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An Interdisciplinary Approach to Studying Seismic Hazard Throughout Greece.

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Abstract. This paper describes and reviews the progress of a three year (11/97-11/00) European Commission FP4 (Climate and Natural Hazards) funded project entitled GPS Seismic Hazard in Greece (SING), A major international interdisciplinary consortium is investigating and comparing strain derived using both geodetic and seismic methods.
The specific objectives of SING are to assess strain accumulation throughout Greece, to identify areas of high seismic hazard, to develop new and more efficient operational and computational methods for GPS, and to improve our understanding of the relationships between geodetic strain, seismic catalogues and geological data. New GPS networks have been installed in regions of significant hazard and initial computations have been carried out. To date, a primary result of SING is the integration of 33 historical geodetic data sets to provide a national strain map, giving the first full picture of geodetic strain in Greece and providing the basis for the setting up of the new geodetic networks.
This paper presents an overview of the project's goals, the methodologies employed and initial results.

Keywords. GPS, seismology, geodynamics, Greece, plate tectonics, geology, seismic hazard, strain accumulation.

1 Introduction

Greece lies within a region of intense intra-plate deformation. Three major plates (African, Eurasian and Anatolian) surround the region and induce both a highly complex and varied series of geophysical phenomena, described in figure 1. There are on average eight >M5 earthquakes annually in Greece Ambraseys and Jackson (1990), making the area both a natural scientific laboratory and region of extreme seismic hazard.

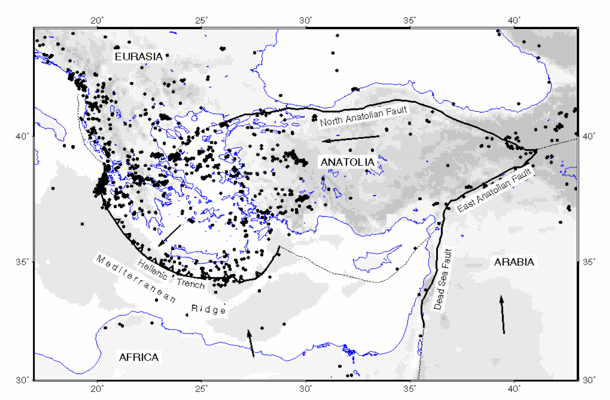

Fig. 1 The tectonics of the Eastern Mediterranean region. Earthquakes shown are M_b > 4.5 (<40km depth) between 1964 and 1993 from Clarke et al. (1998).

The aim of the three year GPS Seismic Hazard in Greece (SING) project is to identify areas of high seismic hazard in this highly tectonically active region. This is achieved by utilising a multidisciplinary approach whereby ground strain accumulation from precision Global Positioning System (GPS) positions is compared to geological, geophysical and seismic activity records. The region studied through SING extends from longitude East 20.5º to 28º and from latitude North 35º to 41.5º.

There have been a number of geodetic measurement campaigns in the region to study this phenomena in the last ten years, including, for example, Billiris et al. (1991), Kahle et al. (1996), and Clarke et al. (1998). This project aims to build on the successes of the previous projects through the combination of results, the extending and combining of geodetic networks and the identification and study of specific areas of seismic interest.

The overall goal from this GPS network is to obtain an integrated 'kinematic model' that will accurately describe (spatially and quantitatively) the geodetic strain distribution throughout Greece. This will then be integrated with the seismic catalogue and other geologic data to serve as a basic tool for seismic hazard assessment.

The project utilises a novel approach to data collection whereby a minimal number of GPS receivers occupy a large number of stations in an accurate and cost effective manner. Geodetic conclusions are expected from the approach with respect to the optimum observation strategies to obtain the necessary accuracy.

The task of seismic hazard assessment within zones of intra-plate deformation is entirely different in character and more complicated from that at plate boundaries where the main task is to monitor usually well defined fault(s) and to accumulate data that relate to the risk of future earthquakes on that fault(s). Where the deformation is spread out over a wider area, as it is in Greece, the primary task is to determine where, within the area, the tectonic strain accumulates most rapidly. Only then can the task of assessing hazards associated with slip on individual faults within the region begin.

One of the primary initial objectives of SING is to search and integrate all available strain data. To achieve this, a data-base of previously obtained geodetic data is being developed. Coordinates, velocities and strain rates determined by the groups involved in this proposal, and abstracted from publications of other groups will be integrated. Existing seismic hazards maps of Greece, computed by utilising different methodologies, are to be collected in order to delineate areas of high seismic hazard based on pure seismological data.

The work carried out in this project is of significant importance for more reliable seismic hazard assessment, for land use planning, GPS data capture and processing methods and to help towards earthquake surveillance. The application of the techniques used and developed in this project is of extreme importance in other areas of the world, especially in areas where money is at a premium.

To summarise, the four primary objectives of SING are;

- To identify areas of high seismic hazard in Greece.
- To assess strain accumulation throughout Greece, and in specifically targeted areas.
- To develop new and more efficient operational and computational procedures for the use of GPS in the delivery of high quality positional data within regional and global control networks.
- To improve the understanding of the relationship between strain accumulation and seismic hazard by integrating geodetic derived strain information with existing seismic catalogues and other geological data.

2 Methodology

The approach undertaken uses GPS geodetic techniques to provide the spatial and temporal accumulation of strain across Greece and compares this to the regional seismic and geological data to ameliorate understanding of the mechanisms of earthquake hazards.

The target is to observe 300 stations annually using geodetic quality GPS receivers. The siting and repeat occupation intervals of stations follows a three-tiered approach; small station spacing in areas of identified high seismic risk, large equidistant spacing country-wide (to fill in gaps from previous networks) and a number of permanently or semi permanently occupied sites. A forced antenna centring mechanism has been developed for the project, allowing the antenna to be screwed directly on to the station mark. GPS data from both permanent International GPS Service (IGS) sites and semi-permanent stations occupied for relatively short time periods (three days plus) is also collected. This allows the stations in Greece to be linked to the International Terrestrial Reference Frame (ITRF) as well as producing an observation strategy whereby local stations can be observed with respect to 'local' permanent (during the observations) stations, reducing baseline lengths and observation periods. New GPS networks have been installed in regions of significant hazard,

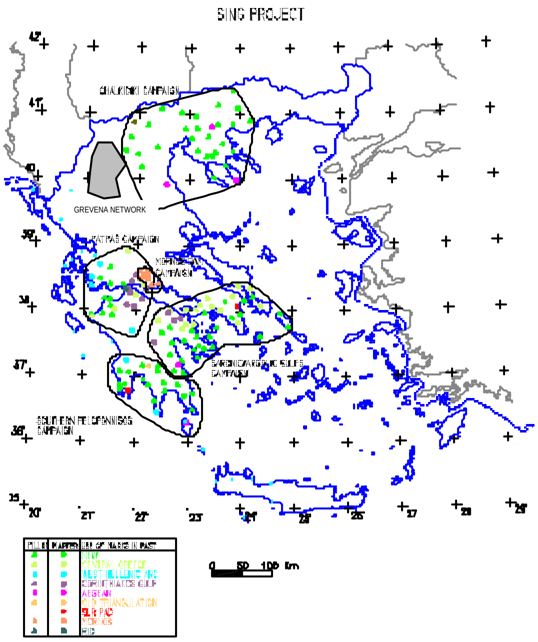

Fig. 2 Observed stations in the SING project during 1998.

figure 2; Chalkidiki, Patras, Saronic/Argolic Gulfs and Southern Peloponnisos. Further measurements were made during 1998 at the existing networks of Grevena, Mornos Dam and the Western Hellenic Arc.

The efficient monitoring of the SING network requires the consideration of alternative strategies to the more commonly adopted permanent or campaign style of GPS data collection. As part of this work, the concept of a quasi-continuous approach has been developed. This approach is one in which small numbers of receivers are moved from station to station as and when they (and the logistical support) are available. In this way large numbers of stations can be monitored in a flexible way without the need for either a dense array of permanently located receivers or campaigns involving large groups of people and the associated complex logistics. The receivers can be quickly mobilised to regions of seismic interest if necessary. The practical implementation of a quasi-continuous procedure involves the establishment of temporary base stations whilst other receivers are moved in the local regions. The efficiency of the system is then a function of the time spent on each station and the distance between the stations, and one goal of the project is to investigate these issues. The particular observation system that is used consists of two permanent observing receivers at ITRF linked sites within Greece, a limited number of semi-permanent stations (observing for a few days) and a small number of mobile GPS receivers moving from point to point in a quasi-continuous manner.
The kinematic GPS observing technique will be used to measure road profiles in the Korinthos and Evia regions.

Existing seismic hazards maps of Greece, computed using different methodologies, have been collected in order to delineate areas of high seismic hazard based on pure seismological data. These maps can be categorised into two groups depending upon the approaches used to compute them. The first includes seismic hazard maps computed on the basis of seismological data without considering geological or other geophysical data. The second category includes hazard maps computed on the basis not only of pure seismological data but also of seismotectonic data and other geophysical information. An estimation of the rates of crustal deformation in some specific seismotectonic zones of Greece, from earthquake moment tensor mechanisms, has been made. Owing to different fault planes solutions for the same earthquakes being available, the rates of crustal deformation cannot be uniquely determined. However, focal parameters are considered as being highly reliable, in the cases where they are obtained by computing synthetic seismograms. The analysis was made using Kostrov's formulation according to the hypothesis that the average strain rate of the seismic deformation in a region is a function of the sum of symmetric moment tensors, the seismogenic volume of the deforming zone, the rigidity and of the time considered in the analysis. Emphasis has been given on estimating seismic hazard based on the physical parameters of the seismogenic fault, such as:

- fault area
- slip rate
- seismic moment.

All these parameters were considered for computing the prior estimates of the seismicity together with the mean rate of earthquake occurrence.

3 GPS Processing Strategy

GPS data processing has been carried out with the Bernese, Rothacher and Mervart (1996), and GIPSY-OASIS II (GIPSY), Webb and Zumberge (1997) scientific software packages. IGS raw data, precise orbit and earth orientation products have been used in the processing along with NOAA antenna phase centre information. Investigations into baseline repeatability's have been carried out to aid the scaling of the formal errors output by the GPS processing packages allowing more realistic estimates of attainable precision to be calculated.

GPS processing methods follow two strategies;

i) Calculate an average position for the permanent station CG54 (in the ITRF) over the period of observations of the local region being measured. This is calculated either through the Precise Point Positioning (PPP) technique using GIPSY, Zumberge et al. (1997), or through baselines to a sub-set of 'A' class IGS sites using Bernese. The coordinate is transformed to ITRF 96 at the mid point of the observations and the weighted average coordinate taken.
The PPP strategy solves for each station individually using a minimum of 24 hours of raw GPS data, fixed precise orbits, satellite clock correction files, satellite shadow event files and precise earth orientation parameters.

The two methods used different processing software and philosophies (only similarities being the orbits, earth rotation parameters and antenna phase centre offsets used) and were compared. Eight daily solutions were combined for the two approaches and gave very encouraging solution differences of;

East (m)	North (m)	Vertical (m)
-0.0011	0.0082	0.0006

CG54 was then fixed and the semi-permanent site in the region of observations is calculated from all days of data in a network approach and the weighted average value taken.

ii) A daily network solution containing the fixed local semi-permanent station and the local stations is calculated.

The parameterisation and modelling of the atmosphere and GPS satellite and receiver locations, the motion of the earth and the receiver and satellite clocks is key to the highest quality processing. For example, with GIPSY;
Tropospheric modelling uses an elevation dependent model for the hydrostatic component and a random walk function for the water vapour content.
Transmitter and receiver clocks are estimated as white noise functions. Stations with high quality clocks (for example the Hydrogen Maser at Wettzell) have greater weight in the solution.

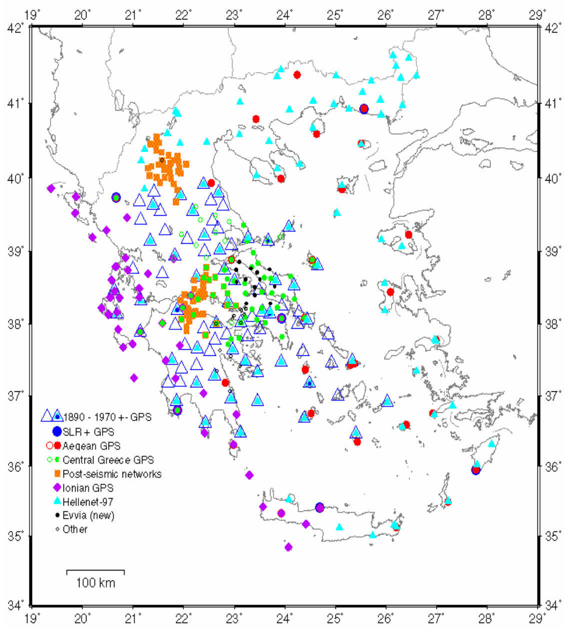

Fig. 3 Stations used in the combination of historical geodetic coordinate sets.

Formal errors are scaled using a combination of baseline repeatability measures and the χ^2 value.

4 Results

To date, a primary result of SING is the integration of 33 historical geodetic data sets, as seen in figure 3, from the past ten years to provide a velocity field, figure 4 and national strain map, figure 5. Coordinates and covariance matrices from the data-sets were combined into the same reference frame and an overall database, velocity field and strain map produced. The velocity field shows actual annual station velocities relative to a stable European reference frame. Open arrows show the motion of the Anatolian and African plates derived from the Nuvel 1A NNR model. The strain field is based on a spline interpolation of the whole velocity field. The strain field provides an accurate estimate across the Aegean Sea and mainland Greece, but does however wrongly determine strain at the southern extents, owing to the current lack of geodetic data in that region. The combined field gives the first full picture of geodetic strain in Greece and provides the basis for the siting of the new geodetic networks. This data-set will continuously evolve over the time span of the project and will be combined with new geodetic data from the region. The geodetic strain map is being used to compare with actual seismic ground deformation to gauge potentially hazardous regions throughout Greece.

The investigation into optimal observing methods

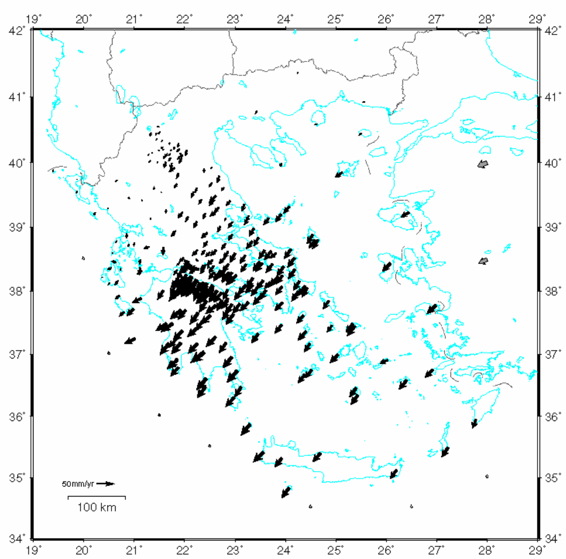

Fig. 4 Velocity field built up from the combination of 33 geodetic data sets relative to a stable European reference frame. The scale bar equals 50mm/year.

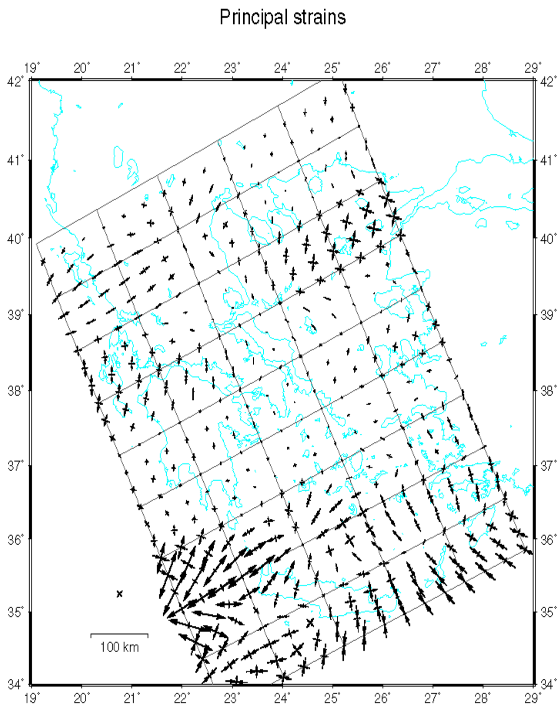

Fig. 5 Strain field based on a spline interpolation of the velocity field in figure 4. The scale bar equals 0.1ppm/year.

has led to an optimised observation strategy for the remaining project fieldwork/processing. The method involves looking at the relationship between processing strategy, baseline length, occupation time and precision. A subset of data collected during the 1998 SING fieldwork has been processed using the GIPSY software. Results indicate minimum observation periods necessary to obtain the required precision.

Approximately fifty subsets of SING data have been processed. Different length baselines between stations with greater than four hours of common data were used. The baseline was then processed four times; with all available data and with four, three and two hour sub-sets. The processing run with all data was assumed to be 'truth' and the three other runs compared to this The standard deviations of all differences between 'truth' and the computed sub-set values are shown in table 1. Figure 6 shows a plot of the differences from truth for the derived two-dimensional component.

Table 1. Standard deviation of component differences from the defined 'truth', (m).

s	4 hours	3 hours	2 hours
East	0.002	0.003	0.005
North	0.003	0.004	0.010
Vertical	0.011	0.016	0.020
2D	0.003	0.003	0.010

This study has shown that for baselines of up to 100km, there is no significant difference between the ‘truth’ and coordinates derived from either three or four hours of data. However for observation periods of two hours, the difference from truth changes dramatically and the solution becomes significantly less accurate. This conclusion has helped in observation planning for the 1999 fieldwork.

The results from this work have immediate implications for groups with limited resources (manpower, money or equipment) who wish to observe large GPS networks in a quasi-continuous manner, as long as similar careful processing strategies are employed.

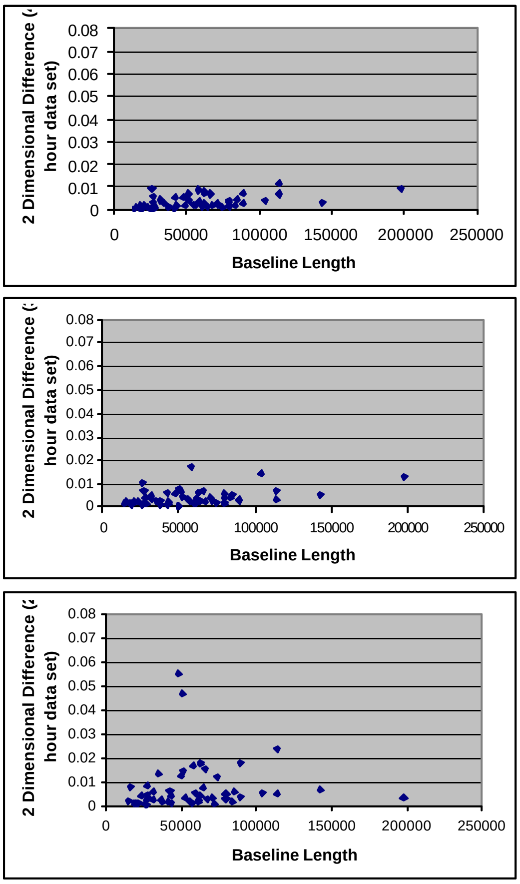

Fig. 6 Differences from truth for the derived two-dimensional component.

Results from initial investigations in to historical seismicity indicate that for northern Greece, seismic hazard seems to be overestimated using solely historical data and underestimated using only seismotectonic data. The next step is to incorporate information from different sources to reliably assess the seismic hazard within a seismogenic zone.

Of special interest is the situation that has been identified around the Gulf of Corinth where geodetically measured strain is as much as four times higher than that implied through the study of the seismicity and geology. Although there has been significant debate, for example Clarke (1998) and Roberts (1996), in the scientific literature on this topic, a full explanation of this difference has not yet been found. SING aims to add to the understanding of this anomaly.

Acknowledgements

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