13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 901

AN ATTEMPT OF EARTHQUAKE PRECURSOR & DEFORMATION MONITORING BY MEANS OF REAL-TIME HIGH RATE GPS

Matthias Becker[1] and Radovan Marjanovic Kavanagh[2]

SUMMARY

Until recently deformation monitoring was usually done by periodic geodetic position measurements of discrete points, which served for the determination of time dependent vectors. Alternative techniques with continuous data even in real-time using different electronic sensors, like extensometers or tilt meters, do not give the complete information about deformations with respect to a large scale reference frame. The only solution was a combination of different measuring techniques, methods and instruments, whereas a complete integration of all sensors into one consistent system is hardly possible.

In the last few years GPS instrumentation evolved to a strong and accurate measuring tool. The modern GPS instrumentation allows high precision kinematic applications even in real-time. Additionally, a sampling rate of typical more than 5 Hz allows the use of the system even for applications with high velocities and accelerations. The major advantage of these systems is that they give 3D coordinate information down to millimeter resolution.

This paper describes the conceptual design of the installation of a real-time kinematic GPS array on known points (where co-located measurements with other techniques took place) in a region near Zagreb, the capital city of Croatia. This region is known as a local earthquake hazardous region where a series of earthquakes took place during the past. Most of these earthquakes originated in the Earth's crust in depths of about 10-20 km. This very active seismic zone crosses the Mount Medvednica situated at the northern part of Zagreb.

The new GPS real-time measuring technique will provide a monitoring and warning capability, which could be very helpful in hazard mitigation. The combination with earlier data of these points with continuous measurements will help to determine the long-term deformation of the local Earth's surface.

[1] Institute of Geodesy, Bundeswehr University Munich, Germany, matthias.becker@unibw-muenchen.de
[2] Faculty of Mining, Geology & Petroleum Engineering, University Zagreb, Croatia, ramaka@rgn.hr

INTRODUCTION

As known from numerous authors significant earthquake precursor phenomena in the form of local deformations of the Earth's crust do not occur at all events and are hard to detect anyway. Tilting and changes in creep rate as an indication for increased seismic risk can be detected by local tilt- (Altiner et al., 2000), strain- or creep-meters (e.g. Roeloffs, 2001), geodetic distance measurements or by repeated or continuous GPS measurements (e.g. Lyons et al., 2002). Today the use of permanent GPS, at least at selected anchor stations, in combination with epoch-wise area-measured densifications is the primary tool. With high rate GPS data up to one or even 20 Hz in case of seismic events, pre-, co- and post-seismic site motions can be recorded (Márquez-Azúa et al., 2002), (Melbourne et al, 2002). Recent results with epoch-wise GPS derived positions at each second showed that the detection of seismic surface waves from large earthquakes with periods of 20 s and amplitudes of 20 cm (Kouba, 2003) is possible. Higher sampling rates are useful for co-seismic and structural monitoring (Hudnut and Behr, 1998). GPS may be considered as the ultimate seismometer giving not only the periods, but also the amplitude and absolute position changes during seismic or otherwise caused motion (Linlin Ge et al., 2000). With a good communication infrastructure of cable-, radio-modems or wireless LAN networks the real-time monitoring is a feasible option today.

The question is, weather or not precursory signals of earthquakes occur and if no signals are detected is it due to the low sensitivity of our instruments or just because there are no precursors. This question can only be answered by the installation of continuously observing devices. In such a way geodetic monitoring of the Earth's crustal deformation, with modeling and prediction of tectonically related three-dimensional movements should become the tool for the study of seismic risk in an earthquake prone area (Altiner, 2000). So when monitoring local deformations of the Earth's crust a combination of GPS with terrestrial methods, such as precise distance meters, strain-meters or tilt-meters is still feasible and of interest. However, it is very important to take in account the stability of the monuments due to environmental influences as temperature, air pressure and water table changes (Wyatt, 1982). A separation of such induced movements from tectonically induced signals is necessary in order to completely understand the deformation process of the Earth's surface due to seismic or tectonically induced stresses.

The accuracy of today's instruments for deformation measurements is still at the level of the deformations itself in most areas. Thus, a proper data interpretation and analysis is very important. From the view point of accuracy the major difficulty of earlier long-time deformation monitoring arrays, like strainmeters or tiltmeters, was always the long-term stability (instrumental long-term drift). Using GPS this is not an issue; the reference frame connection is stable and can be monitored over large areas by the integration of the local deformation network into the operational global IGS (Beutler et al., 1998) and national permanent GPS networks.

GEOLOGICAL AND TECTONIC SETTINGS

The town Zagreb - the capital of Croatia with about 1 million inhabitants - is located close to the northern edge of the boundary between the Eurasian plate and the Adriatic micro plate. This densely populated region represents a strongly menaced seismic zone. Besides the northern part of Zagreb, mainly across Mt. Medvednica, there are several seismic zones protruding even into the centre of the city. From 120 years of earthquake recordings these small seismic zones mostly at the crossings of longitudinal and transversal faults have been derived (Cvijanović et al. 1980). Basic tectonic movements at great depths causes most of these earthquakes in the epicentral area of Mt. Medvednica. These are the reasons for the neo-tectonic activity and the rising of the Mt. Medvednica horst over longitudinal faults. This leads to the conclusion that the mentioned faults are active causing increased seismicity. According to the zoning mentioned and the predictions of several authors this is the probable location of a major earthquake expected in the future. That is the main reason for establishing a deformation monitoring net covering the epicentral area of Mt. Medvednica and the broader area of Zagreb.

DESIGN OF THE GPS NETWORK

In the early nineties around the predicted earthquake area near Mt. Medvednica a deformation monitoring network for testing was installed. A prior net optimization (Stanek, 1990) and several geodetic observation campaigns in combination with gravity measurements took place. Later, a GPS net over a larger area of the city of Zagreb was projected to serve for several different tasks with very high accuracy criteria (Čolić et. al, 1999). Some stations of this GPS net were used for geodynamical research and monitoring (Medak and Pribičević, 2001). Especially for these reasons the stations have been carefully stabilized and founded to preserve long term stability. The points of the net have been chosen very carefully to cover this seismic area and allow a description of the expected movements. After a period of five years of successful observation campaigns it can be expected that the planned measurements with permanent GPS receivers will provide highly precise results in future as well. The advantage of new geodetic technologies, especially the combination of permanent and RTK GPS densification applications is enormous and this "new geodesy" provides now a strong tool for many interdisciplinary programs of seismologists, geophysicists, geologists, and others.

The dedicated GPS net consists now of 40 well founded stations located mostly outside the city. Most of them are constructed after the scheme shown in Fig.1. (Medak and Pribičević, 2002). The pillars were consolidated with four anchors directly inserted into bedrock or clay. The upper part of the pillar is made of reinforced concrete and a double tube with Styrofoam insulation around the part of the pillar which is

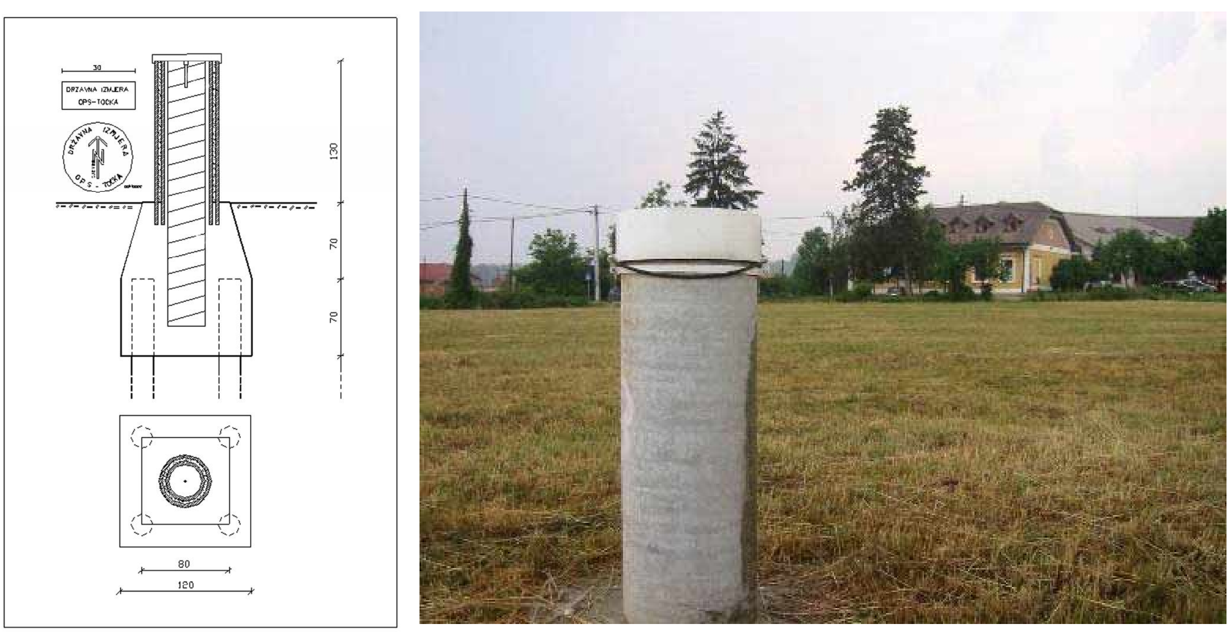

Fig.1. Pillar construction and foundation for points outside of the city, Example Pt. 1006.

outside of the ground. At the top of the pillar a special screw adapter for GPS receiver antennas is inserted. This screw is protected with a cover, and locked.

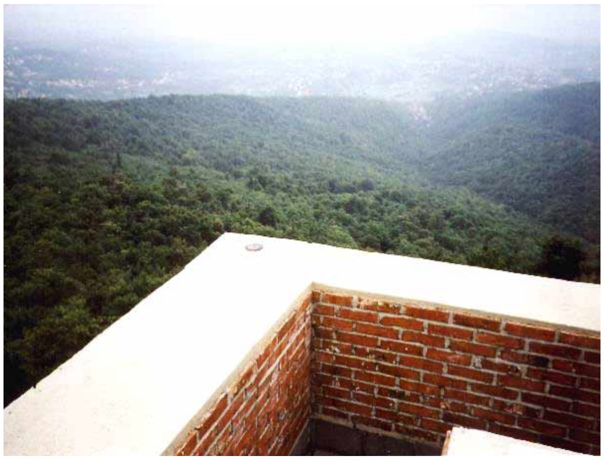

Fig.2. Marker of point 1036 at the Mt. Sljeme at Medvedgrad and antenna of the permanent GPS station Pt.1038

At several points where it was possible, and where the movements of the objects itself are to be observed, the antenna-screw was directly installed in a wall or concrete, Fig.2. Three points of the GPS net (Pt. 1038, Pt. 1043 and Pt. 1039) were installed with special metallic rods. They were planned as permanent stations on buildings and two of these are working presently, see Fig.2.

With the design and the outreach of this network and the new inclusion of permanent sites the determination of the neo-tectonic activities related to the occurrence of earthquakes, pre- co- and post seismic deformation should be possible. For modeling of the fault motion and slip distribution a structural model of the broader part of the city of Zagreb was designed recently. To drive such a model stress and strain relations and their changes in quantitative form from geodetic measurements have to be observed. The measurements in our net lead exactly to this goal; this means the GPS network will serve for the determination of movements of the broader Zagreb region.

Results from repeated measurements obtained in this network show that there are detectable displacements and there is a feasibility for determining earthquake-safe areas in the broader area of Zagreb. Displacements from repeated GPS observations from a period of 4 years are shown in Table 1 and Fig. 3.

Tab. 1. Selected GPS points and the calculated displacements from 1997 to 2001

Pt.Nr.	***Name***	***Abbrev.***	***B***	***L***	***dB[cm]***	***dL[cm]***	***dh [cm]***
1006	Blaguša	BLGS	45.92571	16.13530	0.7	-1.3	2.1
1013	Sesvete	SSVT	45.83485	16.10654	-1.5	0.2	2.9
1036	Medvedgrad	MDVG	45.86908	15.94044	1.2	-0.6	2.6
1038	GZAOP	CAOP	45.79124	15.89491	1.5	-0.6	2.6

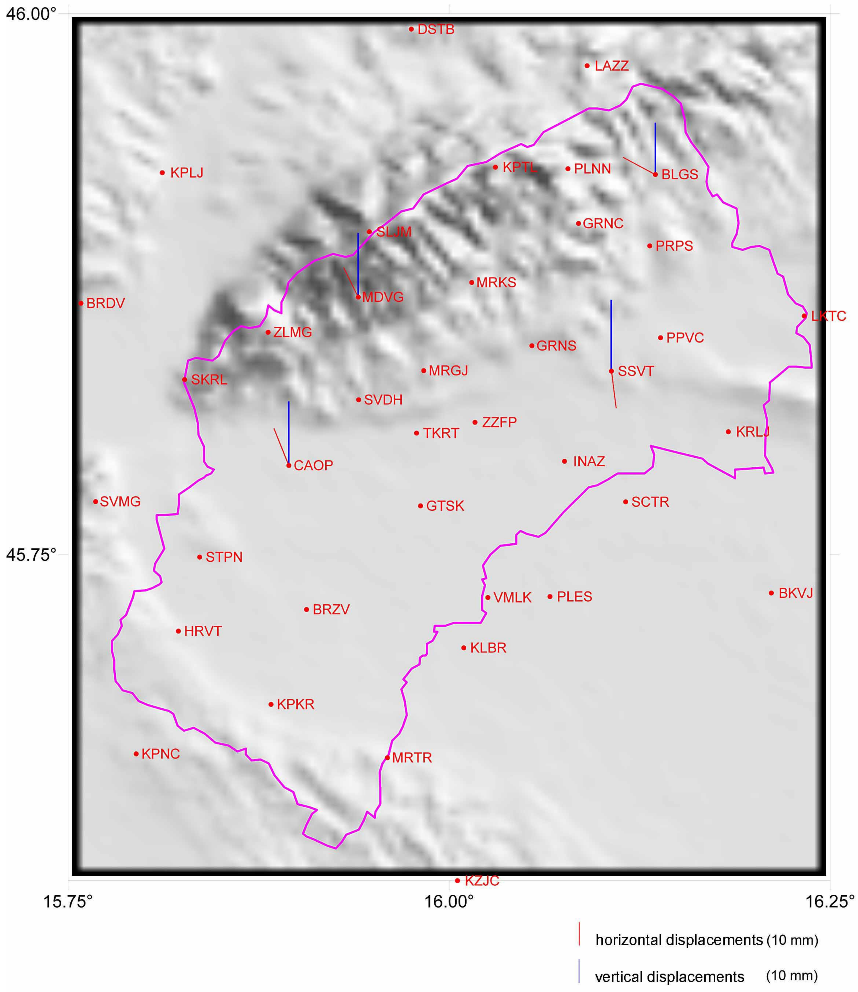

Fig.3. Points of the GPS net and the displacement vectors of four points for the period 1997 - 2001 from repeated GPS measurements

DESIGN OF PERMANENT GPS STATIONS

In order to establish an on-line and continuously recording GPS monitoring network suitable reference station hardware has to be compiled. The permanent sites of a multi-purpose reference station network have to provide:

- GPS dual frequency data of carrier and phase observations in rates of at least 1Hz
- Continuously streaming data or data of selectable batches of 5-60 minutes
- Preferably 10 or 20 Hz data in a seismic ring buffer
- Optional meteorological data each 15 min in RINEX format (with an accuracy of 0.5hPa for air-pressure, 0.3K for temperature, 2% for humidity)
- Dorne Margolin Choke Ring or equivalent antenna
- Geodynamical grade solid mount in bed rock, pillar or consolidated old building

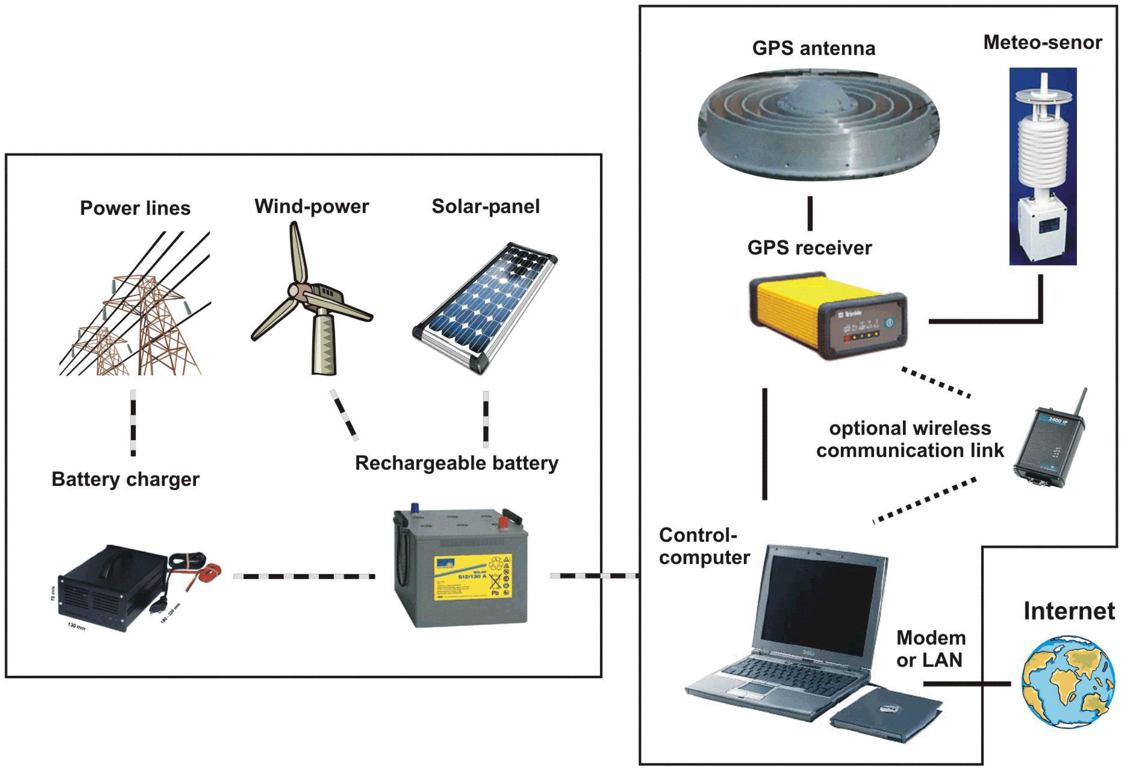

Figure 4: Components of a GPS permanent station.

In designing an actual station layout three main aspects have to be considered:

- Sensor and communication hardware
- Control and communication software
- On-site facilities and real facts at each site, power, security, communications

In (Becker et al., 2003) a model station for the use in the Central European Geodynamics Program CERGOP-2 is described, see Fig. 4. Similar design is intended to be used for the Mt. Medvednica – Zagreb stations. For applications with less demanding accuracy requirements or larger rates, like slope monitoring, a cheaper setup with single frequency receivers is possible, lowering the price of the costs per site by a factor of 3 to 4.
A main concern in view of real-time application and monitoring is the data flow. If permanent phone connections or direct Internet-access is not feasible at a site, for limited areas of up to 20 or more km with unobstructed lines of sight wireless LAN bridges are a good choice. Otherwise spread spectrum radio modems can serve for the communication to the internet access point.

The first goal is the monitoring with 3 to 5 receivers on selected sites. Receiver handling, data collection and download will be managed via internet bi-directional connection. Data analysis will be done in two steps, firstly the kinematic or batch-wise position determination, secondly the deformation analysis and optional alarming and warning routines. Various ways of data analysis are under investigation and will be selected on the basis of the hardware configuration finally installed. Options based on proprietary or GPS manufacturer-provided software are:

- Baseline-wise epoch solutions from streaming data for each pair of receivers
- Baseline-wise batch solutions with intervals of 5 to 15 minutes
- Network solution with all receivers per epoch or per batch of data
- Individual RTK solutions for every receiver by using the differential corrections of one selected receiver

Positioning results will then be fed to the deformation analysis process using the GOCA package (Kälber and Jäger, 2001) to detect stable points and moving object points. The object points are determined there with respect to the stable points by a network adjustment, which is performed for each epoch or interval of available position and covariance data. Unstable reference points are identified by statistical tests. Time series of displacement, velocity and acceleration for each object point are computed by a Kalman-Filter-approach and can be used for alarms if the deformation passes user-defined probability levels.

Longer batches of raw data of this network in combination with the public Croatian and EUREF permanent GPS station data will be utilized in the Bernese software package to compute daily coordinate solutions in the ITRF and to allow the long time geodynamical monitoring of crustal deformation with utmost precision.

FIRST RESULTS OF A HIGH RATE GPS EXPERIMENT ANALYSIS

In order to test the resolution and precision of high-rate GPS observations an improper installation of a GPS antenna on a pole of about 7 m of height was analyzed. Fig. 5 shows the motion in two orthogonal directions of the antenna pole close to its resonance frequency due to wind influenced vibrations. The top of the pole moved about 6 cm peak to peak due to its inadequate mounting. Data was recorded with a Leica SR500 GPS System with a sampling rate of 10Hz. The reference station was about 12 km distant and sampling in 1Hz only. Therefore the data of the (stable and well fixed) reference station were interpolated to the 10 Hz interval of the mobile system.

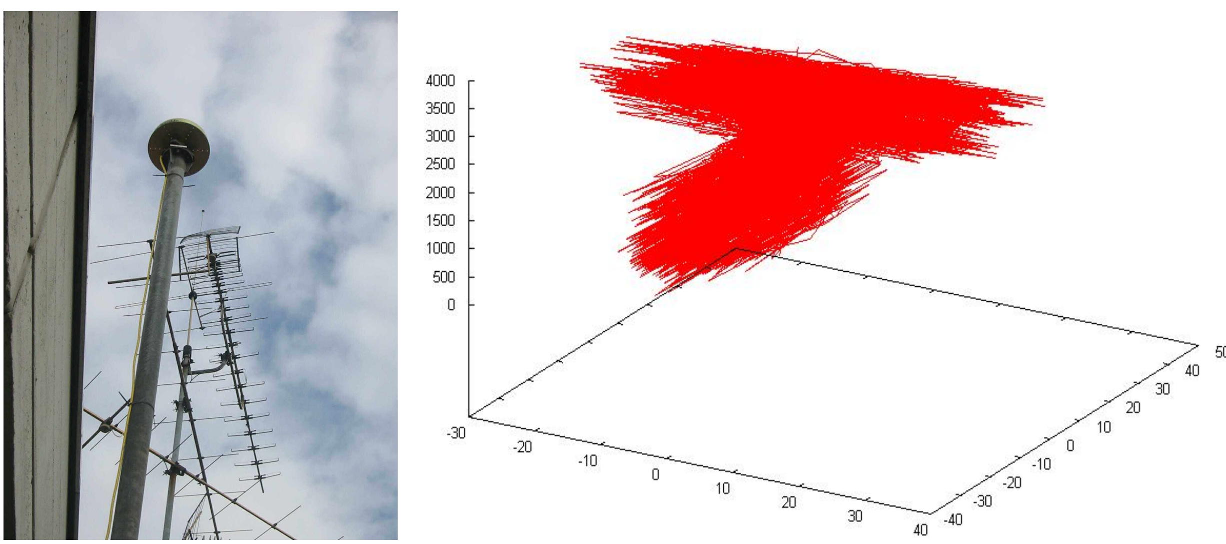

Fig. 5. Mast with choke-ring antenna and its motion over about 4000 epochs of 10 Hz data during excitation, displacement in mm.

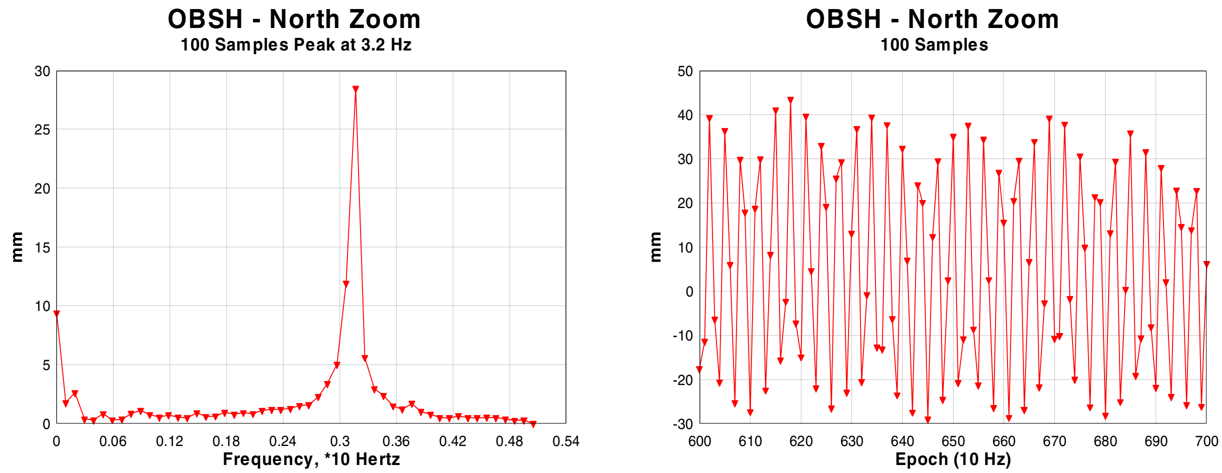

Fig. 6. Power spectrum (frequency) of the antenna motion and zoom of displacements from kinematics 10 Hz GPS solutions.

As shown in Fig. 6 the motion was very well resolved by the kinematic epoch-wise position estimation. Applying Fourier analysis the eigenperiod of the pole close to 3.2 Hz is prominently identified in the frequency spectrum. This experiment clearly shows that – at least over short gliding intervals, the use of GPS as seismometer and for construction monitoring is feasible. More advanced filtering techniques can be used to separate true motion from ionospheric, multipath and other noise generating disturbances. Especially the height component is certainly more critical in modeling.

CONCLUSIONS

In this paper the concept for a combined network for geodynamics, fault monitoring and high frequency motion recording GPS network is developed. It is based on an existing network in the Zagreb area, which will be equipped with GPS hardware and monitoring software capable of providing on-line and off-line positioning results at the sub-cm level. The possibility of high data rates with sampling and processing data for various intervals in parallel opens the way to quite a number of different utilizations. Goals are the parameterization of the fault system around Zagreb and Mt. Medvednica, from the aerial deformation field, the detection of pre-, co-and post-seismic motions in case of a seismic event and hopefully the provision of an on-line alarm system. The reference stations may also be used as anchor sites for the densification by epoch-type occupations of a dense network at selected sections of the deformation zone.

REFERENCES

1. Altiner, Y., K. Čolić, R. Marjanović-Kavanagh "Some preliminary results and analysis of different geodynamic techniques with special remark on GPS and tiltmeter measurements in Croatia", 12 th WCEE, Auckland, EQC New Zealand, 2000
2. Altiner, Y. Analytical Surface Deformation Theory for detection of Earth's Crust Movements, Springer Verlag , Frankfurt, 1999

3. Becker, M., M. Kirchner, G. Grenercy “Creation of New Permanent Observation Facilities in CEI Countries – Network Design and Permanent Station Configuration”, Proc. CERGOP-2 Progress Meeting, Warsaw, Sept. 27.-28. 2003, Reports on Geodesy / Warsaw University of Technology, ISSN 0867-3179; Warszaw, No. 3 (66), 2003, 45-54
4. Beutler, G., M. Rothacher, T. Springer, J. Kouba, R.E. Neilan "The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences" In: 32nd COSPAR Scientific Assembly, Nagoya, Japan, July 12 to 19, 1998, 27-50
5. Cvijanović, D., E. Prelogović, D. Skoko, K. Marić, D. Mišković "Seizmotektonska rajonizacija Medvednice, Zbornik referata 6. Jugoslavenskog simpozija o hidrologiji in inženirski geologiji, Portorož, 1980, 13-25
6. Čolić, K., B. Pribičević, D. Švehla "3-D Geodynamic Network of Broader Area of the City of Zagreb", Second International Symposium Geodynamics of the Alps-Adria Area by means of Terrestrial and Satellite Methods, Dubrovnik, Croatia, September 1998, Zagreb & Graz 1999, 75-86
7. Hudnut, K.W, J.A. Behr “Continuous GPS monitoring of Structural Deformation at Pacoima Dam, California”, Seismological Research Letters, Vol. 69, No. 4, 1998, 299-308
8. Kälber, S. and R. Jäger “GPS-BASED ONLINE CONTROL AND ALARM SYSTEM (GOCA)“ Proceedings 10th FIG International Symposium on Deformation Measurements, Orange, California, March 19 through 22, 2001
9. Kouba, J. ”Measuring seismic waves induced by large earthquakes with GPS” Studia Geophysica et Geodaetica, 47, 4, 2003, 741-755
10. Linlin Ge, S. Han, C. Rizos, Y. Ishikawa, M. Hoshiba, Y. Yoshida, M. Izawa, N. Hashimoto and S. Himori” GPS Seismometers with up to 20Hz Sampling Rate”, GPS99 Conference Tsukuba, Japan, Earth Planets Space, 52, 2000, 881–884
11. Lyons, S.N.,Y. Bock, D.T. Sandwell “Creep along the Imperial Fault, southern California, from GPS measurements”, JGR, 107, B10, 2002
12. Márquez-Azúa, B.,Ch. DeMets “Crustal velocity field of Mexico from continuous GPS measurements, 1993 to June 2001: implications for the neotectonics of Mexico”, JGR, Vol. 108, B9, 2003
13. Medak, D., B. Pribičević "Geodynamic GPS-Network of the City of Zagreb-First Results". The Stephan Mueller topical conference of the European Geophysical Society : Quantitative neotectonic and seismic hazard assesment: new integrated approaches for environmental management. Balatonfüred, Hungary, 23rd September 2001
14. Medak, D., B. Pribičević "Geodynamic Network of the City of Zagreb", Proceedings of the Faculty of Geodesy, University of Zagreb on the Occasion of the 40thAnniversary of Autonomous Activities 1962-2002, Zagreb 2002, 145-156
15. Melbourne, T.I.,F.H. Webb, J.M. Stock, Ch. Reigber “Rapid postseismic transients in subduction zones from continuous GPS”, JGR, Vol. 107, B10, 2002
16. Roeloffs, E. “Creep Rate changes at Parkfield, California 1966-1999: Seasonal, precipitation induced and tectonic”. JGR, Vol. 106, No. B8, 2001, 16,525-16,547
17. Stanek H. and K. Čolić "Local Geodetic Network "Kašina" - Zagreb for Geodynamic Usage Optimization in Accuracy and Reliability by Simulation", Proceedings of the first international symposium Gravity field determination and GPS - Positioning in the Alps - Adria Area, Dubrovnik and Hvar, October 2-7-1989, Graz, 1990, 405-426
18. Wyatt, F. "Displacement of Surface Mounts : Horizontal Motion." JGR, Vol. 87, No. B2, February 10, 1982, 979-989