USE OF SATELLITE SAR DATA FOR SEISMIC RISK MANAGEMENT: RESULTS FROM THE PRE-OPERATIONAL ASI-SIGRIS PROJECT

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ABSTRACT

The scope of the SIGRIS pilot project is the development of an infrastructure to provide value-added information services for the seismic risk management, assuring a close integration between ground-based and satellite Earth Observation data. The project is presently in the demonstration phase, and various information products are constantly generated and disseminated to the main user, the Italian Civil Protection Department. We show some examples of the products generated during the Crisis management of the 2009 L'Aquila earthquake in Central Italy. We also show an example of products generated for the Knowledge and Prevention service in support of the seismic hazard assessment in the area of the Straits of Messina.

1. THE SIGRIS SYSTEM

The SIGRIS (Italian acronym for Earth Observation System for Seismic Risk Management) pilot project was funded by ASI in 2007 to develop an infrastructure to demonstrate pre-operative services for the Seismic Risk management. The system was devised and developed by INGV (scientific coordination) and ACS (industrial partner with project responsibility), and is operated by INGV. Its only final user is the Civil Protection Department (DPC) which is the Italian government authority devoted to the coordination of all public activities in the management of the Seismic Risk.

The SIGRIS system was conceived to provide either Knowledge and Prevention (K&P) services and Crisis Management (CM) services, in support of the related civil protection activities.

The K&P service products are used to support the seismic hazard assessment. They are generated with relaxed time constraints (yearly update) and strict accuracy requirements. The products generated for the CM service require tight time constraints, and are released in rapidly updated versions, to improve their effectiveness in the generation of Crisis scenarios.

The SIGRIS system architecture is shown in Figure 1. Its main components are:

1. The ARC (Archival) component, responsible for storing and keeping track of all the data and processing results handled by the system. At present there is a capacity for 12 TBytes of data/product results.

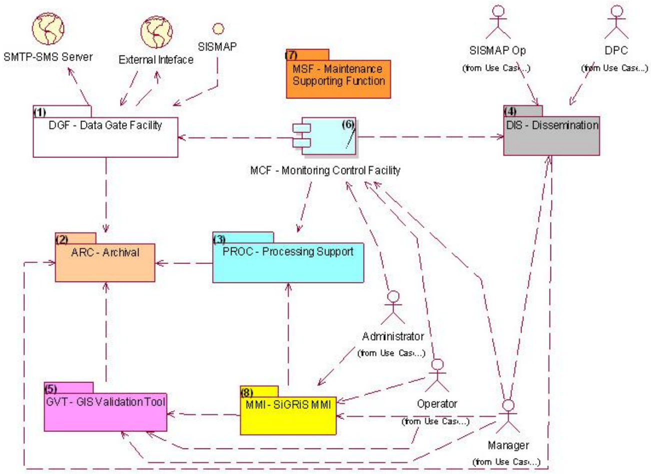


Figure 1 – The main components of the SIGRIS system architecture

2. The PROC (Processing) component contains all the processing modules and many general processing functionalities within an encapsulated environment. This is a dynamic component, since the continuous research and algorithm development generates periodic updates of the processing modules.
3. The MMI (SIGRIS MMI), component contains the Man Machine Interfaces exported by the SIGRIS system. The main interface for product generation and management is based on a GIS platform (ESRI products) from which the operator can manage most of the system functionalities and processing modules, most of which written in IDL, Matlab, Fortran.
4. The GVT (GIS Validation Tool) component provides the system with several specialized plug-ins (user- defined validation tools) and functionalities in order to validate the product results.
5. The DIS (Dissemination) component is responsible for providing validated output results to the final user (DPC). The DIS component is

based on a Web GIS system, developed according to the Open GIS communication protocols (WMS/WFS OGC protocols).

At present the SIGRIS system is able to generate 10 value added products.
For the *Knowledge & Prevention service* some products are, for example:

- Maps of low-rate ground deformation at the fault scale, to evidence the state of stress of the crust in a region. For this product we use time series Differential SAR Interferometry techniques: PS-InSAR [1], SBAS [2] and CGPS data.
- Regional crustal strain rate maps from CGPS data.
- Based on the previous two products, we generate a further, value-added product: models of strain accumulation on large active faults, and their parameterization for seismic hazard assessment.

Quasi real-time products to be generated for the *Crisis service* are:

- Maps of the co-seismic ground displacement field, generated using satellite SAR data in different wavelengths, and ground surveys (GPS, leveling, geological analysis).
- Parameterization of the seismic dislocations through inversion modeling of DInSAR and seismological data.
- Early assessment maps of the environmental effects of large earthquakes, from high resolution optical and SAR data.
- Early damage assessment maps for urban areas struck by large earthquakes, from high resolution optical and SAR data.
- Maps of post-seismic deformation and stress transfer induced by large earthquakes, using continuous and frequent monitoring based on SAR and CGPS data.

SIGRIS is aimed at promoting a better integration of remote sensing data into the decision chain of operational Seismic Risk management. The partnership ensures that such integration can be pursued efficiently: INGV is already maintaining and managing on assignment for DPC, a real time seismic surveillance system based on seismic, geodetic, geochemical ground networks. In fact the SIGRIS GIS interface provides a common platform for the integration and cross-comparison of satellite and ground data sets, which are jointly analyzed using state-of-the-art signal processing algorithms and geophysical modeling techniques. Continuous research activities are also a fundamental asset in SIGRIS, necessary to update and improve either the algorithms for geophysical data extraction and those for the numerical modeling.

2. SIGRIS EO data

The EO data used for the SIGRIS services are: high resolution optical imagery from EROS B, QuickBird, GeoEye, WorldView; SAR data from ERS, ENVISAT, ALOS, COSMO-SkyMed. The latter are the preferred data for the Crisis service, given the short revisiting and delivering times. ERS/ENVISAT data are used also for Crisis product, but, thanks to the long-dated archives, they are more extensively employed for the analysis of low rate deformations in the inter-seismic phase.
The COSMO-SkyMed constellation of 4 remote sensing X-band SAR satellites (3 already in orbit) was devised to provide near-real time, all-weather, accurate information for both military and civilian use [3]. Its main civilian applications concern the monitoring of natural disasters and of their consequences on man made structures and the environment. Interferometric capabilities were not in the initial requirements of the COSMO mission. Fortunately they were added later, and now the COSMO short revisiting interval (down to few hours), high spatial resolution (1-3 m) and extreme manoeuvreing flexibility (left-right looking, 20°-59° incidence angle), make for the best available InSAR data set for disaster management applications.

3. SIGRIS DEMONSTRATION: EXAMPLES

The release of the first version of the SIGRIS system was due for mid-July 2009, after which the demonstration phase would commence.
So, when a magnitude Mw=6.3 earthquake hit Central Italy and the L'Aquila province, the SIGRIS system was not completely qualified and operational, yet a large effort was carried out to generate the SIGRIS information products within their temporal and accuracy constraints.
Now the system is fully operational and demonstration of its performances is ongoing. We present in the following sections some examples of SIGRIS products generated and released to the user (DPC).

3.1. The L'Aquila earthquake Crisis

The Mw=6.3 L'Aquila earthquake occurred on April 6, 2009, at 03:32 local time. At 05:00 SIGRIS issued requests to ASI, ESA, and some commercial optical data providers for image acquisition over the epicentral area.
The first COSMO-SkyMed image was acquired on April 6 at 17:30, but had no matching pre-seismic image. The first interferogram could be generated with an April 9 image (Figure 2a). It showed a few broken fringes, but was too noisy to be used for seismic source modeling.
On April 12, both ENVISAT and COSMO acquired good post-seismic images, allowing the generation of

very coherent interferograms, showing the full co-seismic displacement field (Figure 2b,c). The data were received with 1-day and 3-day delays, respectively, and were disseminated shortly after to the Civil Protection.

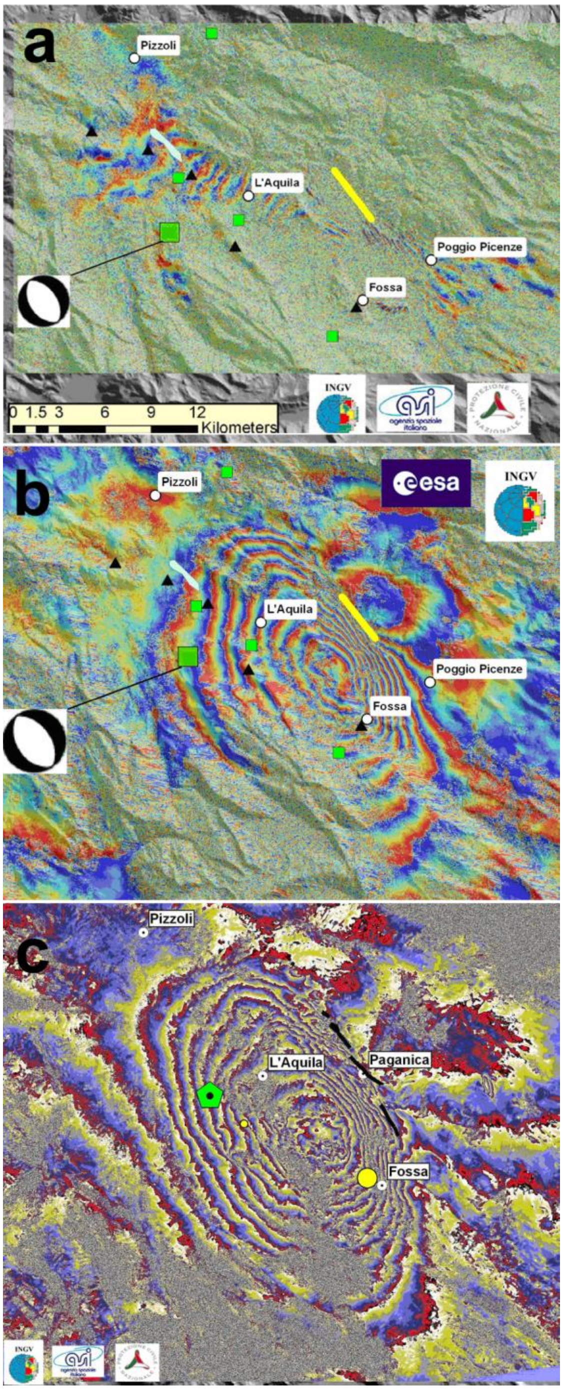


Figure 2 – The first SIGRIS products generated for the L'Aquila earthquake crisis: a) 19/2/2009-9/4/2009 COSMO interferogram, b) 27/04/2008-12/04/2009 ENVISAT interferogram, c) 4/04/2009-12/04/2009 COSMO interferogram.

On April 15 an ENVISAT ascending image was acquired. By combining the unwrapped phases of the three best interferograms, and a data set of about 20 3D displacements obtained by an emergency GPS network, we calculated the East and Up components of the co-seismic displacement field, which were disseminated to the DPC on April 17 (Figure 3).

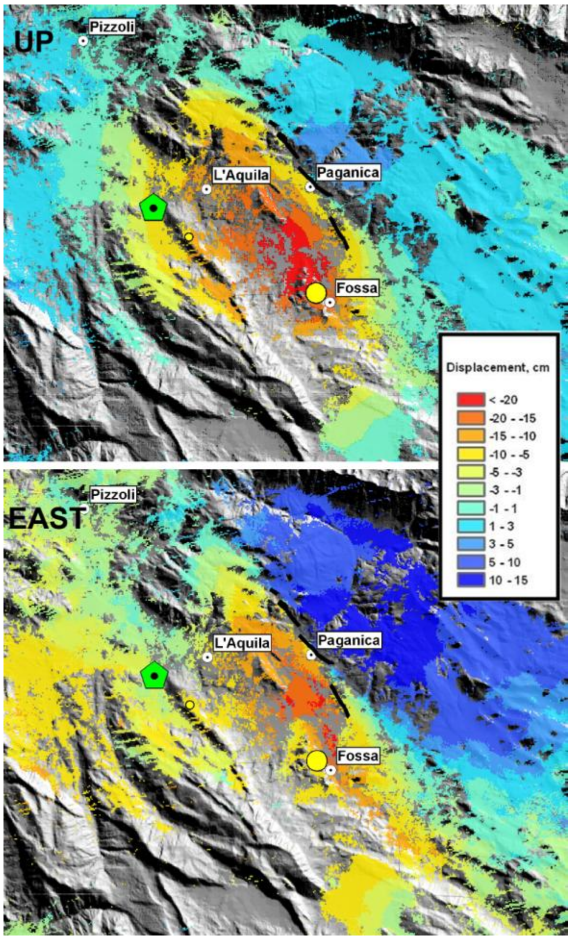
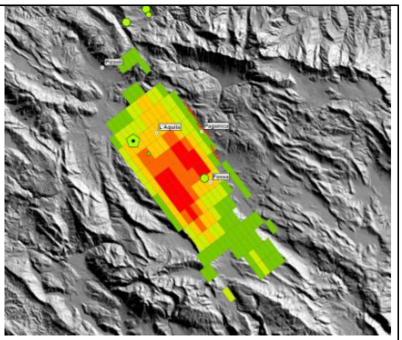
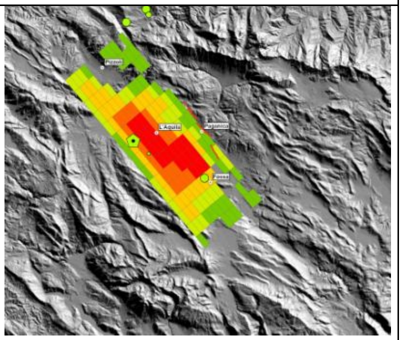
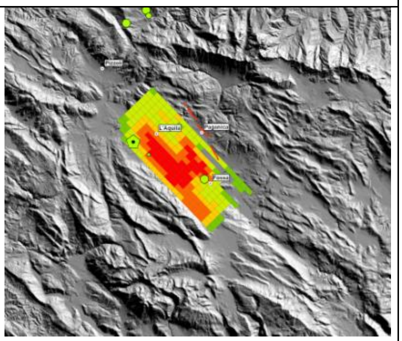


Figure 3 – The Up (top image) and East (bottom image) components of the displacement field of the L'Aquila earthquake.

Based on the progressively available displacement maps [4], we then generated three increasingly accurate seismic source models (Figure 4), which were the first models to show were exactly the fault was located [5]. About 8 months from the mainshock, using also ALOS data and several GPS 3D site displacements, we generated a final source model which comprehends a secondary source to the North (Figure 4).
Using high resolution optical imagery from QuickBird, and COSMO coherence analysis we generated, and quickly released to the DPC, various damage assessment maps of the urban areas of L'Aquila and neighboring villages (Figure 5) [6].

Model N. 1 ENVISAT desc Generated on April 15	
Model N. 2 ENVISAT desc COSMO asc GPS Generated on April 16	
Model N. 3 ENVISAT asc ENVISAT desc COSMO asc GPS Generated on April 17	

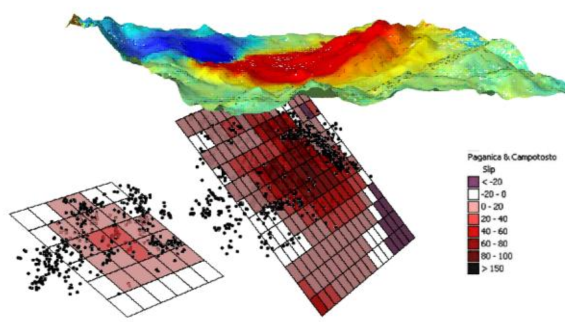
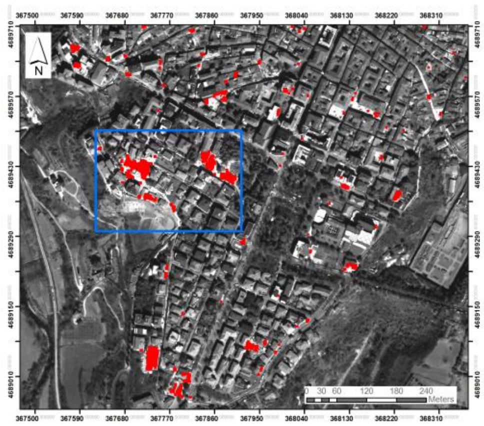


Figure 4 – The three seismic source models generated by SIGRIS during the first 11 days of the L'Aquila seismic crisis, and (bottom image) the final source model generated with all geodetic data available 8 months after the quake.



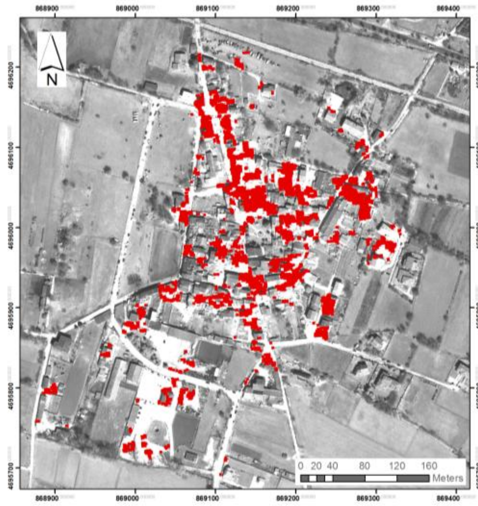


Figure 5 – Top image: early damage assessment map of the L'Aquila city; bottom image: damage assessment map of the Onna village.

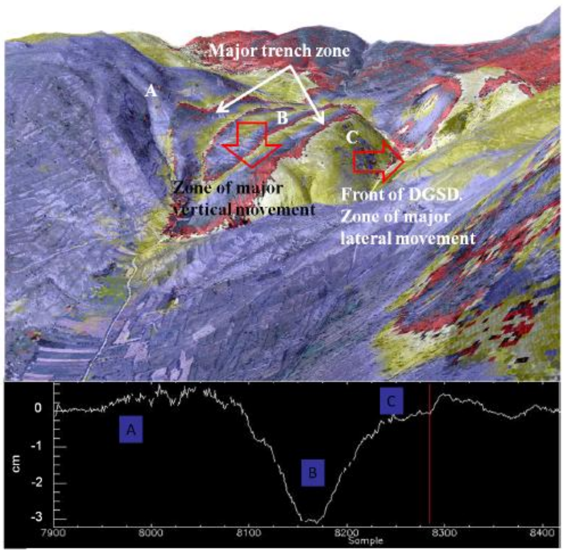


Figure 6 – 1-km wide gravitational mass movement detected on COSMO hi-res (5 m) interferogram

Finally, using the 5 m resolution COSMO interferogram, EROS B stereo pairs, and field geological analysis, we generated maps showing the location and main descriptive parameters of large gravitational mass movements triggered by the quake (Figure 6).

3.2. Assessment of strain accumulation on active faults

As mentioned before, one of the K&P SIGRIS products consists of maps of the low-rate crustal deformation.
Using the rich ERS 1-2 archives and, when available, also ENVISAT imagery, we generated maps of interseismic ground velocity for various Italian seismically active zones.

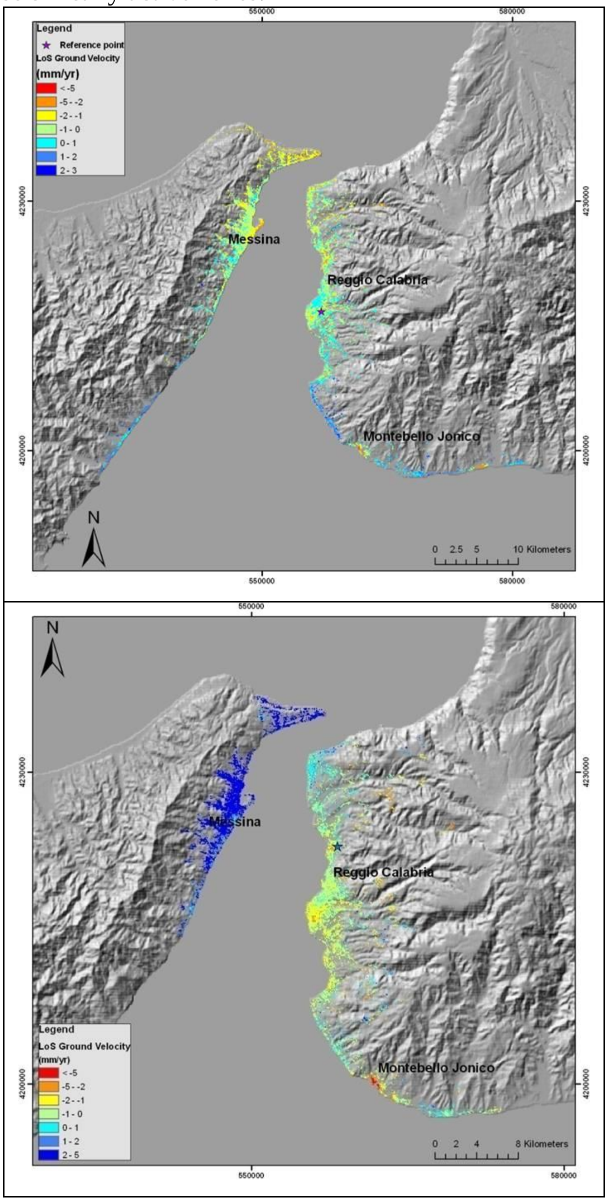
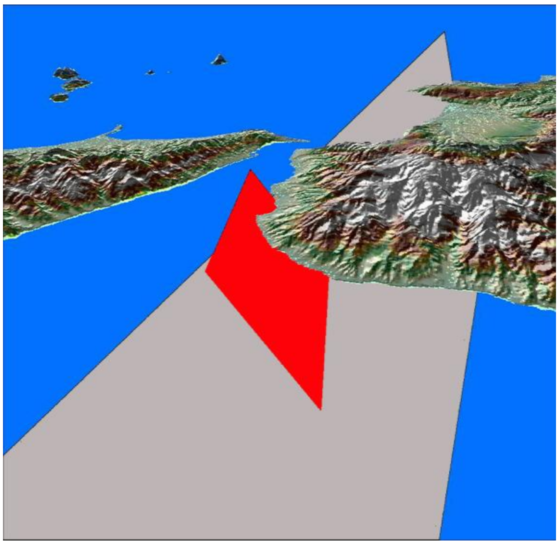


Figure 7 – Ascending (top) and descending (bottom) ground velocity maps for the Straits of Messina, obtained by SBAS analysis of ERS/ENVISAT data

Figure 7 shows the ascending and descending ground velocities in the Straits of Messina.
They were obtained applying the SBAS technique to a data set of 71 descending ERS images (1992-2002) and 37 ERS + 34 ENVISAT ascending images, and calculating a total of 183 + 181 interferograms .The temporal correlation, strongly influenced by the relief and vegetation, is rather low, and good coherence is maintained only on the urbanized coastal areas. Still a clear regional deformation signal is visible across the Straits, as well as some local subsiding areas along the southern Calabria coast.

3.3. Models of faults showing strain accumulation

This is an important product to support the seismic hazard analysis, since it may yield important constraints on fault geometry, dimensions, kinematics, and activity rates. For example we show in Figure 8 fault geometry and parameters calculated by non-linear inversion of the LoS velocities of the Straits of Messina. They are in reasonably good agreement with the geometrical parameters of the seismic source calculated by inversion of co-seismic leveling data after the Mw=7.1 Messina earthquake in 1908.



Length (m)	**Width (m)**	**Depth (m)**	**Strike (deg)**	**Dip (deg)**	**Rake (deg)**	**Slip (cm)**
500000	100000	9051	10	70	-125	0.5

Figure 8 – Active fault in the Straits of Messina: the red rectangle is the 1908 earthquake source simulated from co-seismic leveling displacements; the grey rectangle is the infinitely long dislocation used to simulate the interseismic velocity field observed by SBAS analysis of ERS/ENVISAT data. The table shows the parameters of the fault showing strain accumulation.

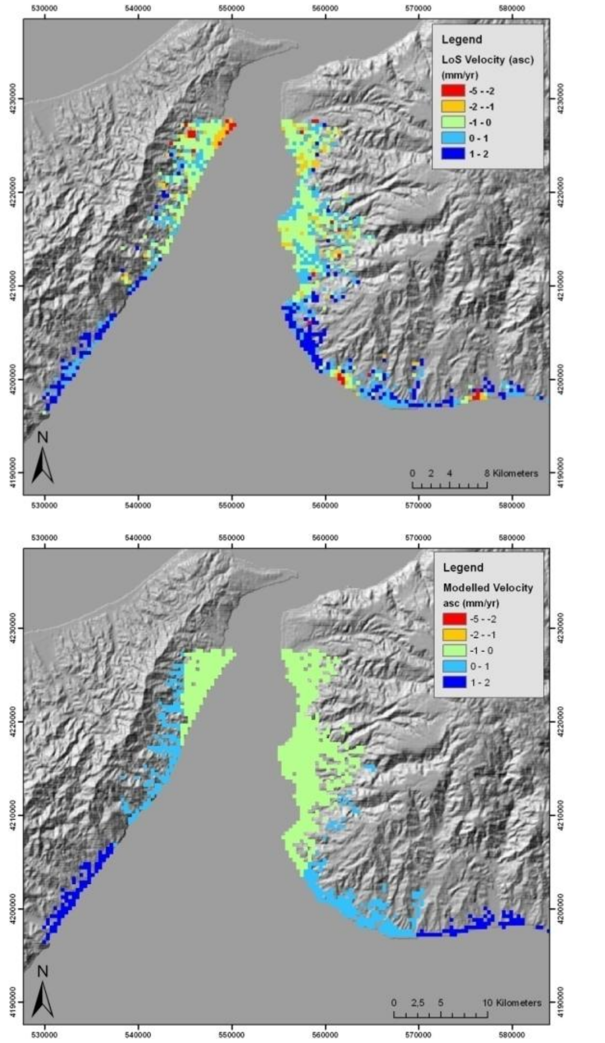


Figure 9 – Top image: observed ascending velocities in the Straits of Messina. Bottom image: interseismic velocity field simulated by the model dislocation in Figure 8.

Considering the uncertainties in the location of the sources, we an attribute the observed DInSAR velocities (see Figure 9) to stable slip occurring on the deeper part (below 9-km depth) of the 1908 seismic dislocation.

4. CONCLUSIONS

During the L'Aquila seismic crisis the SIGRIS system, although not yet qualified, responded rapidly and well, and the main products for the seismic Crisis were delivered within a 5-10 day timeframe.
The main delays in product generation were caused by slow access to the EO data, due to either deferred acquisition (for optical imagery) and the lack of an urgent data production and delivery procedure.
The ongoing demonstration of the SIGRIS system is showing that the effective operational use of satellite data for the management of the seismic risk is feasible, with some limitations mainly arising from the lack of satellite systems specifically devised for this task.
The main issues in this respect concern the compromises among frequency band, temporal decorrelation, revisit time, spatial, and displacement resolutions, which force the monitoring strategy to rely on a multi-sensor approach. To be effective, this strategy must be implemented in close coordination between system operators (usually public scientific community with a role in operational seismic risk management), and the data providers (space agencies or commercial providers).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Ferretti A., C. Prati, F. Rocca, Permanent Scatterers in SAR Interferometry, IEEE Transaction on Geoscience and Remote Sensing, 39, 1, 8-20, 2001.
2. Berardino, P., G. Fornaro, R. Lanari, and E. Sansosti, A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms, IEEE Trans. Geosci. Remote Sens., 40 , 2375–2383, 2002
3. ASI, 2008, COSMO-SkyMed: Dual system for Earth observation, http://www.cosmo-skymed.it/en/index.htm
4. Stramondo S., M. Chini, C. Bignami, S. Salvi, S. Atzori, X- C- L-Band DInSAR investigation of the April 6th, 2009, Abruzzi earthquake. IEEE Geoscience and Remote Sensing Letters, doi:10.1109/LGRS.2010.2051015
5. Atzori, S., I. Hunstad, M. Chini, S. Salvi, C. Tolomei, C. Bignami, S. Stramondo, E. Trasatti, A. Antonioli, and E. Boschi (2009), Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy), Geophys. Res. Lett., 36, L15305, doi:10.1029/2009GL039293.
6. Dell'Acqua F., C.Bignami, M. Chini, G. Lisini, D. Polli, and S. Stramondo, Earthquake rapid mapping by satellite remote sensing data: L'Aquila April 6th, 2009 event. Submitted to IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2010