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Interseismic ground velocities of the Central Apennines from GPS and SAR measurements and their contribution to seismic hazard modelling: preliminary results of the ESA CHARMING project

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Abstract: The contribution of space geodetic techniques to interseismic velocity estimation, and thus seismic hazard modelling, has been recognized since two decades and made possible in more recent years by the increased availability and accuracy of geodetic measurements. We present the preliminary results of a feasibility study performed within the CHARMING project (Constraining Seismic Hazard Models with InSAR and GPS), funded by the European Space Agency (ESA). For a 200 km x 200 km study area, covering the Abruzzi region (central Italy) we measure the mean surface deformation rates from Synthetic Aperture Radar and GPS, finding several local to regional deformation gradients consistent with the tectonic context. We then use a kinematic finite element model to derive the long-term strain rates, as well as earthquake recurrence relations. In turn these are input to state-of-the-art probabilistic seismic hazard models, the output of which is validated statistically using data from the Italian national accelerometric and macroseismic intensity databases.

Key words: *Active Tectonics, Seismic Hazard, SAR, GPS*

Introduction

The CHARMING project (Constraining Seismic Hazard Models with InSAR and GPS) is a feasibility study funded by the European Space Agency's (ESA) Support to Science Element (STSE) Pathfinders 2013 programme. The context of CHARMING is Probabilistic Seismic Hazard Assessment (PSHA), i.e. the scientific field which aims to quantify the probability that ground motion at a specified site will exceed some level of a given shaking parameter of engineering interest (e.g. Peak Ground Acceleration, PGA) during a specified future time frame The main aim of the project is to investigate whether surface deformation measurements, derived from GPS and Synthetic Aperture Radar (SAR) data, can be successfully incorporated into PSHA models and improve their quality. In particular, we investigate several aspects related to the marginal benefit provided by the integration of SAR compared to GPS alone, since to our best knowledge this project represents the first attempt worldwide to incorporate SAR measurements into PSHA models.

The areas of interest analyzed within the project include a large portion of central and southern Italy. A restricted development area, comprising the central Abruzzi region, is used for technique developement and validation. At a later stage the developed methods shall be applied to a wider experimental area (larger rectangle in Fig. 1). For these areas we generate interseismic velocity maps, using a combination of ~100 permanent GPS stations (Fig. 1) and measurements derived from coast-to-coast acquisitions of the ERS-1/2 AMI, ENVISAT ASAR and ALOS PALSAR satellite SAR sensors (Fig. 2). The geodetic measurements are screened to exclude contributions of non-tectonic origin (e.g. subsidence). Subsequently, a kinematic finite element model and a tapered Gutenberg-Richter model are applied to the mean velocity measurements to derive long term strain rates and earthquake rates, i.e. the number of earthquakes in a given time period above an established magnitude threshold, Finally, state of the art PSHA modelling techniques are used to generate probabilistic models for PGA and other shaking parameters. A statistical validation of the PSHA model output is carried out, using data from national accelerometric and macroseismic intensity databases.

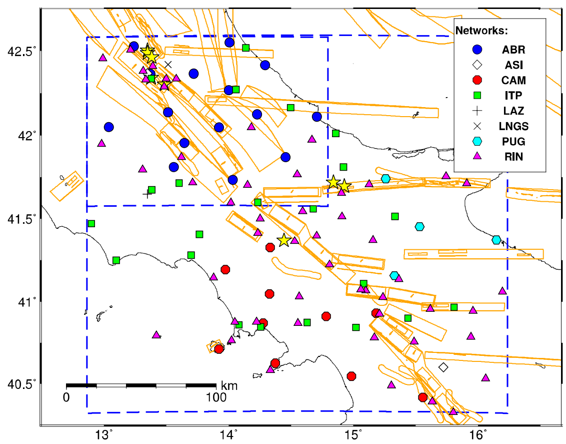

Figure 1: GPS stations and networks within the development (smaller) and experimental (larger) areas (dashed blue rectangles). Orange polygons represent composite and individual seismogenic sources according to the DISS v.3.1.1 catalogue (Working Group, DISS 2010). Yellow stars represent major earthquakes (Mw > 5.0), occurred since 1992.

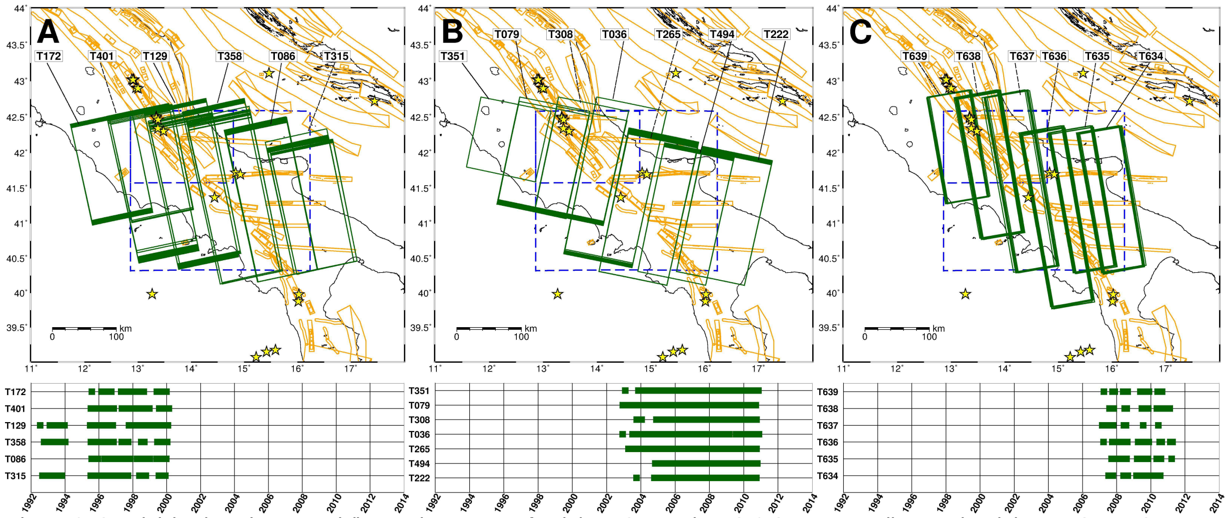

Figure 2: Spatial (top) and temporal (bottom) coverage for (A) ERS-1 and ERS-2 SAR ascending tracks, (B) ENVISAT ASAR descending tracks acquired with Imaging Swath 2 (IS2), and (C) ALOS PALSAR Fine Beam Single and Dual ascending tracks. See the caption of Fig. 1 for other plot features.

Geodetic data and methods

GPS data were processed with the method of Devoti et al., (2014) to obtain mean deformation rates. Only stations with >3 years of observations were retained. For the stations in the epicentral area of the the Mw 6.3 2009 L'Aquila earthquake, measurements were truncated to Dec. 31. 2008.

SAR image processing was performed with the combined Persistent Scatterer and Small Baseline approach of (Hooper et al., 2008), implemented in the StaMPS (Stanford Method for Persistent Scatterers) software. One of the tracks (ENVISAT 308 descending) was independently processed with the Small Baseline Subset (SBAS) technique of (Berardino et al., 2002). Ascending and descending passes of the ENVISAT and ERS-1/2 satellites and ascending passes of the ALOS PALSAR sensor (Fig. 2) were processed to derive SAR line-of-sight (LoS) deformation rate maps. These were then calibrated with GPS measurements, projected onto the LoS, to ensure a common reference frame and to correct residual long-wavelength errors in the SAR measurements arising from atmospheric propagation, orbital uncertainties and other sources (Marinkovic and Larsen, 2013). East and Up Cartesian deformation components can be derived in regions of overlap between at least one ascending and one descending SAR acquisition.

In the project's development phase, two experimental approaches are also investigated. The first consists in the application of the Intermittent SBAS (ISBAS) approach (Sowter et al., 2013), which can potentially provide a significant increase in the coverage of the LoS measurements. The second is based on a multi-temporal extension of the Spectral Diversity or Multi Aperture InSAR (MAI) technique (Scheiber and Moreira, 2000; Bechor & Zebker 2006), and could potentially provide a high sensitivity also to the flight-path (~N-S) deformation component.

Discussion

Within the development area, the mean deformation rates from GPS and SAR show in general an excellent level of agreement. An example is shown in Fig. 3, for ENVISAT ASAR descending track 36, for which the differences show a standard deviation of 1.5 mm/year in the SAR LoS (Fig. 4). Our preliminary results also exemplify the complementarity of these two measurement techniques in the Central Apennines. While the GPS is essential to constrain the long-wavelength patterns (>30 km), the SAR can potentially "fill in the gaps" between GPS measurements, thus defining more clearly the spatial extent of features and the location of transition zones.

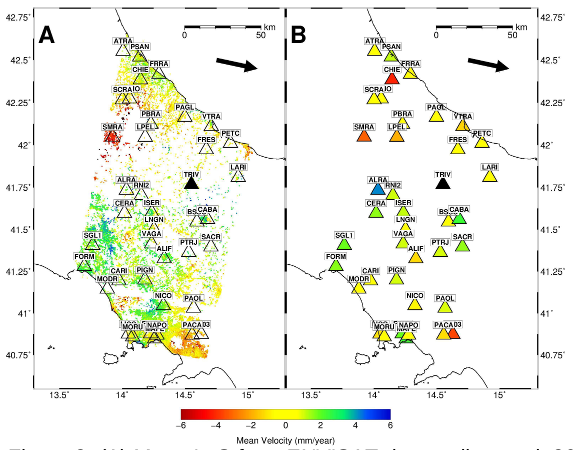

Figure 3: (A) Mean LoS from ENVISAT descending track 36 and (B) from GPS projected onto the SAR LoS. Positive and negative values indicate motion towards and away from the radar respectively. Measurements are referred to the location of the TRIV station. SAR velocities represent an average of measurements in a 1 km radius from the GPS stations.

A preliminary analysis of the GPS data highlights several signals ascribable to the local tectonics. The GPS vertical component (Fig. 5A) shows an overall NW-SE oriented uplift along the central Apennines from 0.5 to more than 2 mm/yr. This long-wavelength velocity pattern could be attributed to the general NE-SW oriented extension of the Apennines chain (D'Agostino et al., 2001). Some local subsiding stations are also recognized, namely SMRA, CHIE, LPEL and VTRA. For the latter three, the subsidence is likely to be very local. However, the SMRA subsidence, possibly associated to the combined action of sediment compaction and ground water pumping, appears to have a larger spatial scale in the SAR measurements (Fig. 3A), so that a tectonic contribution cannot be entirely excluded.

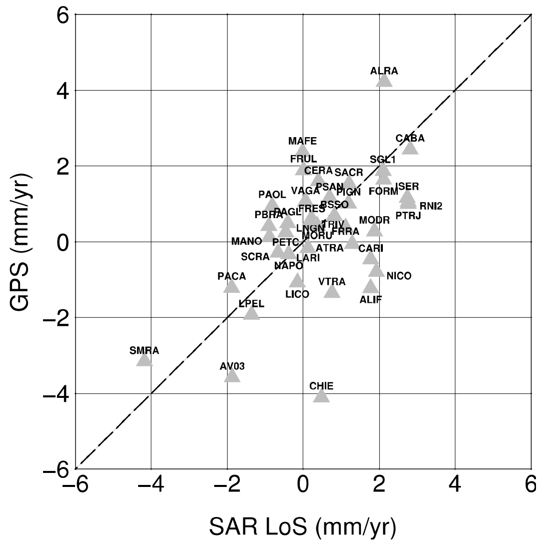

Figure 4: Scatter plot of InSAR (descending ENVISAT track 36) and GPS velocities (projected along the SAR LoS).

The GPS east and north velocities (Fig. 3A and 3B) show a regional pattern broadly consistent with the NE-SW Apenninic extension. At a more local scale however, we observe interesting velocity gradients between the ALRA, RMI2, CERA and ISER GPS stations, in the area north and east of PBRA and north INGP station. In the first case a > 1 mm/yr extension between the SORA-BLRA-VVLO-OTRA block, with respect to the ALRA-RNI2-CERA one, can be detected. The same area shows shortening velocity gradients in the GPS North component (> 1 mm/yr), resulting in a general NE-SW oriented left-lateral deformation zone located between the Matese mountains, to the south, and the Marsica ones, to the north. Although the processed SAR data is not centred on this area, the resulting LoS velocity map (Fig. 3A) seems to show similar deformation patterns.

North of PBRA station, we observe two blocks (PBRA-LPEL and ATRA-PSAN) moving eastward more quickly (from 1 to > 2 mm/yr) than CDRA-OVRA, SCRA-MANO and CHIE-FRRA blocks. In the same areas, for the North component, a N-S shortening (~ 1 mm/yr) between the PBRA-MANO-CDRA-OVRA block and the CHIE-FRRA-PSAN-ATRA one can be detected. Thus, the resulting deformation pattern is a NE movement of the Maiella mountain zone (PBRA-LPEL) with respect to the Chieti (CHIE) one (i.e. a shortening) and a northward movement of the Gran Sasso zone (CDRA) with respect to the Chieti one, resulting in a general NE-SW oriented extension. SAR velocities seem compatible with these patterns, even though further processing of all adjacent tracks from all sensors is needed to confirm these trends.

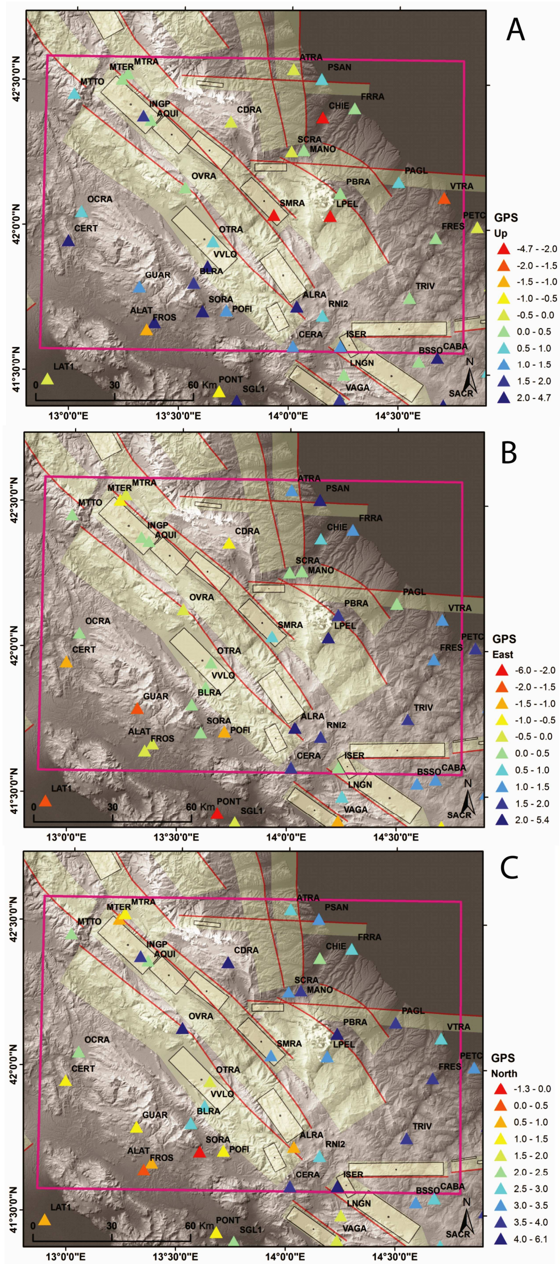

Figure 5: UP (A), East (B) and North components of the GPS velocities from Devoti et al. (2014), development area (purple rectangle) and DISS catalogue seismic sources.

Another interesting velocity gradient concerns the NE part of the development area, in which the MTER-MTRA block is moving westward (~1 mm/yr) and southward (~2 mm/yr) with respect the MTTO-INGP-AQUI block, which shows eastward and northward movements. These velocities result in a left-lateral deformation zone located north of L'Aquila (AQUI), where some seismic sources give place to others to the north. This structural setting is very similar to that of the southern side of the development area, near the CERA station, where we also observe a southward interruption of the main seismic sources, which give place to other structures. Moreover, comparing the GPS data distribution with historical data (Rovida et al., 2011) and seismological data (http://iside.rm.ingv.it) in the timespan of the geodetic measurements (1992-2008 period), it is apparent that in both time intervals these two deforming areas are characterized by an intense seismic activity with respect to adjacent ones, thus strengthening a possible tectonic interpretation (Fig. 6).

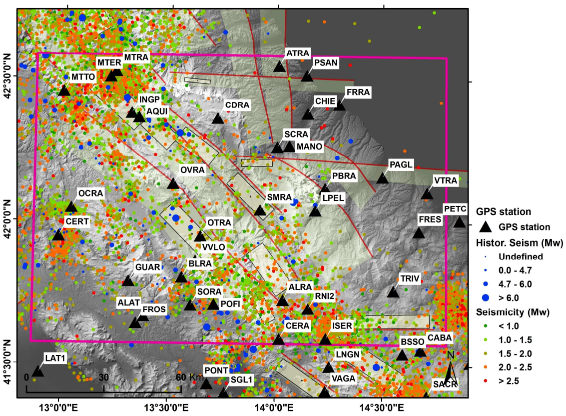

Figure 6: Historical (Rovida et al., 2011) and instrumental seismicity (1992-2008 period) (http://iside.rm.ingv.it), development area (purple rectangle) and DISS catalogue seismic sources.

A preliminary model run was carried out on the GPS data alone, within the development area of interest. We built a finite element model to derive long term average velocity fields accounting for the main tectonic features of the study area. From this model, we then calculated the earthquake rates, i.e. the number of earthquakes in a given time period above an established magnitude threshold, following the Seismic Hazard Inferred From Tectonics (SHIFT) approach (Bird and Liu, 2007; Carafa and Kastelic 2014). Finally, state of the art PSHA modelling techniques were used to generate probabilistic models for horizontal peak ground acceleration (PGA) and other shaking parameters. Our preliminary results, in terms of PGA with 10% probability of exceedance in 50 years on hard ground (Fig. 7), show that expected PGA exceeding 0.2g characterize large part of Apennines and, in particular, two areas have the highest level of hazard with values exceeding 0.4g.

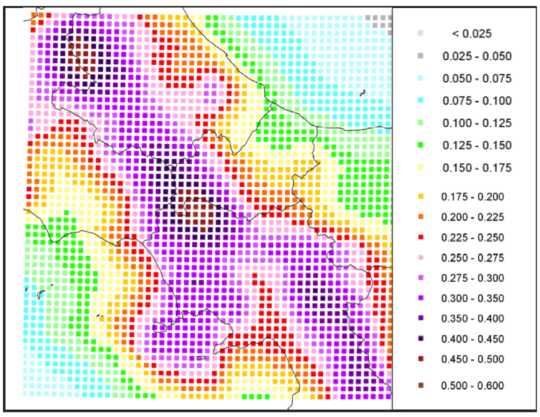

Figure 7: Seismic hazard map showing the PGA distribution with 10% probability of exceedance in 50 years, computed on hard ground (VS30 > 800 m/s) and using the Akkar et al. (2014) ground motion model.

A statistical validation of the PSHA model output was carried out using data from the national accelerometric and macroseismic intensity databases. Our first results suggest that our model is not rejected by the observations, thus supporting the viability of our approach for seismic hazard purposes.

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References

Akkar, S., Sandıkkaya, M. A., & J.J. Bommer, (2014). Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. Bull. Earthq. Eng., 12 (1), 359-387, doi: 0.1007/s10518-013-9461-4.

Bechor, N.B.D. & H.A. Zebker, (2006). Measuring two-dimensional movements using a single InSAR pair. *Geophys. Res. Lett.*, 33, L16311, doi:10.1029/2006GL026883.

Berardino, P., G. Fornaro, R. Lanari & E. Sansosti, (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans. Geosci. Remote Sens.*, 40(11), 2375–2383. 2002.

Bird, P., & Z. Liu, ,(2007). Seismic hazard inferred from tectonics: California.Seismological Research Letters, 78,1, 37–48. doi:10.1785/gssrl.78.1.37

Carafa, M. M. C., & Kastelic, V., 2014.Earthquake rates inferred from active faults and geodynamics: the case of the External Dinarides.Bollettino Di Geofisica Teorica Ed Applicata, 55,1, 69–83.

D'Agostino, N., R. Giuliani, M. Mattone & L. Bonci, (2001). Active crustal extension in the Central Apennines (Italy) inferred from GPS measurements in the interval 1994–1999. Geophysical Research Letters, Volume 28, Issue 10, pages 2121–2124

Devoti, R., G. Pietrantonio & F. Riguzzi, (2014). GNSS networks for geodynamics in Italy. Fisica de la tierra, Vol. 26, 11-24.

Hooper A., (2008). A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches. *Geophys. Res. Lett.*, Vol. 35, L16302, doi:10.1029/2008GL034654.

Marinkovic, P. and Y. Larsen (2013). Consequences of long-term ASAR local oscillator frequency decay—an empirical study of 10 years of data, European Space Agency, *in Proc. of the Living Planet Symposium (abstract)*, Edinburgh, U.K.

Rovida, A., R. Camassi, P. Gasperini & M. Stucchi (eds.), (2011). CPTI11, the 2011 version of the Parametric Catalogue of Italian Earthquakes. Milano, Bologna, http://emidius.mi.ingv.it/CPTI, DOI: 10.6092/INGV.IT-CPTI11

Scheiber, R. & A. Moreria, (2000). Coregistration of interferometric SAR images using spectral diversity, *IEEE Trans. Geosc. Rem. Sens.*, 38 (5), 2179-2191, doi:10.1109/36.868876.

Sowter A., L. Bateson, P. Strange, K. Ambrose, & M. Syafiudin, (2013). DInSAR estimation of land motion using intermittent coherence with application to the South Derbyshire and Leicestershire coalfields, *Rem. Sens. Lett.*, 4(10), 979-987, doi:10.1080/2150704X.2013.823673

Wessel, P & W.H.F Smith,(1998). New improved version of the generic mapping tools released. *EOS Trans. Am. Geophys. Union*, 79, 579.

Working Group, DISS, (2010). *Database of Individual Seismogenic Sources (DISS), Version 3.1.1: a compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas.* (http://diss.rm.ingv.it/diss/).