Seismic Hazards Pilot

Final Report

(April 2014 – November 2017)

Summary:

The CEOS Seismic Hazards pilot has managed to address seismic hazards by providing access to data, but also access to tools and hosted processing to generate needed information mainly after emergencies, as well as linking to available EO capacities thanks to the contribution of expert users (partner geoscience centers with EO expertise). So far, the pilot has primarily focused on EO practitioners and has very few end users, although some of the pilot EO experts have managed to provide information to operational end users in concrete cases e.g. the case of the 2016 Italian seismic sequence (Amatrice, Visso and Norcia): INGV and CNR-IREA has provided reports (based on satellite EO products EO and in-situ data) to the Italian Civil Protection Department (DPC).

The CEOS Seismic Hazards pilot has been a well-set example to establish the basis of a new initiative with global activity in long-term seismic risk estimation, scientific research and in a best effort basis, emergency response. The pilot is intended to end and a follow-on activity, the Seismic Hazards Demonstrator is proposed to continue to develop, expand and demonstrate the benefit of satellite EO for DRR by, focusing on the objectives of the tectonics community. In comparison to the pilot, the new activity shall focus on: (i) larger AOIs', e.g. active fault mapping and strain rate mapping in global scale, (ii) response to a larger number of events (10-12 earthquakes per year), (iii) applying new approaches e.g. establishing a consensus methodology for product generation and (iv) expanding the user base to increase the benefit to the community.

Pilot leads:	**Collaborating organizations:**
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Initial Objectives:

Main Pilot objectives are:

A. Support the generation of globally self-consistent strain rate estimates and the mapping of active faults at the global scale by providing interferometric synthetic aperture radar (InSAR) and optical data and processing capacities to existing initiatives (wide extent satellite observations)

B. Continue to support the Geohazard Supersites and Natural Laboratories initiative (GSNL)

for the seismic hazard activities (satellite observations focused on supersites)

C. Develop and demonstrate advanced science products for rapid earthquake response (observation of earthquakes with low to intermediate magnitude, M>5.8)

The Pilot's broader CEOS objective is to demonstrate how satellite EO can be used to improve geodetic monitoring of faults and the earthquake cycle, and provide scientific information to support the response to seismic events.

Achievements (linked to objectives and also to CEOS objectives in the proposal):

Since 2014, the Seismic Hazards pilot has achieved to:

i. Generate advanced science products as part of an effort of the international scientific community in interpretation of major seismic events: Greece (Cephalonia) 2014, Nepal (Gorkha) 2015 (in collaboration with the GSNL), Greece (Lefkada) 2015, Ecuador (Muisne) 2016, Italy (Amatrice, Visso, Norcia) 2016 and New Zaland (Kaikoura 2016). See the *CEOS Seismic Hazards pilot - Sustainability Strategy for further details about the above events.*

ii. In some cases, the value-added products were provided to civil protection authorities in order to understand the extent of the affected areas and better focus their activities during the emergency. In the timeframe of the Seismic pilot there were two cases where the products were provided to DRM organisations: 2016 Ecuador and Italy earthquakes.

iii. Validation results were completed for California based on GPS velocities and Turkey based on GNSS measurements.

iv. Active fault mapping completed over Sagaing fault, Myanmar and San Ramon fault, Chile using tri-stereo Pleiades imagery.

v. A number of papers, posters and presentations has stemmed out of pilot group work, as well as web-articles and posts.

vi. Respond to the major 2015 Nepal earthquake starting with the provision of ALOS-2 data. Within a few weeks, a GSNL Event Supersite was established to cover the area, gathering a large number of EO sources (satellite and in situ data) for the generation of scientific products.

vii. Ensure wide area acquisitions: Ensure EO data coverage over wide areas and a long-time span (few EO missions, very wide extent) as with Objective A).

viii. Gather user priorities about observation strategies: allow the community to voice its priorities concerning the observation strategy of CEOS contributors through their EO missions (the pilot managed to change the operations plans of some contributing missions e.g. the world tectonic mask for repeat Copernicus Sentinel-1 IWS acquisitions every two cycles). In particular, the operational plan of Copernicus Sentinel-1 has been adjusted to provide observation data in support to global strain rate mapping.

ix. Collaborate with the Geohazards Exploitation Platform (GEP, https://geohazards-tep.eo.esa.int/#!) activity originated by ESA to directly support pilot users exploiting satellite data to assess seismic hazards and in particular users of the GSNL community. Following its precursor Supersites Exploitation Platform (SSEP) the GEP is focusing on the following priorities:

- Supporting data storage and dissemination, particularly ensuring that many different EO sources are available for the CEOS Seismic Hazards and Volcano pilot teams and the GSNL users
- Providing hosted processing for seismic hazard assessment: such as in the case of terrain motion monitoring based on InSAR or stereo-optical data, as needed for e.g. the Geohazards Supersites & Natural Laboratories initiative (GSNL).
- Supporting collaborative work (e.g. sharing pilot results with the community) and community building.

Data accessed (list satellites and make statement)

The space agencies that contribute to the pilot are ESA, ASI, NASA, CNES, DLR and JAXA. Table 1 shows the quota available per year, for the period November 2014 to November 2017.

Agency	ASI	CNES Pleiades	CSA	DLR	ESA	JAXA ALOS-2	NASA	USGS Landsat-8
Quota (Total number of Images available for 3 years)	**900**	**150**	**6**	**on request**	**open**	**300**	**-**	**open**
Used (Total number of images)	**302**	**67**	**6**	**361**	**>1000**	**88**	**-**	**-**

Since 2014, the pilot partners have accessed and used:

- CosmoSkyMed images to monitor the Haiyuan fault in China and the Shahdad fault in Iran under Objective A and to provide advanced science products for the 2014 Greece (Cephalonia) earthquake, the 2015 Greece (Lefkada) earthquake and the 2016 Italy earthquake under Objective C.
- ALOS-2 images to monitor the North Anatolian fault and the Andes under Objective A and to respond to the 2015 Nepal earthquake and the 2016 Italy earthquakes (Amatrice, Norcia, Visso) under Objective C.
- TerraSAR-X images to monitor the North Anatolian fault under Objective A and to cover the 2015 and 2014 Greece (Lefkada and Cephalonia) earthquakes.
- Radarsat-2 images to cover the 2015 Greece (Lefkada) earthquake.
- Pleiades images to monitor the 2016 Italy and New Zealand earthquakes under Objective C, as well as for active fault mapping in Myanmar and Chile.
- Copernicus Sentinel-1 images to cover the 2015 Nepal and Greece (Lefkada) earthquakes and the 2016 Ecuador and Italy earthquakes (Amatrice, Norcia, Visso) under Objective C, but also for validation (based on GNSS measurements) and strain rate mapping in the North Anatolian fault.

In some cases, there were constrains in using data:

- Pleiades license requirements (available only to French users): Until July 2016, Pleiades data were not available for non-French users, so the first pilot request was accepted in November 2016 (one year before the end of the pilot).
- Slow data ordering procedure for TerraSAR-X: It takes some time to receive a confirmation from Airbus.
- Sentinel-1 accounting system: Currently there is no available data accounting system for Copernicus Sentinel data used in CEOS group (an integrated accounting system will be

available in GEP version 2.0 in May 2017), nevertheless the pilot counts overs 1000 frames used, since about 1000 frames were processed by COMET over the Alpine-Himalayan Belt.

- ALOS-2 direct data order: Until May 2016, it was not clear that the pilot could directly order data on JAXA's system (until the quota were expended), without an intermediate approval. Pilot partners have turned to other projects to obtain the necessary data in a timely manner.

Products:

- Preliminary inspection of Sentinel-1 & ALOS-2 interferograms for the Nepal Event site– COMET
- Ground displacement measurements with Sentinel-1 and ALOS-2 for the Nepal Event site – NASA JPL
- Coseismic displacement maps, fault geometry and kinematics and slip distribution (for the Nepal Event site) – INGV
- Integration of CNES's DIAPASON processor on the GEP
- Azimuth displacement map using CSK data for the Lefkada earthquake– INGV
- Sentinel-1 interferogram and displacement map for the Lefkada earthquake – INGV & NOA
- Fault model using Sentinel-1, CSK and Radarsat-2 data for the Lefkada earthquake – INGV & NOA
- Interferograms based on ascending and descending Sentinel-1 pairs for the Lefkada earthquake – NOA
- Wrapped and unwrapped interferograms using Radarsat-2 data for the Lefkada earthquake – NOA
- Cumulated ground displacement map over Tibet (Tibetan lake) generated using ISTerre's NSBAS chain, currently integrated on GEP – ISTerre
- Fine-beam interferograms using ALOS-2 data over Kathmandu– NASA JPL
- Range change map using Sentinel-1 data over Lefkada/Greece– NASA JPL
- LOS displacement map using Sentinel-1 data over Lefkada/Greece and Ecuador – NASA JPL
- LOS maps using Sentinel-1 data over NAFS – COMET
- E-W velocity maps using Sentinel-1 data over Turkey (NAFS) – COMET
- Ground displacement maps using Sentinel-1 data over Accumoli/Italy – CNR-IREA DPC
- Deformation maps using ALOS-2 data over Accumoli/Italy – CNR-IREA, DPC
- Source fault slip using ALOS-2 and Sentinel-1 data over Accumoli/Italy – INGV
- Interferogram using CSK data over Accumoli/Italy– INGV
- Interferogram using Sentinel-1 data over Accumoli/Italy generated using DIAPASON on GEP – INGV
- Interferogram using Sentinel-1 data over Accumoli/Italy generated using SBAS on G-POD and published on GEP – CNR-IREA
- Sentinel-1 Interferogram & Displacement map over Ecuador – CNR IREA, DPC
- Sentinel-1 Interferograms over New Zealand – NOA
- ALOS-2, CSK, and Sentinel-1 interferograms over Amatrice – INGV
- Source model using Sentinel-1, ALOS-2 and CSK datasets for the Amatrice earthquake – INGV
- ALOS-2 and Sentinel-1 interferograms over Visso and Norcia – INGV
- Source model using ALOS-2 data over Norcia and Visso – INGV & CNR-IREA
- Sentinel-1 coseismic range offsets over New Zealand – COMET
- E-W and N-S displacement maps from Sentinel-2A image correlation over New Zealand – COMET
- ALOS-2 coseismic displacement map over New Zealand – COMET
- High-resolution deformation data for the entire Alpine-Himalayan seismic belt showing ground movement – COMET
- ALOS-2 interferograms (LOS and Along-track deformation) over New Zealand – NASA JPL
- Tools for automated generation of Sentinel-1 frame interferograms (to be also integrated in GEP)– COMET
- Preliminary DEM extraction from VHR stereo data (Pleiades) over the Sagaing fault in

Myanmar – University of Leeds/COMET

- Hillshaded DEM derived from tri-stereo Panchromatic Pleiades imagery highlighting San Ramon FAULT segments, Santiago-Chile – University of leeds/COMET
- San Ramon fault trace map: Point cloud of elevations for the 30 km long trace - University of Leeds/COMET
- San Ramon fault scarp map: Profile distances - University of Leeds/COMET
- Velocities of the Ganos fault in Turkey using TerraSAR-X data - INGV

The above products generated for the 2016 Ecuador and Italian earthquakes were also shared (through INGV and CNR-IREA) with the DPC. INGV delivered synthetic reports to DPC s showing the co-seismic displacement observations, the geometry and kinematic of the seismic sources, and the fault slip distributions on the earthquake rupture. These scientific products were validated with a variety of independent information coming from in situ data and models, and were used also at the INGV Crisis Unit to improve the general understanding of the seismic sequence and of its possible evolution.

Dissemination:

A number of publications, posters and presentations in International conferences and meetings is listed below, as well as a number of web–articles and stories.

1. Fattahi and Amelung, (2014), "InSAR uncertainty due to orbital errors", GJI
2. John Peter Merryman Boncori, Ioannis Papoutsis, Giuseppe Pezzo, Cristiano Tolomei, Simone Atzori, Athanassios Ganas, Vassilios Karastathis, Stefano Salvi, Charalampos Kontoes, and A. Antonioli, The February 2014 Cephalonia Earthquake (Greece): 3D Deformation Field and Source Modeling from Multiple SAR Techniques, Seismological Research Letters Volume 86, Number 1 January/February 2015
3. Fattahi and Amelung (2015), "InSAR bias and uncertainty due to systematic and stochastic tropospheric delay"
4. Doin, M. - P., Twardzik, C., Ducret, G., Lasserre, C., Guillaso, S., & Sun Jianbao. (2015). InSAR measurement of the deformation around Siling Co Lake: Inferences on the lower crust viscosity in central Tibet, J. Geophys. Res.-Solid Earth, 120, 5290–5310, doi:10.1002/2014JB011768.
5. Grandin et al. (2015), "Rupture process of the Mw=7.9 2015 Gorkha earthquake (Nepal): insights into Himalayan megathrust segmentation"
6. Fielding et al. (2015), Geodetic Imaging of the Coseismic and Postseismic deformation from the 2015 Mw 7.8 Gorkha Earthquake and Mw 7.3 Aftershock in Nepal with SAR and GPS
7. Angster et al. (2015), Field Reconnaissance after the 25 April 2015 M 7,8 Gorkha Earthquake, Seismological Research Letters, Vol. 8, No. 6
8. Papadopoulos et al. (2016), The Mw6,5 earthquake of 17 November 2015 in Lefkada Island and the seismotectonics in the Cephalonia Transform Fault (Ionian Sea, Greece), Geophysical Research Abstracts, Vol. 18, EGU2016-9041-1, 2016
9. Yue H. et al. (2016), Depth varying rupture properties during the 2015 Mw 7.8 Gorkha (Nepal) earthquake, Tectonophysics, In Press
10. Elliott JR; Walters RJ; Wright TJ (2016) The role of space-based observation in understanding and responding to active tectonics and earthquakes, Nature Communications, 7, doi: 10.1038/ncomms13844
11. Hussain E; Hooper A; Wright TJ; Walters RJ; Bekaert DPS (2016) Interseismic strain accumulation across the central North Anatolian Fault from iteratively unwrapped InSAR measurements, Journal of Geophysical Research: Solid Earth, 121, pp.9000-9019. doi: 10.1002/2016JB013108
12. Floyd MA; Walters RJ; Elliott JR; Funning GJ; Svarc JL; Murray JR; Hooper AJ; Larsen Y; Marinkovic P; Bürgmann R; Johanson IA; Wright TJ (2016) Spatial variations in fault friction related to lithology from rupture and afterslip of the 2014 South Napa, California earthquake, Geophysical Research Letters, 43, pp.6808-6816. doi: 10.1002/2016GL069428
13. Hussain E; Wright TJ; Walters RJ; Bekaert D; Hooper A; Houseman GA (2016) Geodetic

observations of postseismic creep in the decade after the 1999 Izmit earthquake, Turkey: Implications for a shallow slip deficit, Journal of Geophysical Research: Solid Earth, 121, pp.2980-3001. doi: 10.1002/2015JB012737
14. Wright TJ (2016) The earthquake deformation cycle, ASTRONOMY & GEOPHYSICS, 57.
15. Elliott JR; Jolivet R; Gonzalez PJ; Avouac JP; Hollingsworth J; Searle MP; Stevens VL (2016) Himalayan megathrust geometry and relation to topography revealed by the Gorkha earthquake, Nature Geoscience, 9, pp.174-180. doi: 10.1038/ngeo2623
16. Poster at AGU 2016: LiCSAR: Tools for automated generation of Sentinel-1 frame interferograms, Pablo J. González, Richard J. Walters, Emma Hatton, Karsten Spaans, Alistair McDougall, John Elliott, Andrew J. Hooper, and Tim J. Wright
17. Gruppo di lavoro IREA-CNR & INGV, 2016. Sequenza sismica di Amatrice: risultati iniziali delle analisi interferometriche satellitari, DOI: 10.5281/zenodo.60935
18. Gruppo di lavoro IREA-CNR & INGV, 2016. Sequenza sismica di Amatrice: aggiornamento delle analisi interferometriche satellitari e modelli di sorgente, DOI:10.5281/zenodo.61682
19. Gruppo di lavoro IREA-CNR & INGV, 2016 Sequenza sismica di Amatrice: risultati iniziali delle analisi interferometriche satellitari, DOI: 10.5281/zenodo.60938
20. Gruppo di lavoro IREA-CNR & INGV, 2016 "Sequenza sismica del Centro Italia 2016-2017: aggiornamento delle analisi InSAR e modello preliminare di sorgente per gli eventi del 18/1/17", DOI: 10.5281/zenodo.266966
21. Gruppo di Lavoro INGV sul terremoto in centro Italia, 2016. Rapporto di sintesi sul Terremoto in centro Italia Mw 6.5 del 30 ottobre 2016, doi: 10.5281/zenodo.166019
22. Gruppo di Lavoro INGV sul Terremoto in centro Italia, 2017. Relazione sullo stato delle conoscenze sulla sequenza sismica in centro Italia 2016-2017 (aggiornamento al 2 febbraio 2017), doi: 10.5281/zenodo.267984
23. Presentation at AGU 2016 meeting: S. Salvi et al., 2016, Co-seismic deformation fields and source modelling for the 2016 Central Italy events from the inversion of InSAR and GPS data, AGU 2016
24. Bignami, C., Tomolei, C., Pezzo, G., Guglielmino, F., Atzori, S., Trasatti, E., Antonioli, A., Stramondo, S. and Salvi, S., 2016. Source identification for situational awareness of August 24th 2016 central Italy event. Annals of Geophysics, 59.
25. Poster at AGU 2016 meeting: Casu, F., et al., "The Mw 6.0 2016 Amatrice (Italy) Earthquake: Source Geometry Inferred from DInSAR Measurements and Geological Data", S43F-3207 AGU Fall Meeting 2016
26. Lavecchia, G., R. Castaldo, R. de Nardis, V. De Novellis, F. Ferrarini, S. Pepe, F. Brozzetti, G. Solaro, D. Cirillo, M. Bonano, P. Boncio, F. Casu, C. De Luca, R. Lanari, M. Manunta, M. Manzo, A. Pepe, I. Zinno, and P. Tizzani (2016) "Ground deformation and source geometry of the August 24, 2016 Amatrice earthquake (Central Italy) investigated through analytical and numerical modeling of DInSAR measurements and structural- geological data", Geophys. Res. Lett., 43, 12,389–12,398, doi: 10.1002/2016GL071723
27. Kargel, J. S., et al. (2016), Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake, Science, 351(6269), 140+online, doi:10.1126/science.aac8353.
28. Yue, H., et al. (2016, in press), Depth varying rupture properties during the 2015 Mw 7.8 Gorkha (Nepal) earthquake, Tectonophysics, doi:10.1016/j.tecto.2016.07.005.
29. Presentation at EGU General Assembly 2017: A Bayesian analysis of the 2016 Pedernales (Ecuador) earthquake by Baptiste Gombert et al., Session SM2.1/EMRP4.12 - Earthquake source processes - Imaging methods, numerical modeling and scaling, Abstract identification number EGU2017-12363.
30. Huang, M.-H., E. J. Fielding, C. Liang, P. Milillo, D. Bekaert, D. Dreger, and J. Salzer (2017), Coseismic deformation and triggered landslides of the 2016 Mw 6.2 Amatrice earthquake in Italy, Geophysical Research Letters, 44(3), 1266-1274, doi:10.1002/2016GL071687.
31. Liang, C., and E. J. Fielding (2016), Interferometric Processing of {ScanSAR} Data Using Stripmap Processor: New Insights From Coregistration, {IEEE} Trans. Geosci. Remote Sensing, 54(7), 4343--4354, doi:10.1109/TGRS.2016.2539962.
32. Liang, C., and E. J. Fielding (2017, in press), Measuring Azimuth Deformation With L-Band ALOS-2 ScanSAR Interferometry, IEEE Transactions on Geoscience and Remote Sensing, PP(99), 1-14, doi:10.1109/TGRS.2017.2653186.

33. Liang, C., and E. J. Fielding (2017, in press), Interferometry With ALOS-2 Full-Aperture ScanSAR Data, IEEE Transactions on Geoscience and Remote Sensing, PP(99), 1-12, doi:10.1109/TGRS.2017.2653190.
34. Hamling, I. J., S. Hreinsdottir, K. Clark, J. R. Elliott, C. Liang, E. Fielding, N. Litchfield, P. Villamor, L. Wallace, T. J. Wright, E. D'Anastasio, S. Bannister, D. Burbidge, P. Denys, P. Gentle, J. Howarth, C. Mueller, N. Palmer, C. Pearson, W. Power, P. Barnes, D. Barrell, R. Van Dissen, R. Langridge, T. Little, A. Nicol, J. Pettinga, J. Rowland & M. Stirling (2017) Complex multifault rupture during the 2016 Mw 7.8 Kaikoura earthquake, New Zealand, Science, 356, 154, doi:10.1126/science.aam7194.
35. A number of posts on https://geohazards-tep.eo.esa.int/#!blog e.g. https://discuss.terradue.com/t/example-of-hosted-processing-using-s-1-data-in-the-aftermaths-of-the-2016-central-italy-eq/74
36. A number of products shared openly https://geohazards-tep.eo.esa.int/geobrowser/#!context=Community. These products were generated using hosted processing tools on the GEP as well as G-POD.
37. http://comet.nerc.ac.uk/
38. http://www.bbc.co.uk/news/science-environment-38323832
39. http://www.beyond-eocenter.eu/index.php/geophysical/earthquakes/new-zealand-2016
40. http://beyond-eocenter.eu/index.php/geophysical/earthquakes/central-italy-2016
41. http://beyond-eocenter.eu/index.php/geophysical/earthquakes/amatrice-earthquake-2016
42. http://beyond-eocenter.eu/index.php/geophysical/earthquakes/lefkada-earthquake-2015
43. http://beyond-eocenter.eu/index.php/geophysical/earthquakes/nepal-earthquake

Evaluation Against Predefined Criteria

An overall assessment of the Seismic pilot identifies successful and unsuccessful activities, based on the milestones set in 2014. Below the table of milestones is available, including percentage of success of each of the activities.

Successful activities

- Example data for past earthquakes put on the GEP.
- Implementation of processing algorithms for rapid response products on the GEP.
- Demonstration of the generation of different products for 1-2 earthquakes per year (8 events were covered within 3 years in Greece, Nepal, Ecuador, New Zealand and Italy).
- Examine the gaps in existing acquisition plans over the major cities of the world in areas at high seismic risk (COSMO SkyMed, TerraSAR-X, Radarsat). All megacities in areas at high seismic risk are at least partially covered by SAR sensor. The study identified sites with good coverage using nearly global coverage missions as Sentinel-1 and ALOS-2, but for many sites there is not full coverage with ascending and descending acquisitions from Radarsat-2, TerraSAR X, and COSMO-SkyMed.
- Support the GSNL: partially successful
  - Integration of tools on the GEP was successful (e.g. INGV's SISTEM tool). Some GSNL users have made effort to integrate the tools.
  - GSNL users (e.g. INGV) are using other processors/tools to generate products on GEP.
  - GSNL data available through GEP: TSX available, CSK currently on hold by ASI.
- Development of the Web site.
- Development of procedures (for each agency) to ensure optimal data access in case of earthquakes over a certain threshold. (same for volcanoes)

Unsuccessful or partially successful activities

- Results of validation - Turkey, California, Japan, other selected areas (China and Iran): Activity completed for California and Turkey, still on-going over China and Iran, not completed for Japan (the user requested ALOS data for Japan, but no agreement of ALOS data provision at no cost was in place).
- Access to Pleiades (available to non-French users only after July 2016), TerraSAR-X

(sometimes long procedure to get authorisation from Airbus) and Radarsat-2 data is sometimes slow.

- Comparison of results obtained by different groups/algorithms/approaches; consensus report.
- Poor and delayed user feedback.
- Product assessment by the final users and user feedback: Very slow activity due to lack of liaisons with end-users. Only DPC in Italy used products (INGV and CNR IREA) for the 2016 Italian earthquakes and Ecuador earthquake.

Objective	**Milestone**	**Success (%)**	**Comments**
A	Results of validation - Turkey, California, Japan, other selected areas	70%	-Validation of measurements completed for Turkey and California.
A	Strain rate measurement results over pilot areas of focus (see EO data requirements)	50%	Strain rate production is in course. COMET LiCSAR portal is open and massive strain rate measurements will be released by the end of the year.
A	Results of test areas using archived data, initial results for main areas; established beta methodology for processing over large areas (see target for end 2016); preliminary results for validation sites on ERS/Envisat, COSMO SkyMed and TerraSAR-X data in Eastern Turkey and California	100%	-Completed for California. -Preliminary results of Turkey
B	Support the GSNL	70%	-Integration of tools on the GEP was successful (e.g. INGV's SISTEM tool) -GSNL data available through GEP: TSX available, CSK currently on hold by ASI.
C	Example data for past earthquakes put on the GEP (L'Aquila, Van, Emilia, New Zealand)	100%	Successful: e.g. all ERS, ENVISAT and TSX (DLR CEOS/GSNL repository) data collections available through GEP
C	Implementation of processing algorithms for rapid response products on the GEP	100%	Successful. More chains are being integrated currently.
C	Demonstration of the generation of different products for 1-2 earthquakes per year.	100%	Greece (Cephalonia) 2014, Nepal 2015, Greece (Lefkada) 2015, Ecuador 2016, Italy 2016 (Amatrice, Visso, Norcia), New Zealand 2016.
C	Comparison of results obtained by	0%	No progress: it is a complex

	different groups/algorithms/approaches; consensus report.		activity which requires collaboration and funding.
C	Examine the gaps in existing acquisition plans over the major cities of the world in areas at high seismic risk (COSMO SkyMed,TerraSAR-X, Radarsat).	100%	All megacities in areas at high seismic risk are at least partially covered by SAR sensor. The study identified sites with good coverage using nearly global coverage missions as Sentinel-1 and ALOS-2, but for many sites there is not full coverage with ascending and descending acquisitions from Radarsat-2, TerraSAR X, and COSMO-SkyMed.
C	Product assessment by the final users	30%	Very slow activity due to lack of liaisons with end-users. Only DPC in Italy used products (INGV and CNR IREA) for the 2016 Italian earthquakes and Ecuador earthquake.
A, B, C	Development of the Web site.	100%	Successful
A, B, C	Development of procedures (for each agency) to ensure optimal data access in case of earthquakes over a certain threshold. (same for volcanoes)	100%	Successful for space agencies that have agreed to make available their data collections through GEP (ESA, JAXA, DLR, ASI), but more agencies shall make their data available through GEP so the activity is not 100% completed.

Lessons Learned:

Frame and objectives

- CEOS Pilots should have clear objectives not to be confused or interfere with operational disaster response services and capabilities.

Data order and delivery

- For some space agencies, the procedure to obtain post-event data acquisition was too slow. During an emergency, the post seismic images must be acquired within few days of the event.

Data use

- The use of SAR data for Obj. A (strain rate maps) has been boosted by the Sentinel-1 data, at least over areas where there is considerable ground deformation (e.g. Anatolian plate).
- X-band data was used to measure creep and local strain accumulation across large fault zones (initial results by Falk and Barry will be provided by June 2017).

- The use of SAR data for Obj. C has been successful in most cases however the lack of pre-event SAR coverage limited the choice of test cases to very few.
- Accounting of data used can be difficult in absence of user feedback.

Access processing tools

- Make access to EO easier:
  - o Users don't have to download large data files (benefit in countries with Internet bandwidth limitations)
  - o Users don't have to be processing experts (EO chains are automated);
  - o Users can share, compare, reprocess data (persistency of results, back analysis)
- The activity enables EO applications with massive volume and/or intensive processing computing, such as in the case of terrain motion monitoring based on InSAR or stereo-optical data, as needed for e.g. the Geohazards Supersites & Natural Laboratories initiative (GSNL).

Recommendations for rapid generation of results and improved accuracy of results

- A multi-sensor InSAR coverage can strongly improve the accuracy of the ground deformation measurement. The optimum would be to use at least one X-, C- and L- interferogram for each orbit direction (e.g. Amatrice, Cephalonia)
- If several InSAR datasets are available the EO data are normally sufficient to rapidly generate the preliminary source models useful for the initial situational awareness.
- Constraining the modeling with ground-based information (focal mechanisms, relocated seismicity, geological information, etc.) and jointly inverting the SAR results with other geodetic and seismic data (GPS displacements, strong motion data, broadband seismograms), largely improves the source detail. These are normally second order models, requiring several days to be generated.

Seismic pilot and end users

- The pilot carefully addresses expectations of EO practitioners (partners) and end users.
- Work with expert users to adapt geo-information to concrete needs.
- Ensures products are exploited / adopted by end users / decision makers.
- A pre-existing (possibly formal) relationship between the providers of the scientific information potentially useful for the crisis management (for all the objectives), and the local decision-makers, is fundamental to ensure the timely uptake of the information during the emergency (e.g. Nepal earthquake).
- Where there is limited capacity by the local users /decision-makers to interpret the results obtained from EO data, it is important that the final information product provided to the decision makers is obtained through a consensus process participated by all teams.

Sustainability:

The CEOS Seismic Hazards pilot demonstrated that if a good data' coverage is provided to expert-users, the resulting scientific information is of high value for the decision-makers in countries with well-equipped users. The demonstration was especially successful where the expert users were part of a nationally mandated DRM organisation, so that the information could be rapidly provided to the decision-makers using well established institutional channels.
The pilot partly addressed also the need for improvement of EO exploitation capacity in many high-risk countries, by stimulating international collaboration and providing common resources for EO data processing (e.g. the GEP), however these actions need to be expanded to include specific, high level training.

In particular, the CEOS Seismic Hazards pilot group has managed to address seismic hazards by providing access to data, but also access to tools and hosted processing (e.g. with the GEP) to generate needed information mainly after emergencies, as well as linking to available EO capacities thanks to the contribution of expert users (partner geoscience centers with EO expertise). So far, the pilot has primarily focused on EO practitioners and has very few end users, although some of the pilot expert users have managed to engage operational end users in concrete cases (e.g. in the context of earthquake response in Italy and Ecuador).

The CEOS Seismic Hazards pilot has been a well-set example to establish the basis of a new initiative with global activity in long-term seismic risk estimation, scientific research and emergency response. Achieving such results requires commitment both from data providers (in terms of data continuity, new sensors and evolving requirements) and from the expert users, who are often unfamiliar with the opportunities afforded by new technologies.

While the Seismic Hazards Pilot has achieved its goal to test and demonstrate EO based solutions with specialists and end users, in the logic of the CEOS WG Disasters activity, the pilot demonstration isn't intended to last and a new activity, the Seismic Hazards Demonstrator is proposed with the seismic hazards community.

The Seismic Hazards Demonstrator is intended to expand the precursor Seismic Hazards pilot activities. The activity is addressing three challenges identified in the precursor CEOS Pilots:

- Accessing EO data in a cost-effective way, since it is costly to access large volumes of data in order to achieve the objectives of the seismic hazards community (regional to global scale coverage).
- Communicating results to decision makers, based on a consensus methodology for product generation to avoid confusing end-users (especially, those in regions with low quality internet access and no access to processing capabilities).
- Increasing the timeliness of hazard analysis, by pursuing the development and standardization of automated chains for the generation and distribution of hazard maps and preliminary models.

The Seismic Hazards Demonstrator aims to articulate in an orderly fashion with global, regional and national EO based disaster response capabilities. As an example, it is building on the agreement in place since July 2015 between the International Charter and the CEOS WG Disasters.

In parallel, the on-line processing and e-collaboration were experimented though the pilot and the GEP. Based on the community needs and interest for on-line processing, the Geohazards Lab initiative is also proposed. The Geohazards Lab is a multi-thematic platform with federated resources that provides data delivery mechanisms, on-line processing tools and services and an e-collaboration environment (for more details see *Proposition – The Geohazards Lab*).

Next Steps:

Please see also the *Proposition-Seismic Hazards Demonstrator* and the *Proposition-The Geohazards Lab* documents.

User Feedback/Endorsements:

1. Stefano Salvi (INGV), Chair of the GSNL Science Advisory Committee explained that *"while the ESA Sentinel-1 satellite provided very important results, the role of commercial radar missions was also crucial to better resolve the details of the ground deformation and the seismic source. A substantial step forward towards exploiting the full societal benefit of satellite data would arise from the automatic provision of open EO data access for all large disasters"*, *"this development is a crucial step towards empowering society at large with the latest technology to reduce risk from geohazards".*

2. Following the analysis of DInSAR measurements in the aftermaths of the Nepal earthquake, Tim Wright director of the NERC Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET), commented that *"preliminary inspection of Sentinel-1 interferogram told us vital things about the earthquake instantly. The fact that we have a near-guaranteed response, and we can respond quickly, is a huge benefit from Sentinel-1".*

3. Patrick Ordoqui (TRE ALTAMIRA) who organised the integration of the DIAPASON processor in the GEP explained that *"the main benefit of technologies such as GEP is that they give users the possibility to perform complex processing of SAR data in a very user-friendly way. The user has immediate access to vast data archives, and the processors available need very little user interaction. In the case of the Kumamoto earthquake, the interferogram was processed on GEP within hours after the*

availability of the first post-event acquisition".

4. INGV's expert Cristiano Tolomei indicated that*, "One of the most useful tool in a web-platform such as GEP is the possibility to run multi-temporal interferometric processing, implementing different algorithms such as SBAS or other Persistent Scatterer Inteferometric chains, and exploiting the large computing power and storage capabilities present in GEP".*

5. Based on findings from the San Ramon fault (Santiago, Chile), John Elliott from University of Leeds stated: *"The Pleiades imagery performed well in this mixed urban and mountainous environment and allowed for the extraction of a Digital Elevation Model. Having the availability of Pleiades stereo imagery is critical to being able to map active faults in and around cities.*
Pre-existing SPOT-7 derived DEM was too low resolution to map the San Ramon fault accurately. The higher resolution and tri-stereo Pleiades imagery from the CEOS project enabled the generation of a much higher quality DEM which enabled accurate mapping of the fault geomorphology and active trace. We were able to derive fault scarp offsets as well from the DEM."