InSAR monitoring for seismic risk management: the Sentinel 1 contribution

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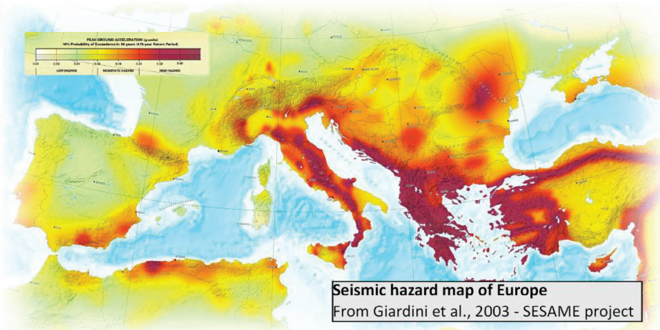
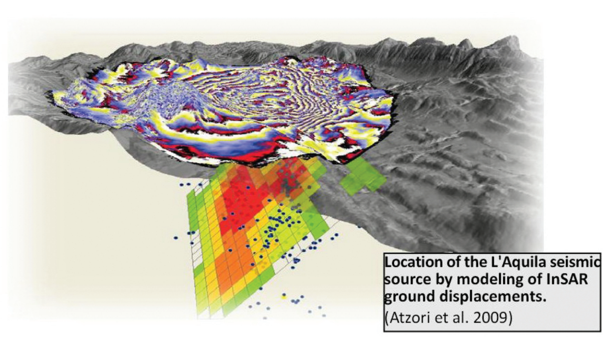
Abstract

We discuss the contribution of the new Sentinel-1 ESA mission in the field of seismic risk management, starting from the experience of the ASI-SIGRIS pilot project (www.sigris.it). SIGRIS demonstrated that the high repeat pass frequency guaranteed by the COSMO-SkyMed constellation resulted in a considerable improvement of the information products for the seismic crisis management, and showed the advantage of the synergetic use of InSAR data from complementary instruments/platforms.

The earthquake risk management cycle

Earthquake risk management phases	Goals	Activities
Assessment and Prevention	*Seismic hazard assessment*	**Estimate of ground motions due to seismic shaking in a certain area and within a certain period of time. Involves the mapping of active faults, the estimate of their kinematic parameters and of the rates of strain accumulation.**
	Mitigation	Policies and technical strategies to reduce the effects of earthquakes, usually in the long term. It mainly relies on reducing the vulnerability of man-made structures, e.g. by implementing strict building codes, and enforcing abidance to these rules.
	Preparedness	All activities aiming to reduce the impact of earthquakes on people. It consists of planning response and recovery measures, and of training the managers and the population to respond effectively to the earthquake emergency.
Warning and Crisis	*Earthquake damage assessment*	**Estimate of the effects of the earthquake on structures and people. Early damage assessment is a less precise inventory needed during the first 2-3 days from each mainshock to direct rescue and relief operations. Precise damage assessment is the longer process of structural classification of building damage, e.g. for insurance and compensation payments.**
	Earthquake scenario	**Consists of all activities for the analysis of the physical scenario for the seismic sequence. E.g. location and assessment of the seismic source, probability of occurrence of other shocks on nearby faults, mapping of ground deformation and surface faulting, mapping of triggered gravitational movements, etc.**
	Earthquake response	Implementation of plans for search and rescue, medical aid, evacuation, sanitary risk reduction, etc.


Seismic hazard map of Europe From Giardini et al., 2003 - SESAME project


Location of the L'Aquila seismic source by modeling of InSAR ground displacements. (Atzori et al. 2009)

Contribution of Sentinel-1 to seismic hazard and earthquake risk management activities

Exploiting the large amount of data acquired by previous ESA radar satellites (ERS 1-2, ENVISAT) and other missions (ALOS, Radarsat, Cosmo-SkyMed, TerraSAR-X), InSAR techniques have shown their potential to generate extremely valuable information for specific activities carried out for the seismic risk management (see a review in Salvi et al., 2012).

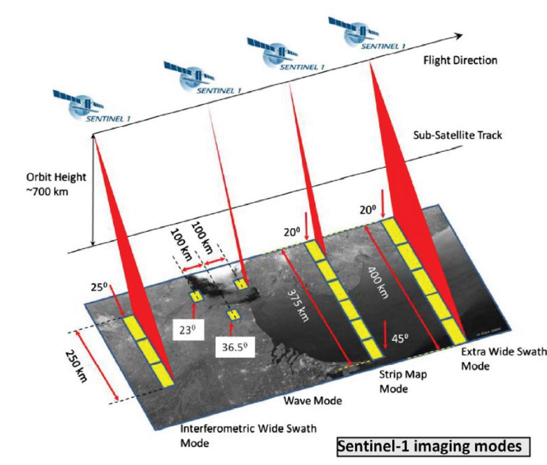
Nonetheless, to date only few attempts have been made to use InSAR data operationally, as a standard source of information for seismic risk management. The main reasons are: non-optimal data coverage, delayed data acquisition and release, limited data analysis/modeling capacities, cost of data.

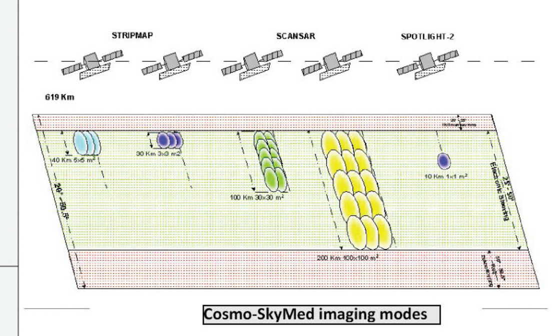
Some of the above limiting factors have been addressed by the most recent SAR missions: COSMO-SkyMed and TerraSAR-X. In particular the COSMO-SkyMed 4-satellite constellation has allowed to dramatically reduce the revisit interval for interferometric acquisitions. The present configuration allows InSAR repeat intervals of 1 day, using the SAR2 and SAR3 satellites, 4 days, using the SAR1, SAR2 and SAR4 satellites, and further combinations thereof.
While for specific seismic risk management applications the operational use of Cosmo-SkyMed has been successfully demonstrated by the SIGRIS pilot project, funded by ASI and INGV (www.sigris.it), other issues remain which cannot be resolved with high resolution missions.
These issues are addressed in the **Sentinel-1 ESA mission**, which is an important part of the GMES Space Component (Torres et al., 2012). The Sentinel-1 mission is planned as a two satellite constellation: the first to be launched in May 2013, and the second to follow in 2015. It will be a C-band mission, but unlike the previous ERS and ENVISAT missions, it will be dedicated to monitoring for operational applications.
We show below the expected contribution of Sentinel-1 for each of the main application fields

Seismic Hazard Assessment (SHA):

Several studies have demonstrated the capacity of InSAR measurements of crustal strain accumulation for the generation of information useful for deterministc SHA, as: the parameterization of the seismic sources (Xinjian and Guohong, 2007; Fielding et al., 2004), the definition of the present strain accumulation rates (Hunstad et al., 2009; Nof et al., 2008; Funning et al., 2007; Motagh et al., 2007; Lyons and Sandwell, 2003; Bürgmann and Prescott, 2000), the partitioning of strain among different faults (Jackson et al., 2006), the improvement of tectonic models in seismogenic areas (Biggs et al., 2006; 2007), etc.

Shortcomings of previous missions	Sentinel-1 contribution	Cosmo-SkyMed contribution
Incomplete coverage and non uniform temporal sampling. Not all worldwide seismic areas have been monitored with sufficiently long, frequent and temporally constant InSAR acquisitions, to guarantee good accuracies of ground velocity (range change rate) estimates.	Systematic data acquisition will be carried out adopting a routine, conflict-free planning, defined a-priori and not dynamically modified as a function of user requests. Data will be acquired over most seismically active areas of the world, in the Interferometric Wide swath mode (IW).	The Cosmo mission capacity does not allow for a routine global InSAR coverage of seismic areas in STRIPMAP mode. Partial coverage could be envisioned in a background mission, but with a trade off with the repeat intervals.
Topography-correlated atmospheric effects and orbital artifacts are also important sources of error which need to be corrected, if the highest precisions levels of 1mm/yr are to be appreciated.	The effective global interferometric coverage will be obtained with a minimum revisit of 12 days with one satellite, and 6 days with two. The closer temporal sampling, precise orbital control, larger swath width, are important preconditions for the estimate and removal of such effects.	The small swath width of the STRIPMAP mode (40 km), the irregular temporal sampling, and the large orbital tube, make Cosmo-SkyMed not well suited to reach the mentioned precision level.
Stability of temporal baselines of interferometric pairs. The optimal temporal difference should assure 60-80% of well coherent pixels in the interferogram.	The 6-day revisit interval, and the constant acquisition plan, can provide coherent interferograms in most multitemporal applications.	Temporal baselines are potentially very short, but cannot be guaranteed on a global basis. X-band interferograms of mildly vegetated areas decorrelate strongly after 16 days separation.
SAR image footprint needs to be large (200-300 km), to investigate crustal strain patterns occurring around large faults, and to allow a better estimation of various noise sources (atmospherical, orbital, non-tectonic).	The 250 km swath width and 5x20 m spatial resolution (range and azimuth respectively) of the IW mode can facilitate detection of stable areas in the images, allowing a better separation of different signals. Larger overlap with CGPS networks can eventually improve ground deformation measurements	The small STRIPMAP footprint (40 km) complicates the data analysis for the separation of the different noise sources .
The novel capacities provided by multitemporal InSAR in the detailed observation of crustal deformation related to the seismic cycle have provided exciting new data, but improved geophysical models are needed to exploit their full information content for SHA.	The large amount of data, their improved quality, the certainty of the long-term data provision (at least 12 years), and their availability at no cost, will certainly boost new research, for both InSAR data analysis and geophysical modeling techniques.	If continuity of data acquisition could be provided on selected seismic areas, the high spatial and temporal resolution of the Cosmo data would certainly stimulate new research.
The provision of services for SHA based on InSAR data can be limited by economic factors, considering the large volumes of data needed and the commercial costs of each image.	The Sentinel-1 data will be freely available for research and commercial use. This policy provides the best conditions for the development of new research and the generation of marketable services.	Cosmo-SkyMed is partly a commercial mission, and its data are sold at market costs.

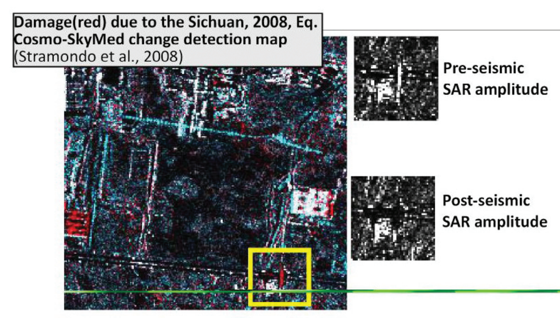

Sentinel-1 imaging modes


Cosmo-SkyMed imaging modes

Early Damage Assessment (EDA):

InSAR coherence- and amplitude-based classification techniques can be effectively employed to map earthquake damage in urban environments (Yonezawa and Takeuchi, 2001; Matsuoka and Yamazaki, 2002; Matsuoka and Yamazaki, 2004; Dell'Acqua et al., 2011), thanks also to their all-weather capability. The damage maps obtained from remote sensing data (high resolution optical data are also used) are very valuable during the first hours and perhaps few days after the mainshock, then they progressively lose importance with respect to more precise aerial and ground surveys.

Shortcomings of previous missions	Sentinel-1 contribution	Cosmo-SkyMed contribution
Delayed post-event image acquisition (and delivery). For the EDA applications, in most cases the limits for an effective operational use of the SAR data are 2-4 days, depending on local civil protection capacities.	Certainty of acquisition and statistics will make possible to obtain Sentinel-1 data within the limits for about half of the cases.	Depending on satellite visibility, 1 or 4 days will be the maximum delay. It will be possible to satisfy all of the requests.
Recency of pre-event image; images older than 1-6 months from the event (depending on SAR band and surface conditions) reduce the interferometric coherence and the accuracy of change detections.	Global routine coverage with 6-day repeat pass will solve this issue.	A background acquisition plan with a minimum temporal baseline of 1 month should be implemented at least for the most important cities in active seismic areas.
Coarse ground resolution. For best results in EDA, the geometrical resolution should be smaller than the average building dimensions.	The resolution in the IW mode may be too low for some urban developments.	The resolution is optimal for this application.



Damage(red) due to the Sichuan, 2008, Eq. Cosmo-SkyMed change detection map (Stramondo et al., 2008)

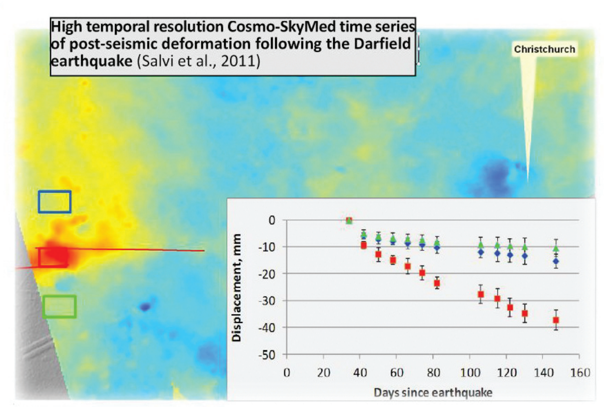
Assessment of the Earthquake Scenario (AES):

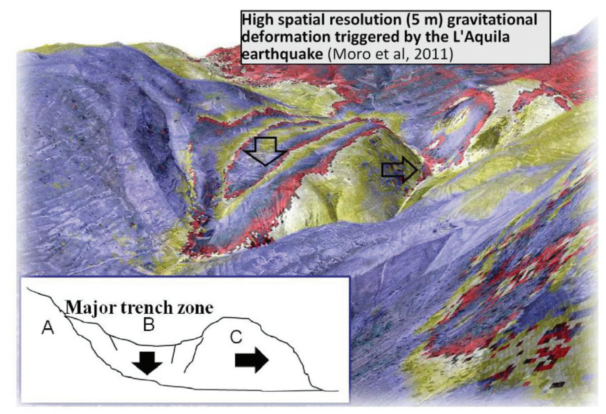
SAR differential interferograms provide the most detailed data on the co-seismic surface deformation. For many areas of the world they are often the only geodetic data available for the modeling of the seismic fault dislocation (see a review in Weston et al., 2012). Inversion of the InSAR displacements allows to map the earthquake source geometry and kinematics with considerable accuracy, especially when multiple interferograms from different SAR sensors and viewing geometries are used (Wright et al., 2003, 2004; Atzori et al., 2009; Atzori et al., under review).

High spatial resolution InSAR data are also very important to investigate gravitational surface deformation triggered by earthquakes in mountainous areas. In fact, they are the only mean to actually detect slow-moving, deep-seated mass movements (Moro et al., 2011).

Multitemporal InSAR analysis of post-seismic deformation may provide important data to model the stress-strain dynamics of fault systems and, in the future, formulate forecasts on the short-term spatial evolution of the seismic sequence (Raymond et al., 2002).

Shortcomings of previous missions	Sentinel-1 contribution	Cosmo-SkyMed contribution
Timeliness of post-event image acquisition (and delivery): the first images for the co-seismic pair should be available in 1-3 days.	Certainty of acquisition and statistics will make possible to obtain Sentinel-1 data within the 3-day limit for half of the cases.	Depending on satellite visibility, 1 or 4 days will be the maximum delay. It will be possible to satisfy most of the requests.
Frequent post-seismic acquisitions aiming to monitor the stress-strain dynamics, should be acquired at 1-2 day intervals, at least for the first few months.	The minimum repeat pass interval will be 6 days. This is suitable for a-posteriori studies of post-seismic afterslip or viscous relaxation, but not for the short term monitoring of stress-strain dynamics.	At full imaging capacity (all satellites), a partial fulfillment of this requirement is possible.
For direct engineering purposes, the Line of Sight scalar measures of ground displacement are not sufficient. Vector displacements should be provided.	This requirement can be partially addressed only using ground data (e.g. GPS), and by integrating InSAR data acquired from different line of sights.	This requirement can be partially addressed only using ground data (e.g. GPS), and by integrating InSAR data acquired from different line of sights.
High spatial resolution InSAR data (1-5m) would be required for optimal mapping of local static deformation relevant to engineering applications.	The resolution of the IW mode (5 x 20 m) is too low for a detailed mapping of static local deformation in interferograms.	The 3 x 3 m resolution of the STRIPMAP mode demonstrated the capacity to detect subtle ground movements, but a comparable resolution DEM is needed.
Instability of the spatial (perpendicular) baseline. This parameter should be kept low to minimise the geometrical decorrelation.	The small orbital tube (diameter of ~100 m) will reduce the geometrical and volumetric decorrelation and the sensitivity to topography. This will improve the interferometric coherence and the accuracy of ground displacement measurements.	At present the baseline stability is sub-optimal. The current orbital tube is much larger than 1 km, implying a high sensitivity to topography. To obtain an altitude of ambiguity close to typical global DEM errors (20 m) at a local incidence angle of 40°, the diameter of the orbital tube should not exceed 400 m.
Timeliness of post-event image acquisition (and delivery): the first images for the co-seismic pair should be available in 1-3 days.	Certainty of acquisition and statistics will make possible to obtain Sentinel-1 data within the 3-day limit for half of the cases.	Depending on satellite visibility, 1 or 4 days will be the maximum delay. It will be possible to satisfy most of the requests.


High temporal resolution Cosmo-SkyMed time series of post-seismic deformation following the Darfield earthquake (Salvi et al., 2011)



High spatial resolution (3 m) gravitational deformation triggered by the L'Aquila earthquake (Moro et al., 2011)

Conclusions

The development of Sentinel-1 was undertaken as part of the GMES space segment, therefore the mission requirements were built on the basis of the outcomes of the GMES services developed at the EU and ESA level. The most important requirements for operational services were: a global interferometric coverage, the continuity and certainty of data supply, a daily revisit interval, a near real time data distribution.

All these requirements, other than the daily revisit interval, have been fulfilled (Torres et al., 2012), and the Sentinel-1 constellation has the potential to stimulate new exciting research and market development of many sustainable services, thanks also to the free availability of the data. In the seismic risk management decision chain, we expect that the new observation capacity offered by Sentinel-1 will promote the development of services for the monitoring of the seismic cycle and especially of the interseismic strain accumulation.

For the earthquake emergency applications, the sub-optimal revisit interval and ground resolution of the Sentinel-1 satellites will require coordination and interoperability with high resolution satellites as Cosmo-SkyMed. The high flexibility allowed by the Cosmo constellation makes possible to plan the two mission in an integrated way. In particular one of the coordination efforts should be the planning of a "seismic-oriented" background regional mission for Cosmo-SkyMed, fundamental to generate the pre-event archive necessary for the InSAR-based emergency products.

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