

GEODYNAMICS OBSERVING TECHNIQUES AT THE OBSERVATORY HVAR (CROATIA)

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SUMMARY:

Croatia lies in a region, which is seismically and tectonically very active. The main reasons for that are the Adriatic micro-plate movements towards the Dinarides, with its different specific densities of rock masses in the crust. Several active zones in the Adriatic Sea but also along the Adriatic coast are known which in the past experienced strong earthquakes with damages in cities like Dubrovnik, Makarska, Rijeka, Ston, and others. In our research project it is planned to install several different measuring instruments in the middle of the Adriatic sea at the Observatory of the Faculty of Geodesy, Zagreb, on the island Hvar. In this paper we give a short overview on the contributions of space geodesy and the type of signals that we have to deal with. Satellite positioning will be based on global PPP and the Croatian Positioning System, gravity and height will be treated and compared to model computations.

Keywords: Adriatic Sea, Earthquakes, LaCoste ET-Gravimeter, GNSS, CROPOS.

INTRODUCTION

Measurements of local signals in particular sites can not be treated separately from global phenomena. Measuring at the level of one part in 10^9 , the interpretation of signal in geometric position, height, tilt or gravity requires the integrated modelling of all disturbing effects in order to identify the signals of interest, e.g. local strain build up local height changes that may indicate risks.

We are planning to install several different measuring instruments in the middle of the Adriatic sea at the Observatory of the Faculty of Geodesy, Zagreb on the island Hvar. Till now the station was equipped with several astronomical equipments a seismograph a permanent internet connection, and periodically with a GNSS receiver, Fig. 1.



Figure 1. View from the Hvar observatory and the pillar with GNSS antenna

Several satellite missions for position, gravity, height are introduced and compared to model computations. As the planned observatory is located on an island, effects from the Adriatic water level change, loading and associated phenomena are of particular interest.

The epoch station of the Hvar observatory had an important role in obtaining results in a kinematic active area of the eastern Adriatic (Caporali et al. 2009). This Central European Geodynamics Project CERGOP/2 was funded by the European Union from 2003 to 2006 under the 5th Framework Programme. The repeated measurements of coordinates of the epoch and permanent GPS stations of the Central European GPS Reference Network (CEGRN), started in the year 1994 (Caporali et al. 2008). The spatial distribution of permanent sites and epoch stations could be seen in Fig. 2. The measurements on the Hvar observatory were performed periodically every two years, always in June, repeating 24 hour sessions for five consecutive days by researchers from the University of Zagreb, Faculty of Geodesy. The data of GPS-observations were processed by CEGRN processing centres giving new insight of geodynamic activities in this research area.



Figure 2. The Central European GPS Geodynamic Reference Network (CEGRN)

THE ROLE OF SPACE GEODESY IN DEFORMATION MONITORING

Caused by geophysical processes in the Earth and by environmental changes, mass transport is induced which is often directly related to earthquakes. To describe these changes and its influence with the goal to define the three main tasks of geodetic research "The Global Geodetic Observing System" (GGOS, 2007) was established, Fig. 3.

These three main tasks are:

- 1) The definition of the geometric shape of the Earth, namely continents, oceans and ice-masses in time.
- 2) The determination of the irregularities of the Earth rotation that means the actual position of the rotation axis, and the change of the rotation speed.
- 3) The determination of time dependent gravity field changes (geoid) which is the base for height determination of the continents and the oceans.

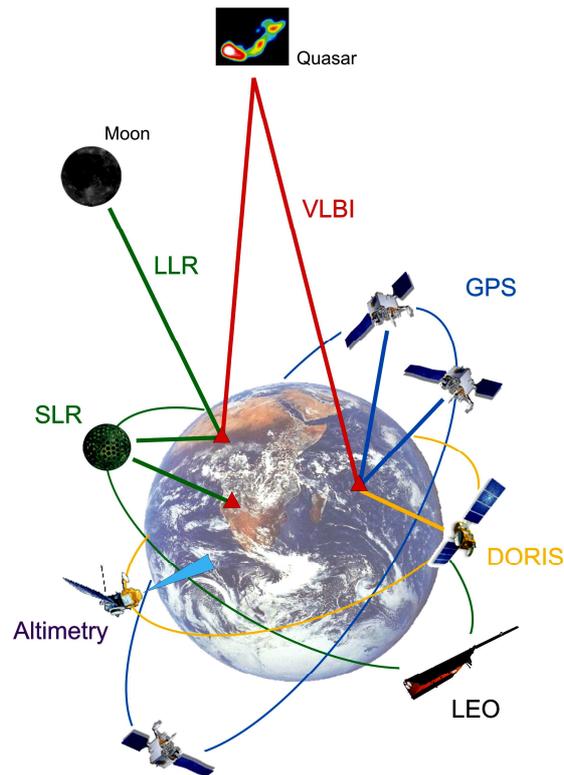


Fig. 3. VLBI and Satellite techniques in the Global Geodetic Observing System GGOS (Source: GGOS).

These parameters must be determined with a relative accuracy of 1 to 10^{-9} over several decades of time for which data from VLBI and several different satellite-missions are to be analyzed together.

THE RIGID EARTH

The geometry of the rigid Earth is determined with Global Navigation Systems, mostly with the USA GPS and the Russian GLONASS but in future also with the European Galileo System and others. Global geodetic networks with several thousand referent-points over continents are in the last decades systematically growing to a system for continuous position determination. Time series of such observations allow to analyse the position change and define the deformation of the lithosphere (as in Blewitt and Clarke, 2003).

Plate Tectonics, Stress-strain analysis caused by hydrology and atmosphere or the Earth and ocean-tides in a range of several centimetres could on such way be monitored from secular, annual to periods of seconds, so earthquake waves can be analysed. For the rigid Earth in a terrestrial reference system, like the ITRF2008, modern GNSS techniques enable position determination at the mm level. In combination with radio astronomic observations of Quasars (VLBI) Earth rotation vector variation can be determined.

THE OCEANS

For about 20 years the usage of altimeter satellites enables the determination of the sea surface and of the sea level change. Based on a very precise satellite orbit determination the height of the sea level is measured from the satellites. An average of 3-7 square km area is determined with an accuracy of 2-3 cm. That gives an information of the momentous sea level and the water mass distribution. As the same area is re-measured after two to four weeks when the satellites have the same orbits an excellent tool for dynamic change detection is given. These data are the base of all studies for global sea-level

changes. Also these data are used for the determination of big sea mass circulation and the influence of climate changes on the sea-level. From the 2007 annual report of the Intergovernmental Panel on Climate Change (IPCC, 2007) the estimated sea level rise is + 3,2 mm/year. Through the interpretation of climatic models and the ocean temperature rise, thermo stretching of the ocean water causes only 1,1 mm/year. So the rest of 2,1 mm/year are affected by other parameters such as mass transport through ice melting, hydrologic circulation, and others (Lombard et al., 2007).

THE GRAVITY FIELD OF THE EARTH

The gravity field reflects the inner structure and the mass contribution of the Earth. Mass transport and dislocation caused by earthquakes, tectonic of plates, sedimentation also ocean, river and sea transport, as well as ice masses and atmosphere can be determined and quantified through gravity measurements (Rummel et al., 2002). Especially to measure these phenomena from 2002 through a cooperation of NASA and Geoforschungszentrum Potsdam the Satellite-mission GRACE (Gravity Recovery and Climate Experiment) is running (Tapley et al., 2004). The main principle of these Satellite-mission is based on an accurate measurement of the distance between two satellites in the same orbit of about of 400 km. The distance between the satellites of about 200 km is varying due to mass anomalies in the Earth. From these distance changes the anomalies in the Earth gravity field can be calculated (Swenson, S. and Wahr, J., 2002). A big advantage of these new measuring principle is (similar as for altimeter data) in high resolution periodic monitoring of the global gravity field change. So if we presume an adequate column of water the resolution of these measurements could be compared as a change of the water column in 3 mm of height in an area with 400 km radius. For the first time there is a strong tool for direct measurement of water reservoir changes of great rivers. (Schmidt et al., 2006). Starting in the 70-ties, Laser satellite data are used for determination of the stationary gravity field and the Earth shape.

A compilation of GRACE and GPS time series data where deformations of the Earth crust under the load of water could be calculated showed good accordance, in particular especially in the Amazonas area where huge loading deformations occur. Earth crust change with annual periods in height of more than 2 cm for the stations in Brasilia are in good accordance with data from hydrologic models (Schmidt et al., 2006). The same principles will be applied for the Mediterranean and especially the Adriatic sea. In addition a comparison with stationary gravity measurements from the middle of the Adriatic Sea (Island Hvar) could improve these models.

GRACE can also directly be used for the measurement of mass changes in the oceans. In combination with satellite altimeter data and ocean models the temperature induced rise of sea level can be obtained and the global temperature and climatic models validated.

The satellite mission GOCE (Gravity Field and Steady State Global Ocean Explorer) is one of the most technically sophisticated missions in the programme of (European satellite agency) ESA. The measurements are based on three pairs of highly sensitive accelerometers mounted in a three axis orthogonal system (Rebhan et al., 2000). These extremely sensitive accelerometers are used for the gravity field determination with a highly improved accuracy. In combination with GRACE the GOCE system will cover an area of 100 km (radius). In addition the local geoid anomalies can be better modelled and interpretations related to hazard mitigation can be improved.

ENVIRONMENTAL EFFECTS

The Institute of Geodesy Darmstadt is performing research on Spatial and Temporal Resolution Limits for Regional Mass Transport and Mass Distribution (STREMP), Fig. 4. The Mediterranean Sea was used as a test-region for an interdisciplinary mission. In cooperation with the Bonn University and the University of Oldenburg, the resolution of satellite data, the accuracy of the common models and the calculation algorithms are analyzed.

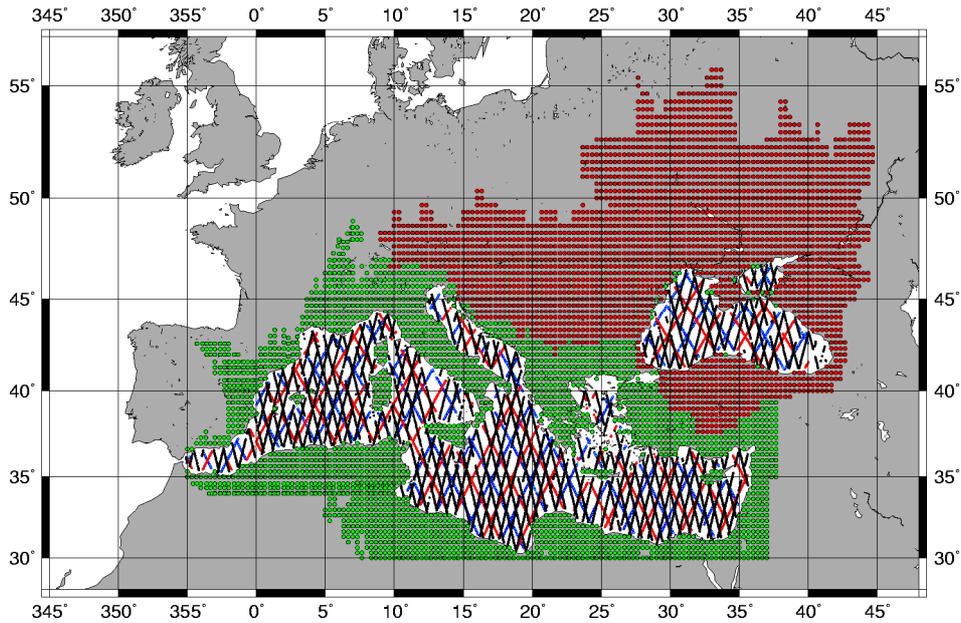


Figure 4. STREMP experimental area (Mediterranean and Black sea) covered by satellite altimeter data the hydrological model areas used for run-off calculation.

The cooperation of altimetry, oceanography and oceanographic model are used to assess the mass changes of the Mediterranean and the Black Sea. The GRACE data enables direct determination of mass changes dm/dt , however they have to be corrected by hydrological models including rainfall and evaporation, Fig. 5.

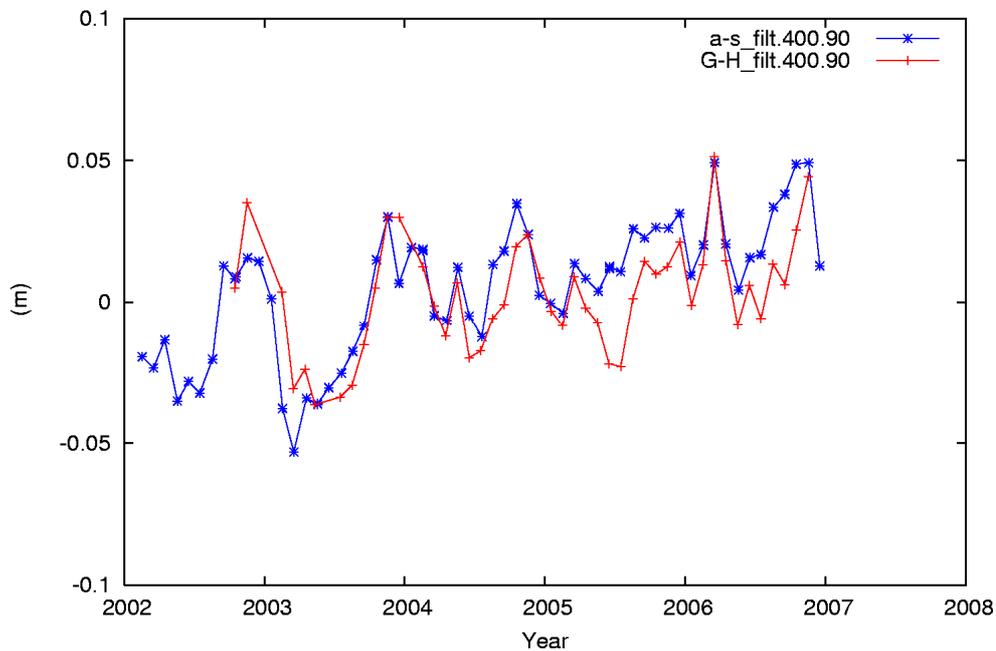


Figure 5. Mass variation in the Mediterranean sea presented as a sea-level change. (stars = satellite altimeter data, crosses = GRACE).

The combination of altimeter data, GRACE, gravimetric and water level measurements with tide gauges on several points at the Adriatic coast will enable better modelling. Promising results of mass changes and the associated model improvements are shown in (Fenoglio et al., 2006), (Fenoglio et al., 2012). It is to be expected that such calculations of mass changes are in accordance with our planned gravity measurements.

LOCAL EFFECTS OF LOADING

Based on the mass changes determined by space geodesy, the local effects of loading can be modelled and be taken into account. For example seasonal and inter-annual oscillations, with peak-to-peak amplitudes of up to 20-30 mm, have been observed in the height series of permanent GPS stations (Blewitt et al., 2001), (Zerbini et al., 2001) on global to local scales. Some local geodynamic networks in Croatia (Medak, 2006) and results from measurement campaigns (Altiner et al., 2006) and the CROPOS net will be used and analysed for deformations and geodynamics. The CROPOS (Croatian Positioning System), consists of a net build up with about 30 permanent GNSS points, Fig. 6.

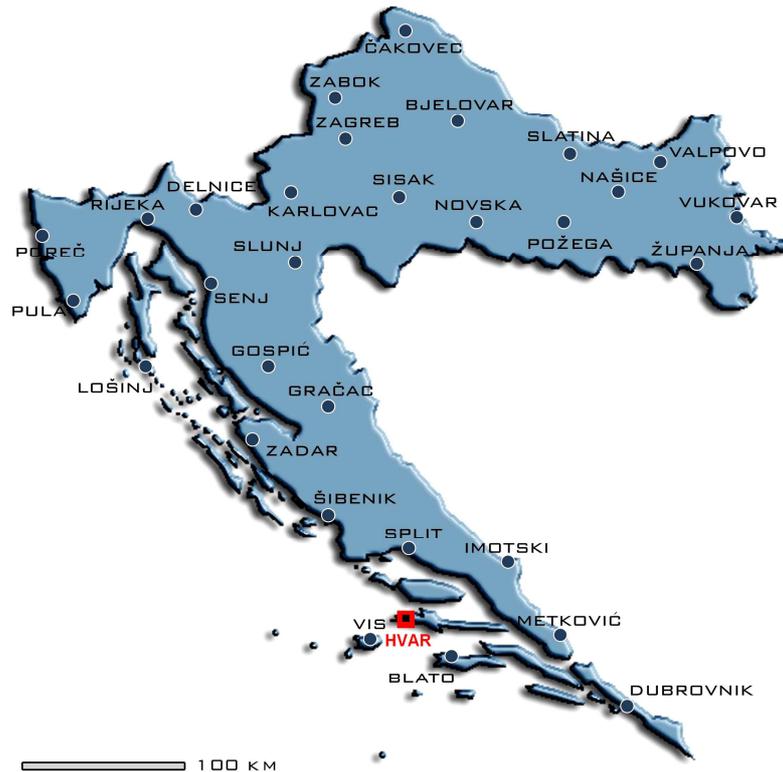


Figure 6. Stations of the CROPOS - Croatian Positioning System

This net will be analysed for geodynamics, the detection of continental deformations and also deformations of the Adriatic micro-plate especially under loading effect influenced by the Adriatic sea. Such fluctuations mostly in height, but also in position can partly be explained in terms of atmospheric tides and hydrological variability (e. g. van Dam et al., 1997), (Chapman, 1970), (Schulz et al. 2009). Depending on the site location (continental, coastal or island) the associated loading effect may be of different amount. In addition variations in ocean bottom pressure (non-tidal ocean loading) driven by the sea-surface height variability as well as by density changes of the water column can also load and deform the Earth's crust (van Dam et al., 1997). A clear correlation of height residuals of the Adriatic tide gauge stations and non-tidal ocean loading, changes the height in the 2-5 cm range (Zerbini et al., 2004).

THE INSTRUMENTATION

At the time the instrumentation aimed for the Hvar observatory is tested and temporarily installed in a shaft at the RGN Faculty of the University Zagreb. The installed instruments at this station are: a GNSS Trimble receiver, an improved and totally modernised LaCoste & Romberg ET recording

gravity-meter, with a capacitive sensor equipped tilt-meter, and a vertical extensometer. Several temperature measuring sensors are installed directly in the instruments and also a meteorological station (pressure, temperature, humidity) is installed. All data are sampled digitally with a one second interval with a data-logger and via LAN transferred to a host computer for registration. During a three months of registration, Fig. 7, 8 and 9, scale and sensitivity tests have been done. From the simultaneous registration of these several channels, Figure 7, cross correlation computations and a harmonic analysis (Wenzel, 1996) will be performed. As a result of these calculations we expect to get the elastic parameters and the resonant frequency for the building and the site.

As late as all instruments and data transfer will operate perfectly we will install them at the Hvar observatory. Then the data transfer from Hvar will be via internet to RGN faculty Zagreb where the data will be registered and processed. In future real time on-line processing is planned. So besides exact real-time high rate GPS position measurements, continuous determination of the gravity change, local deformation measurements and geophysical measurements of shallow and deep strata, all along with detailed geological interpretations, are foreseen for the station Hvar.

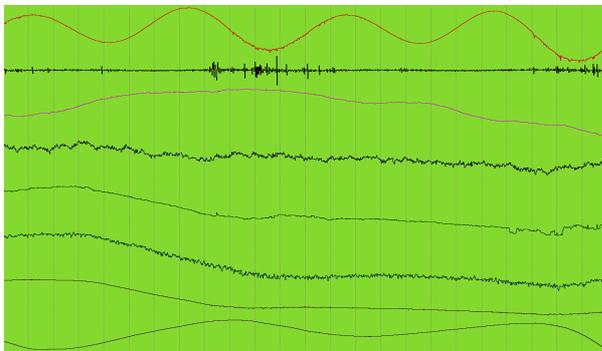


Fig. 5 A part of the 8-channel registration

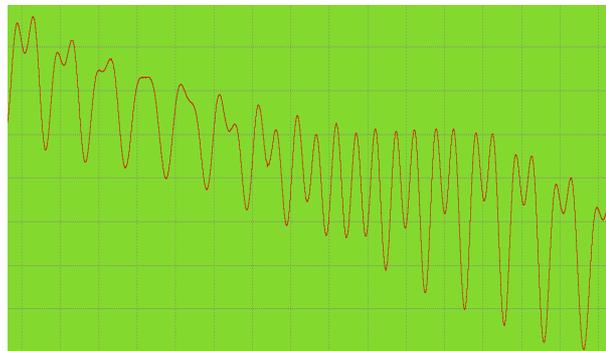


Fig. 6 Earth-tides registered with the ET gravity-meter

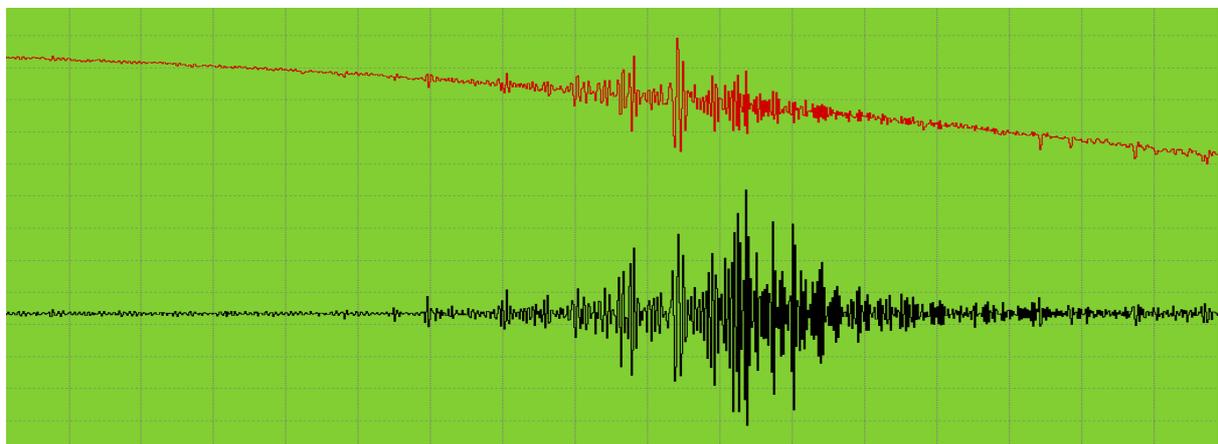


Fig. 7 A simultaneous earthquake registration with the tilt-meter (black) and the gravity-meter (red)

The complexity of local and global modelling based on terrestrial and satellite data necessitates interdisciplinary cooperation of different disciplines. The modern GNSS methods enable very high precision position determination (Altiner et al., 2006). In combination with space and local terrestrial deformation and gravity measurements the elastic parameters of the Earth crust and its structure can better be explained. So fissures and faults of the crust can be determined what is of great importance for earthquake prognostics and precaution (Čolić, 1990).

Terrestrial observations, like those at the Hvar observatory, will in future be important for local densification, calibration and the regional hazard prevention strategy of a global observing system.

REFERENCES

- Altiner, Y., Marjanović, M., Medved, M., Rašić Lj. (2006). Active deformation of the northern Adriatic region. Results from the CRODYN geodynamical experiment. *The Adria Microplate: GPS Geodesy, Tectonics and Hazards, NATO Science Series*, Springer 257-267.
- Blewitt, G., Lavallée, D., Clarke, P. and Nurutdinov, K. (2001). A New Global Mode of Earth Deformation, Seasonal cycle detected. *Science*, **294**, 2342-2345.
- Blewitt, G. and Clarke, P.J. (2003). Inversion of Earth's changing shape to weigh sea level in static equilibrium with surface mass redistribution. *Journal of Geophysical Research - Solid Earth* **108(B6)**, 2311, doi:10.1029/2002JB002290.
- Caporali, A., Aichhorn, C., Becker, M., Fejes, I., Gerhatova, L., Ghitau, D., Grenczy, G., Hefty, J., Krauss, S., Medak, D., Milev, G., Mojzes, M., Mulic, M., Nardo, A., Pesec, P., Rus, T., Simek, J., Sledzinski, J., Solaric, M., Stangl, G., Vespe, F., Virag, G., Vodopivec, F., Zablotzkyi, F. (2008). Geokinematics of Central Europe: New insights from the CERGOP-2/Environment Project, *Journal of Geodynamics*. **45**, 4-5, 246-256.
- Caporali, A., Aichhorn, C., Barlik, M., Becker, M., Fejes, I., Gerhatova, L., Ghitau, D., Grenczy, G., Hefty, J., Krauss, S., Medak, D., Milev, G., Mojzes, M., Mulic, M., Nardo, A., Pesec, P., Rus, T., Simek, J., Sledzinski, J., Solaric, M., Stangl, G., Stopar, B., Vespe, F., Virag, G. (2009). Surface kinematics in the Alpine-Carpathian-Dinaric and Balkan region inferred from a new multi-network GPS combination solution. *Tectonophysics*. **474**, 1-2, 295-321.
- Chapman, S. and Lindzen, R. (1970). Atmospheric Tides: Thermal and Gravitational. D. Reidel Publishing Company, Dordrecht, Holland.
- Čolić, P. K. and Marjanović Kavanagh, R. (1990). An attempt of earthquake prognostic from tilt-extensometer-measurements in combination with GPS in the earthquake-hazardous region near Zagreb. *Proceedings of the fifth international seminar and exhibition on earthquake prognostics*. Lagos, 2 – 6 December 1990.
- Fenoglio-Marc, L., Kusche, J. and Becker, M. (2006). Mass variation in the Mediterranean Sea from GRACE and its validation by altimetry, steric and hydrologic fields, *Geophys. Res. Lett.*, **33**, L19606, doi:10.1029/2006GL026851.
- Fenoglio-Marc, L., Rietbroek, R., Grayek, S., Becker, M., Kusche, J., Stanev, E. (2012 in press). Water mass variation in the Mediterranean and Black Sea, *J. Geodyn.*, doi:10.1016/j.jog.2011.06.007.
- GGOS, (2007), <http://www.ggos.org/>.
- IPCC, (2007), IPCC WG1 AR4 Report, Observations: Oceanic Climate Change and Sea Level, <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>
- Lombard, A., Garcia, D., Ramillien, G., Cazenave, A., Flechtner, F., Biancale R. and Ishii, M. (2007). Estimation of steric sea level variations from combined GRACE and Jason-1 data, *Earth Planet. Sci. Lett.*, **254**, 194-202.
- Medak, D. and Pribičević, B. (2006). Processing of Geodynamic GPS networks in Croatia with Gamit software, *The Adria Microplate: GPS Geodesy, Tectonics and Hazards, NATO Science Series*, Springer, 247-256.
- Rebhan, H., Aguirre, M., Johannessen, J. (2000). The Gravity Field and Steady-State Ocean Circulation Explorer Mission - GOCE, *ESA Earth Observation Quarterly* 66: 6-11, http://esapub.esrin.esa.it/eoq/eoq66/eoq66_goce.pdf.
- Rummel, R., Balmino, G., Johannessen, J., Visser, P., Woodworth, P. (2002). Dedicated Gravity Field Missions Principles and Aims, *J. Geodynamics* **33**:3-20.

- Schmidt, M., Han, S.-C., Kusche, J., Sanchez, L., and Shum, C. K. (2006). Regional high-resolution spatiotemporal gravity modelling from GRACE data using spherical wavelets. *Geophys. Res. Lett.*, **33**, L08403, doi:10.1029/2005GL025509.
- Swenson, S., Wahr, J. (2002). Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research -Solid Earth* **107** (B9).
- Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F., Watkins, M.M. (2004). GRACE measurements of mass variability in the Earth system, *Science*, **Jul 23, Vol 305**, IS BN 5683, PP 3.
- van Dam, T.M., Wahr, J., Chao, Y., and Leuliette, E. (1997). Predictions of crustal deformation and of geoid and sea-level variability caused by oceanic and atmospheric loading, *Geophys. J. Int.*, **129**, 507-517.
- Wenzel, H.-G. (1996). The nanogal software: Earth Tide data processing package: ETERNA 3.3, *B.I.M.*, **124**, 9425-9439.
- Schulz, W.H., Kean, J.W and Wang, G. (2009). Landslide movement in southwest Colorado triggered by atmospheric tides, *Nature Geoscience* **2**, 863 – 866.
- Zerbini S., Richter, B., Negusini, M., Romagnoli, C., Simon, D., Domenichini, F. and Schwahn, W. (2001). Height and gravity variations by continuous GPS, gravity and environmental parameter observations in the southern Po Plain, near Bologna, Italy, *Earth and Planet. Sci. Lett.*, **192**, 267-279.
- Zerbini, S., Matonti, F., Raicich, F., Richter, B. and van Dam T. (2004). Observing and assessing non-tidal ocean loading using ocean, continuous GPS and gravity data in the Adriatic area, *Geophys. Res. Lett.*, **31**, L23609, doi:10.1029/2004GL021185.