect to the reference value is significant or not, with a given confidence level. To this aim, we combined a Fourier analysis, which identifies the frequency components, with a l.s. approach, which provides a comprehensive parametric tests body to evaluate the adjustment results.
Our workflow goes through three steps of data processing and a final stage of data analysis (see Figure 2):

- the first one consists of GPS raw data acquisition from the three receivers, with a quality check of the raw data performed by the central acquisition unit;

- the second is the processing of the GPS data to measure the baselines components, followed by a least squares network adjustment, to determine the rover coordinates in a local frame;
- the third step is the determination of the frequencies content of a time series of estimated positions by means of a preliminary Kalman filter, a DFT computation and the l.s. modelling of the X,Y positions as a function of time;
- the fourth is a statistical analysis frequency time series from the GPS and accelerometer data, to detect changes of behaviour, which will trigger an alarm signal.

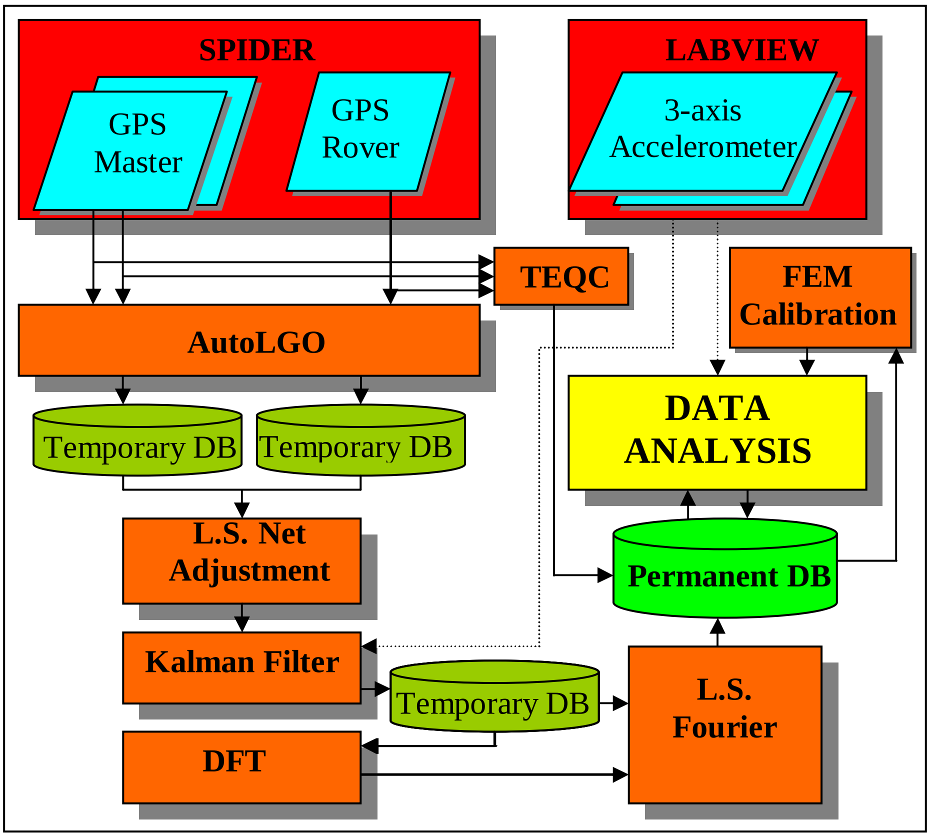

Figure 2 . The flowchart of data processing and data analysis

3.1 Computation of the rover position

Each file of 5' raw data from the two masters and the rover undergoes a quality check of the GPS signal with TEQC by UNAVCO. The results are stored for cross check with subsequent data analysis results and for long term evaluation.
Baselines vectors from each master station to the rover are computed at each epoch by a modified version of LEICA LGO, named AutoLGO, which takes care of the batch processing of the 5' data sets. An applet extracts the two computed positions of the rover and their covariance matrices and a subsequent program computes the l.s. average position, keeping the master coordinates fixed on a local coordinates frame and accounting for the covariance matrices of the two input position. Post-processing adds the advantage of assessment of the tracking quality and a more reliable estimate of the position accuracy. Besides, the estimated

variance of the solution is compared with the a priori variance by a parametric statistical test (χ^2 test). Afterwards, a simple Kalman filter and smoother are applied to remove high frequency noise.

3.2 Frequency analysis

The Discrete Fast Fourier Transform (FFT) is applied to identify in the signal spectrum the frequency components and their amplitudes and phase shifts. A local maxima search algorithm extracts the relevant frequency values (i.e. those above 1 cm in amplitude), looking for peaks in the magnitude spectrum. Given the expected range of frequencies for the structures to monitor and given the sampling rate, the frequency resolution of the DFT from a 5' data sample allows to spot even very small changes. The plot of the first mode frequency over time should therefore carry valuable information on possible trends. It would lack, though, a probability measure to assess the significance of that change. Therefore we decided to add to the analysis in the frequency domain a l.s. analysis. The objective is still to find out the frequency evolution in time, but with a confidence interval attached, to allow testing the hypothesis of frequency change in a probabilistic framework.
The filtered N, E coordinates of the rover are therefore modelled as a function of time, estimating the parameters of a kind of "Fourier expansion" without harmonics. The DFT results give a double benefit: from one hand, over-parameterisation can be avoided, since only the relevant terms are evaluated in the approximating function; on the other hand, it provides the approximate values for the unknowns in the non linear least squares adjustment.
The adopted functional model is therefore the following:

$$E_k = A_0 + \Sigma_i A_i \cos(2\pi fx_i t_k + sfx_i)$$

$$N_k = B_0 + \Sigma_j B_j \sin(2\pi fy_j t_k + sfy_j)$$

where:
E_k, N_k = coordinates of the rover antenna at time t_k;
fx_i, fy_j = relevant frequency components from the DFT;
k = 1, number of observations;
i,j = 1, number of frequencies in E, N respectively.

The stochastic model is derived from the GPS data processing and the averaging of the two rover positions. The covariance matrix of the observations is therefore a block-diagonal matrix, where every block is the 2x2 diagonal block of the N,E coordinates taken out of the 3x3 covariance matrix of the average position of the rover.
The l.s. solution of the observation equations provides all elements relevant for the analysis: besides the unknown parameters, the estimated sigma-nought, the covariance matrix of the estimated parameters and the residuals with their standard deviations. It's therefore possible to test model errors, detect outliers and test the significance of unknown parameters.
Obviously, this functional model is not fully realistic, since it assumes a strictly periodic movement of the chimney top during the 5' time interval. Depending on the wind behaviour, the amplitude as well as the static component of the displacement may change several times.

Indeed, amplitude and phase shift are in this context just nuisance parameters: unless the frequency estimate and its accuracy are severely affected by this coarse modelling of the actual movement, there would be no reason to develop a more sophisticated model. There are anyway several possible alternatives: provided the accuracy of the frequency estimate does not decrease too much, one is simply to shorten the sampling time interval (e.g. from 5' to 30") so that amplitude changes will deteriorate the frequency estimate. A second possibility is to switch to a sequential updating of the solution, with a test on the parameters to find out whether a new value (e.g. for the amplitude of a given frequency) is necessary. Finally, a third possibility might be to model with an appropriate function the time changes of the amplitude and of the static component of the displacement.

3.3 Short-term and long-term statistical analysis

Structural integrity is monitored evaluating changes in the reference values characterizing the dynamic response of the chimney i.e. its eigenfrequencies. We use here two (complementary) approaches: the former evaluates with statistical tests the significance of changes of the parameters at a given time (short-term analysis), the latter estimates a trend of their variation, allowing a prediction in time (long-term analysis).

3.3.1 Short-term analysis: test on parameter changes

The l.s. estimated frequencies can be compared directly to those identified by the calibration of the finite element model. The hypothesis that the estimated value is significantly different from the reference value is tested at a given significance level by a Student-type statistic:

$$t_o = \frac{\hat{x}_i - x^*}{\hat{\sigma}_x} \sim t_{n-1} \, .$$

This test assumes normally distributed observations errors and a linear relationship between observations and parameters: clearly, this is not true in our case.

3.3.2 Long-term analysis: trend estimation

An alternative to a pointwise control of the frequency values is the identification of a trend or frequency drift by a regression analysis. It is in some respect a more flexible approach, since it also allows for the prediction of the future structure behaviour. The simplest model assumes the parameter variations to be approximately linear:

$$y = a\,t + b$$

where y is the estimated frequency at time t.
At every epoch (every 5' of data acquisition) the straight line coefficients are l.s. estimated and it is looked for evidence of systematic deviations from the reference horizontal straight line. If the model is truly linear, that can happen in two ways: either the slope coefficient after some time becomes statistically different from zero or the intercept significantly differs from the reference value. In both cases, the test is the same used in the previous paragraph.

If the trend is steady, the test procedure described above will spot it and will allow to predict its evolution, the sooner the smaller the confidence interval of the parameters.
Two types of changes in the linear trend should also be considered, thought, and highlighted by the time series analysis: a step change and a slope change. The former would mark a sudden decrease in the structure stiffness, the latter a change (most likely an acceleration) in the rate of stiffness degradation. To this aim, the predicted frequency value at each epoch will be tested against the measured value to highlight step changes, again with a statistical test. Slope changes can be identified in the same way, but looking at the first derivative of the frequency. An alternative to both methods would be to test the intercept and the slope coefficient estimated from the data within a moving time window, to increase the sensitivity to local changes.

4. EXPERIMENTAL TESTS

With any sensing technology, calibrations are essential to assess system performance before deployment. To determine sensors accuracy and identify the level of noise and reliability of the measurements, we performed static and dynamic tests to simulate full scale operation. Each master antenna was mounted atop a building (free from sources of multipath and with limited obstructions, to preserve a 15° mask angle) approximately 60 meters apart and their position was determined with high precision, during a 2 days session. The rover unit was fixed to a portable rotating table (see figure 3). Estimated frequency and amplitude were compared to the nominal motion parameters to assess the dynamic tracking capability of the system.
Figure 4 shows the plots of two 5' data sets acquired with an angular rate of about 0.3 Hz on a circle of about 6 cm radius. As can be seen, while the second plot shows a quite stable tracking, in the first there is a systematic shift of the circle centre.

Figure 3 - The turntable with the GPS antenna used in the testing stage

Table 1 contains the results of the l.s. estimation of the frequency using the mathematical model presented in section 3.2. Corrections are not significant to the approximate values (the DFT estimate) for the systematic effects in the GPS data (Test 1); in Test 2, on the contrary, the differences is one order of magnitude larger. Corrections are significant in all cases, due to the very high accuracy in the estimation of the frequency; besides, the standard deviation improves the longer the time interval of the processed observations.

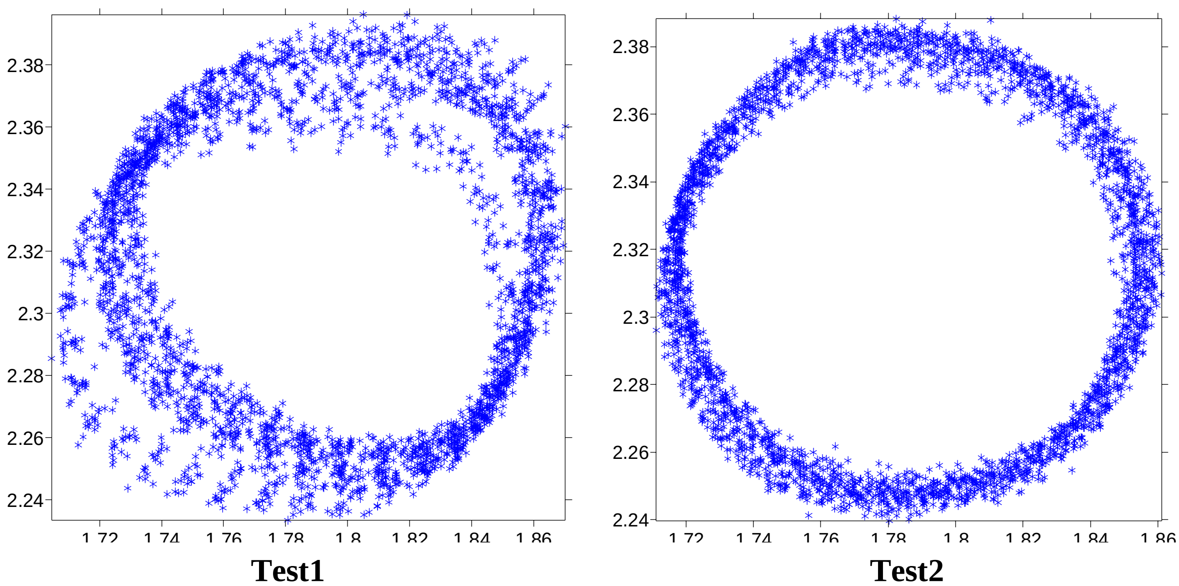

Figure 4 - Plot of two 5’ GPS positions on a turntable, acquired at 10 Hz.

	Test	Approx. value	Correction	Estimate	σ	Signific. Ratio
fx (Hz)	**1**	0.31333	-0.00040	0.31293	0.00000	214
fx (Hz)	**2**	0.29667	0.00566	0.30233	0.00002	324

Table 1 - Results of the l.s. adjustment of the rover trajectory over two sets of 5' GPS sessions (about 3000 observations at 10 Hz sampling rate).

Since the theoretical accuracy of the frequency looks too good, we tried to assess the accuracy potential by simulation. An elliptical trajectory was generated with amplitude and frequency values in the expected range for the chimney (major and minor axes of 18 cm and 8 cm; frequency 1.03 Hz) and sampled at 10 Hz along 20 full cycles. Normally distributed errors with zero mean and 2 cm standard deviation were added to the X,Y coordinates.
As you can see from Table 2, the simulations confirmed the high accuracy potential. In a first simulation (row 1), the true values of parameters were given as approximate values; the solution converges to the correct values. In the second one (row 2), the approximate values were just slightly modified, to find out whether the adjustment converged or not to the true values: this is indeed the same as having the natural frequency changed and looking for significant changes with respect to the reference value. Again, the solution converges to the true values, within the accuracy of estimation.
Finally, a third simulation on the convergence radius to the solution was executed, starting from rather raw values of the frequency (3% error) and of the amplitudes (100 % error). Although by a large number of iterations (71), the solution converges to the true values. Similar series of simulations have been performed changing the shape of the ellipse and the range of approximations, with basically the same results as of Table 2. Therefore, there seem to be great sensitivity potential of the method in highlighting even small changes in the frequency.

	Test	True value	Approx. value	Correction	Estimate	σ	Signific. Ratio
f (Hz)	**1**	1.03	1.03	0.00013	1.03013	0.00013	1
f (Hz)	**2**	1.03	1.0305	-0.00027	1.03023	0.00011	2
f (Hz)	**3**	1.03	1.00	0.03002	1.03002	0.00011	263

Table 2 - Results from simulations of an elliptical trajectory at 1.03 Hz; frequency estimates from 200 samples at 10 Hz with RMS error in X,Y coordinates of 2 cm.

5. FULL-SCALE IMPLEMENTATION

The system is foreseen to be installed on a chimney of the power plant of Piacenza (Italy), 120 m high, and should begin operation in late spring 2005, once the Wi-Fi system and the accelerometers will be installed and the communication and synchronization issues will be solved.
Particular care has been put in the realization of the support for the GPS antenna and receiver, the accelerometers and the case for control electronics on the chimney. The support must be

rigid and firm and, at the same time, must provide a lateral straddle sufficient to offer enough visibility to the antenna. Since the support is close to the chimney top, the best position is that shown in figure 1, with the antenna shielded, to some extent, from the wind and the gases. If the distance from the chimney edge is less than 30 cm, the free zenith angle is larger than 135° and the azimuth angle larger than 180°. The installation point will be in the southern side of chimney.
Figure 5 shows a sketch of the support: the accelerometer (one tri-axial) is mounted in the lower part, while the case with the electronic components (GPS receiver and radio modem) and power supply (with buffer battery) will be fixed under the support in a watertight lodging, adapted with two stirrups for fastening to the wall of the chimney.

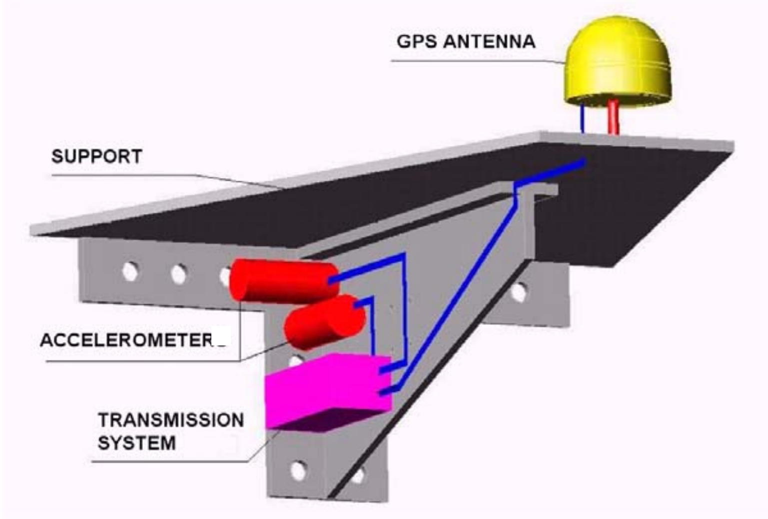

Figure 5 - Sketch of the support with the GPS antenna, the receiver and the accelerometer.

All system components (antenna, accelerometer, console and container) will be connect to each other with a steel cable to a security screw which will prevent falls due to breach or corrosion.

ACKNOWLEDGEMENTS

This work has been financed under a research contract with CESI. Some parts of the project has been also financed in the framework of the National Research Program COFIN 2004 by the Ministry of the University and Scientific Research of Italy. We are grateful for the support of the CESI; in particular: dr. Marco Miserocchi and geom. Fausto Pellini. Thanks also go to the Leica Geosystems staff for technical advice and support.

REFERENCES

Cefalo, Manzoni, Noè, Sluga, 1998, "Misura di oscillazioni di strutture con GPS", Proceedings of 17th GNGTS Congress, Rome, Italy

Çelebi, Sanli, 2002, "GPS in Pioneering Dynamic Monitoring of Long_Period Structures", in Eathquake Spectra, vol. 18, n. 1, pp 47-61

Çelebi, Sanli, Sinclair, Gallant, Radulescu, 2003, "Real-Time seismic monitoring needs of a building owner and the solution", Proceedings of 11th FIG Symposium on Deformation Measurements, Santorini, Greece

Crespi M., 1996 "A software package for the adjustment and the analysis of GPS control. In Reports on surveying and geodesy", Bologna (Italy), Marco Unguendoli editor – Ed. Nautilus, pp 237-264.

Kijewski, Kilpatrick, Williams, Kwon, Young, Abdelrazaq, Galsworthy, Morrish, Isyumov, Kareem, 2003, "Full - Scale Validation of the Wind-Induced Response of Tall Buildings: Preliminary Results of the Chicago Monitoring Project", Proceedings of 2003 Structures Congress, ASCE, Seattle

Ogaja, Rizos, Wang (School of Geomatic Engineering, Sydney, Australia), Brownjohn (School of Civil and Structural Engineering, Singapore) http://www.gmat.unsw.edu.au/snap/ work/singapore_rpb.htm

Yoshida, Tamura, Matsui, Ishibashi, Pagnini, 2003, "Measurement of wind-induced response of buildings using RTK-GPS and integrity monitoring", www.arch.t-kougei.ac.jp/tamura/ Staff/yoshida/ICWE2003_GPS.pdf

http://www.unavco.org/facility/software/teqc/teqc.html

CONTACTS

Ing. Noemi Emanuela Cazzaniga
D.I.I.A.R. – sez.Rilevamento - Polytechnic of Milan
Piazza Leonardo da Vinci, 32
20133 Milan
ITALY
Tel. 0039 02 23996505
Fax 0039 02 23996530
Email: noemi.cazzaniga@polimi.it

Prof. Gianfranco Forlani
Dip. Ing. Civile - University of Parma
Viale delle Scienze
43100 Parma
ITALY
Tel. 0039 0521 905934
Fax 0039 0521 905924
Email: gianfranco.forlani@unipr.it

Prof. Livio Pinto
D.I.I.A.R. – sez.Rilevamento - Polytechnic of Milan
Piazza Leonardo da Vinci, 32
20133 Milan
ITALY
Tel. 0039 02 23996525
Fax 0039 02 23996530
Email: livio.pinto@polimi.it

Geom. Paolo Abruzzi
CESI spa
Via N. Bixio, 29
29100 Piacenza
ITALY
Tel. 0039 0523 684227
Email : abruzzi@cesi.it