Aerial view of Amatrice, Italy on1 September 2016. Photograph: REUTERS/Stefano Rellandini

CEOS WG Disasters Seismic Hazards Consolidation Phase

Version 1.0

CEOS WG Disasters
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Executive Summary

The Seismic Hazards Consolidation Phase aims at addressing priorities of the *Sendai Framework for Disaster Risk Reduction 2015-2030* using Earth observations (EO) and in particular, *Priority 1 - Understanding disaster risk (hazard characteristics)* and *Priority 2 - Strengthening disaster risk governance at regional and global level*. At the 2016 GEO Plenary in Saint Petersburg the decision was made that Disaster Risk Reduction (DRR) is one of the three priority themes for the next few years. The main goal of the Seismic Hazards Consolidation Phase are to provide users with a mechanism to access to satellite EO data (e.g. based on yearly quota as typically done through CEOS Pilots),

The Seismic Hazards Consolidation Phase is an activity proposed as a follow-on of the Seismic Hazards Pilot within the CEOS WG Disasters to enable greater use of *observation data and derived products to assess seismic hazards and their impact*. The CEOS WG Disasters activities are focusing on Disaster Risk Management (DRM) with:

- DRR, addressing needs from both science users in geoscience centres and end users from mandated DRM organisations and workings directly with both types of users outside the disaster response phase,
- Disaster Response, addressing needs from science users in geoscience centres; as a baseline the Seismic Hazards Consolidation Phase fully articulates with operational initiatives such as the International Charter Space & Major Disasters, Sentinel-Asia and Europe's Copernicus Emergency Management Services; it is not interfering with them for data access in the crisis time; outreach to end users is possible based on the 2015 agreement between CEOS and the Charter that makes it possible to expose CEOS results in the disaster response phase to the Charter operational team (the so called Project Manager).

The Seismic Hazards Consolidation Phase 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 Consolidation Phase 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.

Best effort solutions			
	EO data collections CEOS Pilots, follow-on activities & RO GSNL Longer term: GEO-DARMA **Scientific processing environment & derived products** Geohazards Lab		**Rapid delivery of EO Data** International Charter Space & Major Disasters Sentinel Asia
Committed services			
Expert End User	**Value Adding Services** Copernicus Risk & Recovery Sentinel Asia	*Authorized DRM User*	**Rapid Mapping Services** Copernicus EMS UNOSAT etc.

Figure 1: the context of EO based DRM initiatives with examples of EO capabilities for DRM.

1. Background

The precursor CEOS Pilots were primarily concentrating on defining an observational strategy (ensuring data are acquired in advance) and delivering EO data collections to a pre-defined group of users engaged to exploit them and provide feedback. They are primarily looking at DRR i.e. hazard and risk assessment not on an emergency basis and also, to a limited extent disaster response. An overview of the different EO capabilities contributing to DRM is given in Annex 1. For instance, to cite two examples, Pilot activities conducted on an emergency basis include advanced tectonic products for earthquake response primarily for scientific analysis (CEOS Seismic Hazards Pilot).

Overall, for emergency response, the baseline is the collaboration with existing EO disaster response capabilities (see list in Annex 2) providing damage mapping such as for instance the International Charter Space and Major Disasters, with whom, the Copernicus EMS, Sentinel Asia, etc. Through such collaboration the Seismic Hazards Consolidation Phase will generate advance science products for scientific analysis (primarily aiming to scientific users) during the response phase. Since July 2015 the CEOS WG Disasters has an agreement in place with the International Charter to allow sharing such products with the Charter Project Manager to allow reaching end users access them.

The Seismic Hazards Consolidation Phase aims to continue providing access to data alongside the procedures managed by the CEOS Data Coordination Team (DCT).

2. Concrete objectives

Much of the focus of disaster activity is currently on the high-profile response phase (see Figure 2) during which rapid action can save lives. Satellite EO is a recognized solution for enabling more efficient relief actions and supporting aid actors with objective and up to date information. It is however widely accepted that increased efforts on risk reduction during the mitigation and warning phases of a disaster will save more lives and protect property by reducing the exposure of populations to the seismic hazard. An enlarged CEOS action plan should consider the entire cycle of risk management (mitigation, warning, response and recovery), especially considering existing efforts with regard to response, principally through the Charter, Sentinel-Asia and Europe’s Copernicus programme, its end to end services based on the Copernicus Sentinel missions and other contributing missions, as described in Figure 3. While much has been improved in the last ten years, major gaps remain with regard to critical disasters, especially in the area of disaster risk reduction.

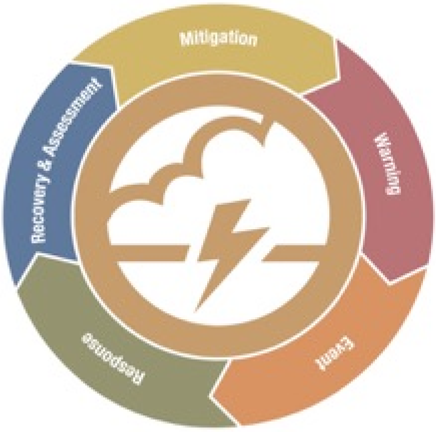


Figure 2: DRM phases: DRR and disaster response. The Seismic Hazards Consolidation Phase is addressing both DRR and disaster response and articulates with operational EO based response initiatives.

Disaster Response Capabilities:	*Example:*	*Access:*	*Content:*
Operational Capability for EO data	International Charter	Predefined users	EO data (VA on a case by case basis)
Operational capability for end to end services	Copernicus EMS, Sentinel Asia, etc.	Predefined users	VA services
	UNOSAT	UN users	
Scientific capability	CEOS Seismic Hazards Consolidation Phase	Predefined users	Advanced tectonics products
	Geohazards Lab	CEOS users and other predefined users	Hosted Processing and e-collaboration
	GSNL	GSNL users	EO and in-situ data

Capabilities for DRR (not on an emergency basis):	*Example:*	*Access:*	*Content:*
Operational Capability for EO data	International Charter via CEOS	CEOS users	Transfer of data through agreement with CEOS WGD
Operational capability for end to end services	Copernicus Risk & Recovery, Sentinel Asia, Servir, etc.	Predefined users	VA services
Scientific capability	CEOS Seismic Hazards Consolidation Phase	CEOS users	Advanced tectonics products, active fault maps and strain rate maps
	Geohazards Lab	CEOS users and other predefined users	Hosted Processing and e-collaboration
	GSNL	GSNL users	EO and in-situ data

Figure 3: Capabilities of different DRM initiatives based on satellite EO.

Based on concrete objectives that are directly derived from the 'International Forum on Satellite EO & Geohazards' (c.f. section 2) the Seismic Hazards Consolidation Phase intends to support the following activities:

A. Concerning DRR activities not on an emergency basis:

- Pursue and expand global tectonics mapping activity such as strain rate mapping (e.g. with the LiCSAR service of COMET);
- Expand active faults mapping from regional to global level including also urban active faults and pursue reconnaissance mapping of active faults using stereo optical data and derived DEMs to ensure that a reference coverage is available in advance over priority areas and to provide fresh coverage in case of significant deformations. This is as per Objective A) of the seismic hazards community;
- Pursue support to the GSNL initiative; when the Geohazards Lab initiative that is proposed in parallel is adopted & implemented, the GSNL initiative shall be supported by it (storage, hosted processing, etc.);
- Develop a collaborative framework with geoscience centres to ensure a consensus methodology for product generation is adopted and to demonstrate relevance of advanced EO products to a broader base of users (see Collaboration with the Charter); concerning geoscience centres typically are End Users (e.g. recipient of the EO data in the Charter jargon) and they have a role to do science as experts and, in some instances, to advise DRM authorities.

B. Concerning DRR activities on an emergency basis:

- Pursue science products based on terrain motion mapping e.g. advanced tectonics mapping using Sentinel-1 for earthquake response (deformation maps, source models, etc.) as per Objective C) of the seismic hazard community; expand this capability with VHR SAR missions (e.g. Cosmo-Skymed, TerraSAR-X, Radarsat) to provide interferograms and motion maps within a virtual constellation; expand this capability with VHR Optical based measurements such as stereo based DEMs and deformation maps.
- Collaborate with EO based disaster response capabilities such as the International Charter Space & Major Disasters, the Copernicus EMS and Sentinel Asia (see section 7): articulate with these initiatives to make sure users are aware and work with these capabilities; on a case by case and best effort basis, propose new products complementary to the damage mapping they provide (for instance InSAR based tectonic products such as earthquake source models as used in the context of the 2016 earthquakes in central Italy).

Examples of the activities proposed by the Seismic Hazards Consolidation Phase are given in Figure 4 below.

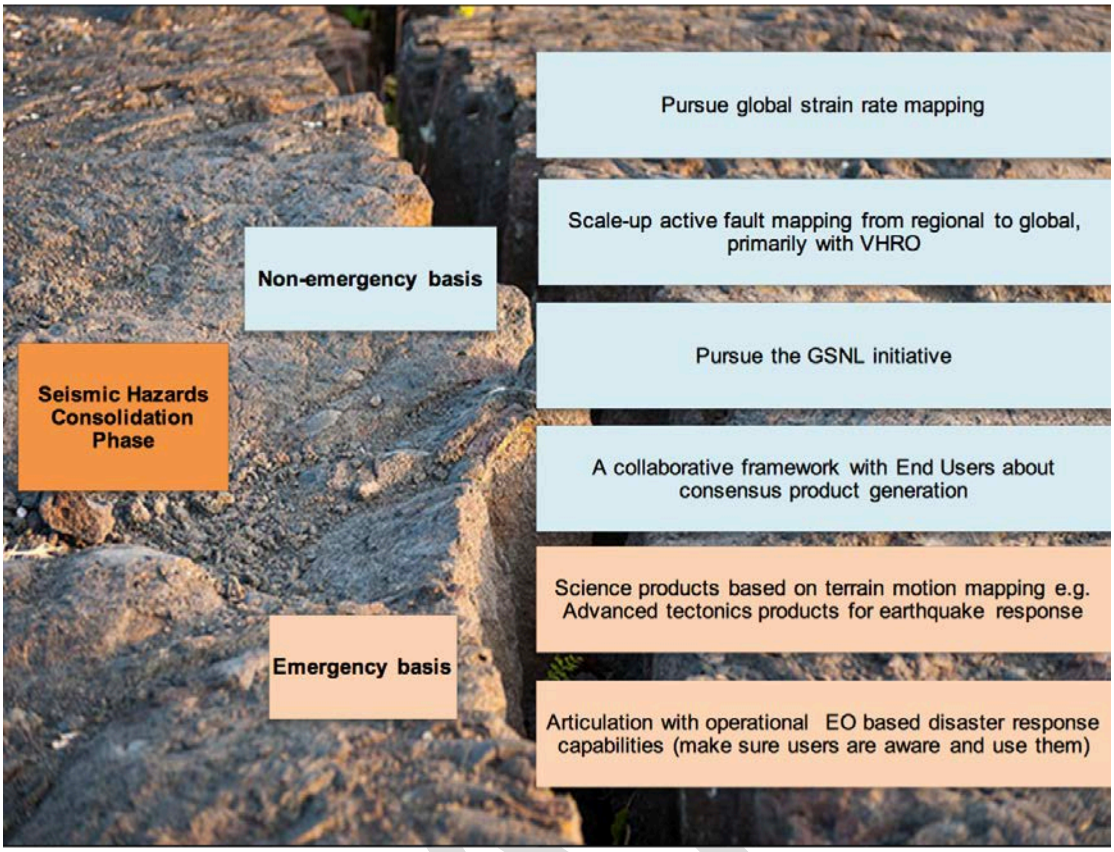


Figure 4: Potential activities of the Seismic Hazards Consolidation Phase. The Seismic Hazards Consolidation Phase is primarily focusing on science users and end users working on seismic hazard mapping and risk assessment for DRR, it also contributes to activities in the emergency response phase although this is not about disaster response users but science users on a best effort basis. Any activity focusing on disaster response users is managed by operational capabilities such as for example the International Charter with whom the Seismic Hazards Consolidation Phase will collaborate to reach end users involved with disaster response.

Geographic priorities: the seismic hazards community has defined and presented its observational strategy in the framework of the CEOS WG Disasters (c.f. report 2013-10-30_CEOS DRM Observation Strategy). Priority areas include global regions concerned with seismic hazards. For instance, the global tectonic mask provided to the CEOS WG Disasters includes large portions of Land surfaces as illustrated in Figures 5.

Figure 5: geographic priorities of the seismic hazards community.

3. Users and Benefit

The user base of the Seismic Hazards Consolidation Phase includes a range of users and practitioners of satellite EO with an interest in observing and measuring hazards and risks related to earthquakes. The views, needs and objectives of these users are captured in the Santorini report (available at: http://esamultimedia.esa.int/docs/EarthObservation/Geohazards/esa-geo-hzrd-2012.pdf) and further consultation and workshops. The type of users concerned includes those involved with the Pilots of the CEOS WG Disasters.

3.1. Types of users

The Seismic Hazards Consolidation Phase is aiming to provide advanced science products to different types of users:

- ***geoscience centres doing research or mandated to provide technical advice to national DRM authorities already contributing to the Seismic Hazards precursor activities***. Geoscience centers such as geological surveys, geophysics centres looking at seismic hazards are the first line users focused on the scientific use of data that aim to understand the physics of seismic hazards and better characterise, understand and model such risks. In many cases, they have an advisory role in decision making of DRM authorities. In some cases, EO experts, being part of these geoscience centres, process, analyse, validate, integrate the EO satellite data (using ground based data) to extract the maximum amount of information useful for DRM, and generate a simple, synthetic information product which can be understood and used by decision-makers to take effective decisions. Examples of geoscience centers already contributing to precursor seismic activities such as the GEP are INGV, CNR-IREA and CNR IRPI in Italy the ARIA center of NASA JPL and USGS in the USA, NOA in Greece, BGS and COMET/Univ. Leeds & Oxford in the UK, ENS, CNRS, IPGP, ISTerre and BRGM in France.
- ***national DRM authorities*** can be considered as second-line users.
  As a baseline, the Seismic Hazards Consolidation Phase articulates with national disaster response activities and with international EO disaster response capabilities such as the International Charter, Copernicus EMS, Sentinel Asia, etc. in order to make sure users are aware and use them. The Seismic Hazards Consolidation Phase will fully take into account the role of national and international initiatives with an operational mission. The main contribution of the Seismic Hazards Consolidation Phase will be to help develop or reinforce the ability of geoscience centres to support national DRM authorities.
- ***academia***: universities and institutes mainly focusing on research.
- ***other users that may benefit from the Seismic Hazards Consolidation Phase*** include national user organisations in the context of international development; beyond DRM authorities a range of national users have information needs related to natural hazard risk management such as for instance authorities in charge of basin for water resources management

(reservoir monitoring against erosion and landslides, etc.), of transportation, energy and extractives, etc.

- in addition, ***users from industry*** may benefit from the capability (e.g. civil engineering, insurance/re-insurance, etc.) noting that the Seismic Hazards Consolidation Phase is focused both on science and end to end solutions to decision makers such as provided by Value Adding service providers. However, the link to industry users is mid-term rather than short term.

The user base of the Seismic Hazards Consolidation Phase is intended to expand thanks to an activity to create a collaborative framework with geoscience centres to raise awareness and initiatives to achieve adoption of new methods (e.g. the consensus product generation concerning advanced tectonic products for earthquake response, as described in section 3.2).

3.2. Benefit to users

The Seismic Hazards Consolidation Phase shall rely on pre-existing relations between geoscience centres and end users/decision makers to better understand the end users' expectations (e.g. there are end users with basic EO knowledge that could interpret EO results or others who prefer to receive analytic reports based on these results) and to ensure faster information exchange.

Although the research is complete for advanced EO products such as terrain motion maps (e.g. InSAR based tectonics product to support earthquake response), a consensus methodology for product generation and guidelines on interpretation by the users are required in order to avoid confusing the users about the content of advanced products such as those relating to co-seismic terrain deformations. This is illustrated in Figure 7 below.

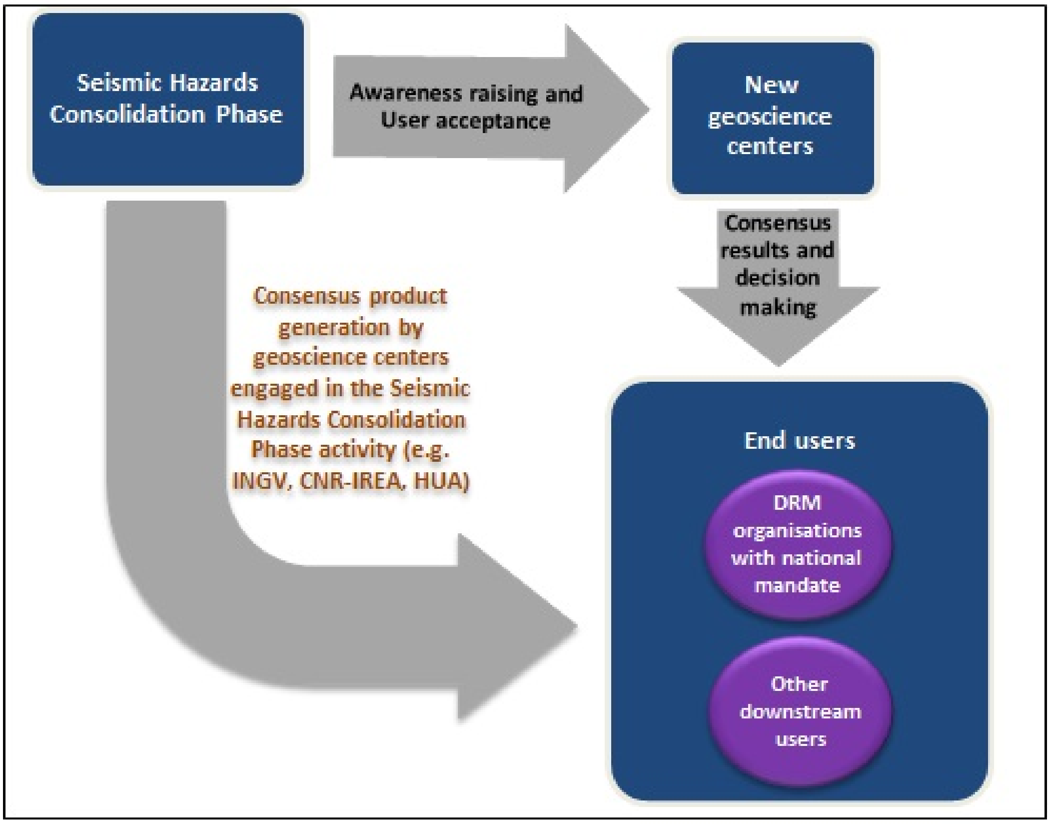


Figure 7: EO information flow from the Seismic Hazards Consolidation Phase to the end-users, example with advanced scientific products i.e. products by expert users engaged in the CEOS initiative potentially delivered to DRM end users (as e.g. in the case of Italy in the Seismic Hazards pilot) on a best effort basis.

4. Contributions

- First screening of contributions from CEOS members:

CEOS agencies that have expressed interest in joining the initiative include ESA, DLR, ASI and CNES (ESA also started to present the activity to CSA, USGS, NASA and JAXA and the seismic hazards community). Contributing to the Seismic Hazards Consolidation Phase may take one or several of the following forms:

i. EO data – *potential sources, examples:* Sentinel-1 and Sentinel-2 from Europe's Copernicus programme, TerraSAR-X from DLR, Pléiades & SPOT-6 from CNES, Cosmo-SkyMed from ASI and ALOS-2 from JAXA to cite the highest data volumes in regards to community needs;
ii. Work on global strain rate mapping
iii. Work on active fault mapping in a global scale
iv. Demonstration of generation of advanced science products using EO data stemming out of the activity and when possible, provision of these results (e.g. reports) to decision makers.
v. Definition/demonstration of new methodologies to generate higher level tectonics products.
vi. Participation in conferences, presentations, publications and web-articles to demonstrate results stemming out of the Seismic Hazards Consolidation Phase.
vii. Participation in collaborative work between the Seismic Hazards Consolidation Phase partners to support the consensus methodology for product generation.
viii. Liaising with geoscience centres (based on pre-existing or new relations) that currently are not contributing to the Seismic Hazards Consolidation Phase to establish a consensus methodology for product generation and achieve adoption.
ix. Support coordination of the activity and articulation with other EO disaster response capabilities.

Contribution from ESA:

- Access to ESA missions data ex archive: ERS SAR and ENVISAT ASAR data will be made available over the areas of the Supersites (GSNL) and over extended areas for tectonic analysis e.g. strain rate assessment, active faults mapping, etc.
- Access to Sentinel-1A & 1B and Sentinel-2A data in line with the Copernicus Data Policy.
- Access to the Geohazards Exploitation Platform through the parallel Geohazards Lab initiative, including in particular: data storage and ICT resources, including transparent access to other cloud providers processing resources; Query interface to select the data (GeoBrowser), interoperability with the data viewers, processing software to ease the use of EO data to support geohazard science including EO data preparation toolbox such as SNAP concerning ESA data, new software and workflows in particular InSAR and stereo-optical processing chains (for instance the MPIC-OPT processing chain developed by CNR EOST), etc.

- Support the coordination/supervision of the Seismic Hazards Consolidation Phase activities.

Contribution from DLR:
DLR shall contribute on the Seismic Hazards Consolidation Phase, on a voluntary basis by:

- Supplying TerraSAR-X data at no cost for scientific use that can be organized by interfacing with DLR's existing data access platform established for the Geohazard Supersite initiative and used also for the CEOS Disaster pilots. Additional data support outside the quotas already approved for Supersites and AOIs of Disaster Pilot projects require a case-by-case decision in coordination with the commercial TerraSAR-X partner Airbus.

Contribution from ASI:
ASI will potentially provide COSMO-SkyMed data and shall make available CEOS and GSNL Cosmo-SkyMed collections through the GEP (already done for the Nepal event supersite).

Contribution from CNES:
Access to up to 20000 km2 of Pleiades data per year.

- First screening of contributions from the seismic hazards community:

Members of the seismic hazards community that have been exposed to precursor activities such as the CEOS Seismic Hazards pilot and the Geohazards Exploitation Platform include INGV (IT), CNR-IREA (IT), CNRS EOST (FR), ISTerre (FR), IPGP (FR), NASA JPL (USA), USGS (USA), COMET (UK), NOA (GR), HUA (GR) and other geoscience centres.

Concrete contributions from the seismic hazards community include:

Contribution from INGV:

- INGV supports the Seismic Hazards Consolidation Phase and intends to coordinate with the existing national and international operational support schemes and frameworks. The INGV contributions will be defined in more detail later, however it is anticipated that INGV is interested in the EO data access provided by the Seismic Hazards Consolidation Phase to generate scientific products useful in the global context of DRR.

Contribution from CNRS IPGP :

- IPGP, in collaboration with IGN, is involved in developing an optical-images correlation tool, MicMac, and its preprocessing tools, in order to compute DEM from any optic satellite sensors providing simple or multi stereo images. This software package is open-source. The code, MicMac, following same methodologies, allows as well computing maps of displacement between two satellite acquisitions of the same scene. In the framework of the Geohazards Lab initiative IPGP will continue such developments to improve multi-sensor capabilities as well as correlation of diachronic images to measure changes. Result of application to earthquakes and volcanic events will be published on the platform. In addition, IPGP will continue its effort to compute high resolution DEM in active tectonic regions worldwide to build a body of data to be used to map active faults. This high resolution topography will also serve as an archive in case of major event, such as earthquake or volcanic eruption, to allow quick re-tasking of satellite acquisitions to compute post-event DEM allowing 3D deformation measurements to be used in non-emergency studies, but potentially as well in emergency situations, assuming that technical capabilities and human resources would have been assigned to such task.

Contributions from COMET:

- Access to COMET-LiCSAR results from Sentinel-1. These will include interferograms, coherence maps and line of sight time series for the tectonic belts,

- Access to strain maps produced by COMET-LiCSAR from the integration of InSAR and GNSS results,
- Rapid access to interferograms and other EO data sets produced by COMET when we respond to Earthquakes,
- Links to COMET's modelling results for earthquakes,
- Access to COMET's InSAR training material and provision of training courses,

Contribution from CEO-YachayTech:

The recently created Earth Observation Center (EOC) in Yachay Tech University in Ecuador will conduct research in the field of remote sensing and geo-information sciences. Data from satellites, planes, drones and geophysical surveys contribute to understand our planet, secure our environment and manage our resources which clearly will transform and improve the understanding of Earth. The EOC will be applied to problems across a whole spectrum including among others, earthquake studies. The CEO will work together with other public institutions in charge of natural disaster management and monitoring.

- Access to EO products from visible data represented as disaster areas, vulnerability and risk maps.
- Access to EO products from earthquake monitoring using interferometry.
- Access to EO products and maps from areas affected by earthquakes.

Contribution from Harokopeion University of Athens (HUA):

Land motion has become increasing concerns in modern cities, affecting both population and infrastructure. Land deformation could lead to serious economic loss through damaged building, roads, gas/water pipes, utilities and telecommunication cables and in cases may indirectly threaten human live. The earthquake cycle of an active fault may include co-seismic rupture and inter-seismic deformation. During the inter-seismic stage that usually ranges from a few hundreds to thousands of years, crustal tectonic strain may be silently accumulated. The strain is released during the inter-seismic period, especially along creeping active faults. Understanding active tectonic processes and related energy release through monitoring of the transient deformation of strain accumulation process has become fundamental for several human activities. Additionally, local deformation type of a fault and the area near the fault may determine the extent of the seismic hazard as well. This allows taking into consideration measures and activities for seismic hazard mitigation.
Monitoring of active faults' inter-seismic behavior in urban areas is of great importance, as the local exposure (population, infrastructures etc.) increases the risks. Recently, inter-seismic crustal velocities and strains have been determined for a number of active areas, through repeated measurements using a Global Position System. In some cases, the terrain is remote and the accessibility is difficult and thus the density of GPS measurements is relatively sparse, or in the case of urban environments, the operation of GPS receivers may be interrupted

due to the frequent blockage of signals. Also, other geophysics methods faced difficulties because of the continuous urban shell. Following SAR interferometry techniques the potential inter-seismic deformation could be detected and measured indirectly through the deformation effect on overlying structures.
Two main products could be derived following interferometric techniques, which can provide essential inputs both monitoring the movement of an urban fault collecting qualitative and quantitative data and the spatial dimension of the urban fault impact on overlying infra-structures contributing thus contributing to prevention tasks. The first one, "Synoptic view of urban deformations", provides a global monitoring of the deformation phenomena recognizing, based also on collateral data, potential active faults and spatial impact. The second one, "Single infrastructure: deformations" provides information on the stability of structures giving hints on the structural their health and, in particular, on the structure response to earthquakes. In general, structures are less affected by uniformly distributed ground displacements compared to differential ground motion. A uniform displacement of a region may not be even noticeable in some cases. Similarly, uniform displacement of a structure does not damage the construction itself. It is mainly the differential displacements that might cause damages to structures. So, in this case appropriate data scale (high resolution SAR scenes) is the required condition.

Contribution from the National Cartographic Center of Iran:
TBD

Contribution from NASA JPL:
TBD

Contribution from University of Miami:
TBD

Contribution from CNR-IREA:
TBD

Contribution from Isterre:
TBD

Contribution from the National Observatory of Athens (NOA):
NOA shall process timely SAR data from missions like TerraSAR X and COSMO Skymed (e.g. the Cephalonia case), using the processing capacities in BEYOND and deliver valuable scientific results and papers/web-articles.

5. Examples of how the Seismic Hazards Consolidation Phase will support DRR

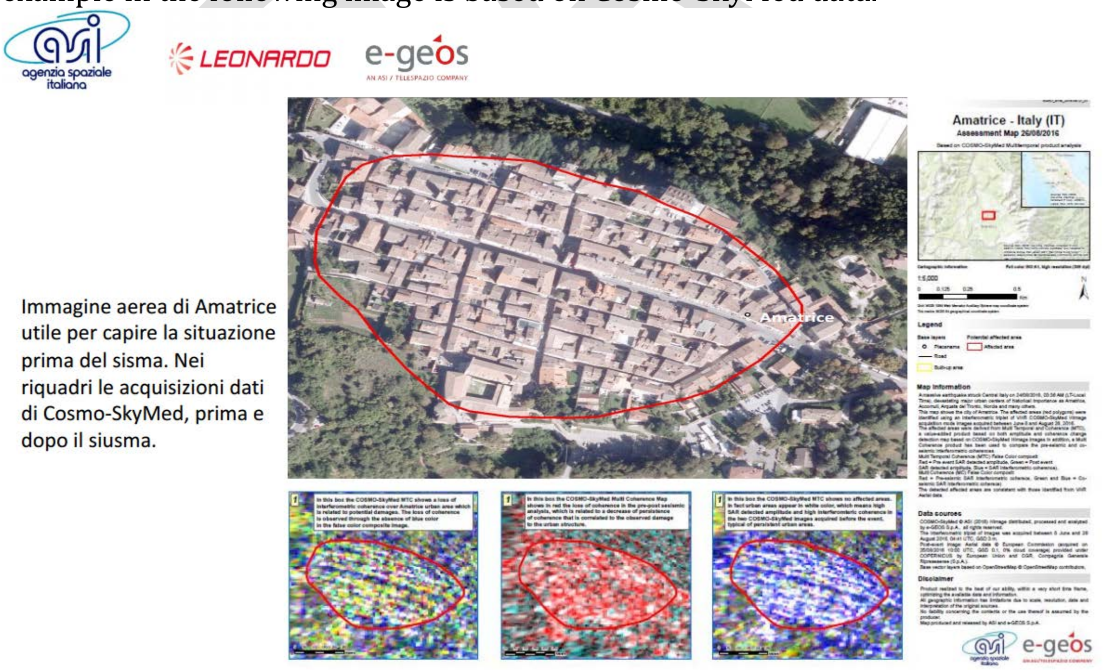
Here below, examples of achievements from the Seismic Hazards pilot and the GSNL are described.

The contribution of the Italian Space Agency ASI at national level for earthquake emergencies in Italy:

On 24 August 2016 at 3:36:32 CEST an earthquake hit Central Italy. It measured 6.0 on the moment magnitude scale and its epicentre was close to Accumoli in a depth of 4±1 km. Buildings in the villages of Amatrice, Accumoli and Arquata del Tronto collapsed and caused nearly 300 fatalities.

As the national responsible organization for the provision of satellite EO data in the context of disaster response in Italy, ASI has organized the tasking and delivery of imagery to help better understand the hazard.

While the Italian Civil Protection was currently in action and had requested support to the Copernicus Emergency Management Service (EMS) with damage mapping services, ASI organized the provision of additional data collections to estimate terrain displacements due to the earthquake and therefore support the geohazard analysis performed by specialist agencies and decision makers. The example in the following image is based on Cosmo-SkyMed data.



ASI also has agreements with other space agencies to organize data acces for geohazard emergencies in Italy. For example the **Italian Space Agency** (ASI) and the **Japan Aerospace Exploration Agency** (JAXA) have signed an agreement in end 2016 to strengthen their cooperation on Disaster Risk Management by using data from Earth Observation satellites.

Central Italy Earthquakes: EO products to expert users and decision makers.

In the context of the CEOS WG Disaster, the CEOS Seismic Pilot is looking at earthquake hazards and has strong links with the Geohazards Supersites and National Laboratory (GSNL) initiative of GEO. Objective C) of the CEOS Pilot is focusing on advanced science products for rapid earthquake response. Typically this concerns events that are not Supersite Events of the GSNL. The same day as the earthquake hit Central Italy, the CEOS Seismic Pilot was activated by the specialists of INGV, the National Institute of Geophysics and Volcanology of Italy, which is the main Center of Competence for seismic and volcanic risks, committed to provide real time, 24/7 monitoring and scientific support to the Italian Civil Protection (DPC). The aim was to provide access to EO data to a variety of pilot contributors, and generate advanced science products to support the emergency activities. This is complementary to the Copernicus Emergency Mapping Service (EMS). The EMS was activated by the national civil protection authorities and generated damage maps, situation maps and other products to help search and rescue.

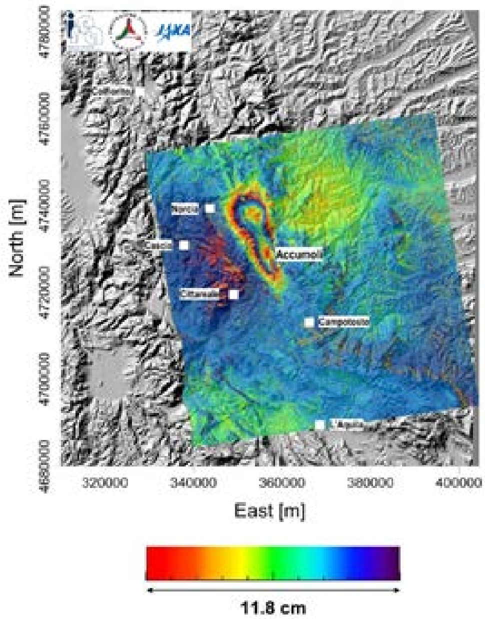


Figure 8. Interferogram generated by CNR-IREA, exploiting ALOS-2 acquisitions of 27th January 2016 and 24th August 2016.

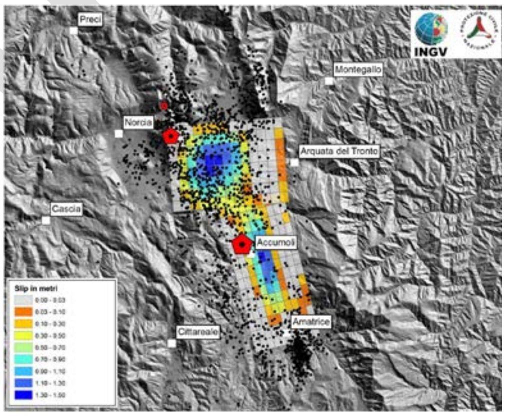


Figure 9. Preliminary earthquake source generated by INGV exploiting the terrain motion measurements from ALOS 2 and Sentinel-1 acquisitions from before and after the 24th August earthquake. These data were modeled to calculate the location, geometry and amount of slip on the source fault. The slip is distributed mainly in two patches with maximum values of about 1.4m.

The CEOS Seismic Pilot activation generated a range of specialised products useful to support seismological analysis. They were mainly based on both VHR SAR missions such as Cosmo-SkyMed and HR SAR missions such as JAXA's ALOS-2 PALSAR mission (**Figure** 8) and the Copernicus Sentinel-1 mission (Figure 9). The InSAR products were ground deformation maps, identifying also earthquake effects as fault scarps and landslides, and seismic source models. Optical data (e.g. stereo VHR Optical data such as CNES's Pléiades data) were also used to generate additional products, such as reconnaissance maps of newly formed active faults, and precise DEMs.

A number of InSAR interferograms were produced using Sentinel-1, Cosmo-SkyMed and ALOS-2 data and the same datasets (Figure 10) were subsequently

used to constrain source models of the fault ruptures (e.g. the source model in Figure 11).
The Amatrice source was independently modeled by INGV using strong ground motion data from the RAN accelerometric network. The kinematic model shows a fault geometry and a bimodal slip distribution similar to that obtained from InSAR data (Figure 12).

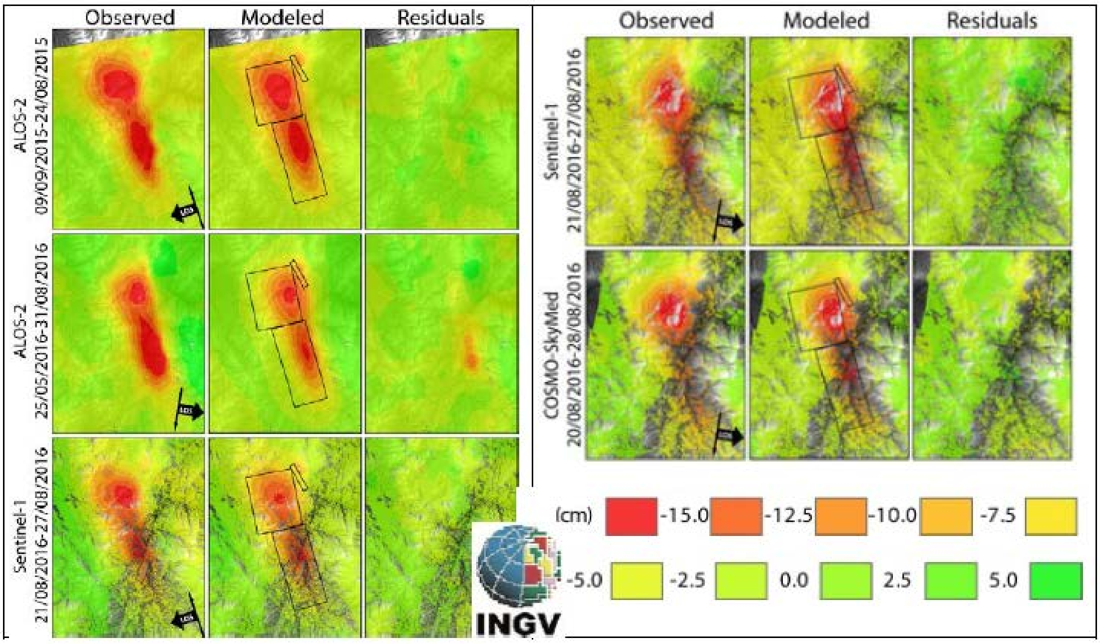


Figure 10 - Input InSAR datasets and results of the source modeling generated by INGV. For each dataset the inverted data (Observed column) the model simulation (Modeled column) and the difference (Residuals column) is shown. These results refer to the source model shown in Figure 11. Note that COSMO-SkyMed data and ALOS-2 data post August 24, were provided by ASI as part of the national response to the emergency.

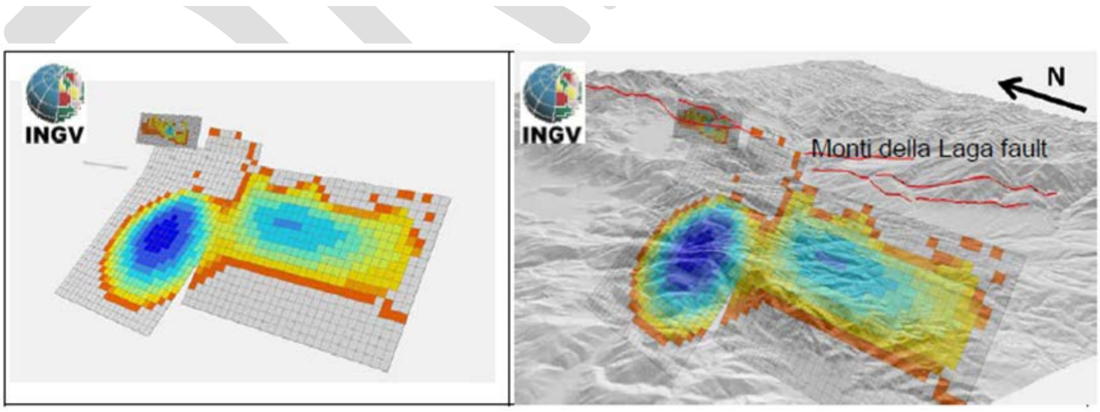


Figure 11 - The source model for the August 24 Amatrice earthquake. It is composed of two nearly co-planar ruptures. The northern rupture shows deeper and stronger slip. The shallow small fault at the northern end simulates the gravitational deformation observed in the Monte Vettore western flank (see Figure 9). This is not connected with the deep slip and is likely not directly related to the fault dislocation. Credits: INGV.

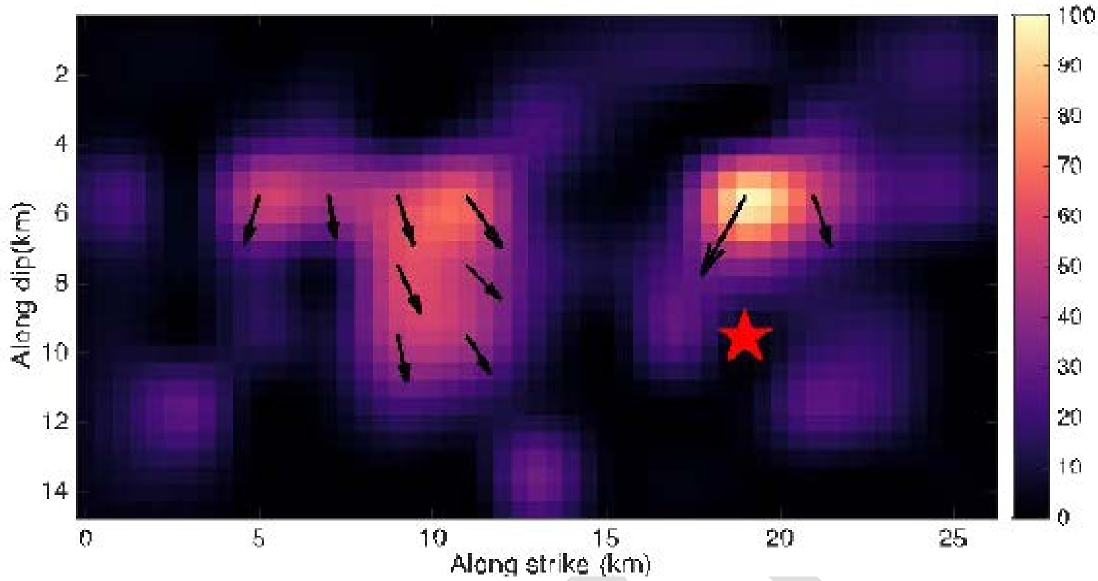


Figure 12 - Slip distribution obtained by the kinematic source modeling using RAN accelerometric data. The analysis by INGV combines satellite EO and non satellite data and is provided to national authorities involved with the crisis. Credits: INGV.

For the Mw 5.9 earthquake that hit Visso on 26 October and the Mw 6.5 that hit Norcia on 30 October, INGV produced ALOS-2 and Sentinel-1 interferograms (Figures 13 and 14). The source model revealed that the main rupture occurred on the Monte Vettore-Monte Bove fault, extended NNW for over 25 km (Figure 16). All COSMO-SkyMed data and ALOS-2 data post August 24, processed by INGV were provided by ASI as part of the national response to the emergency.

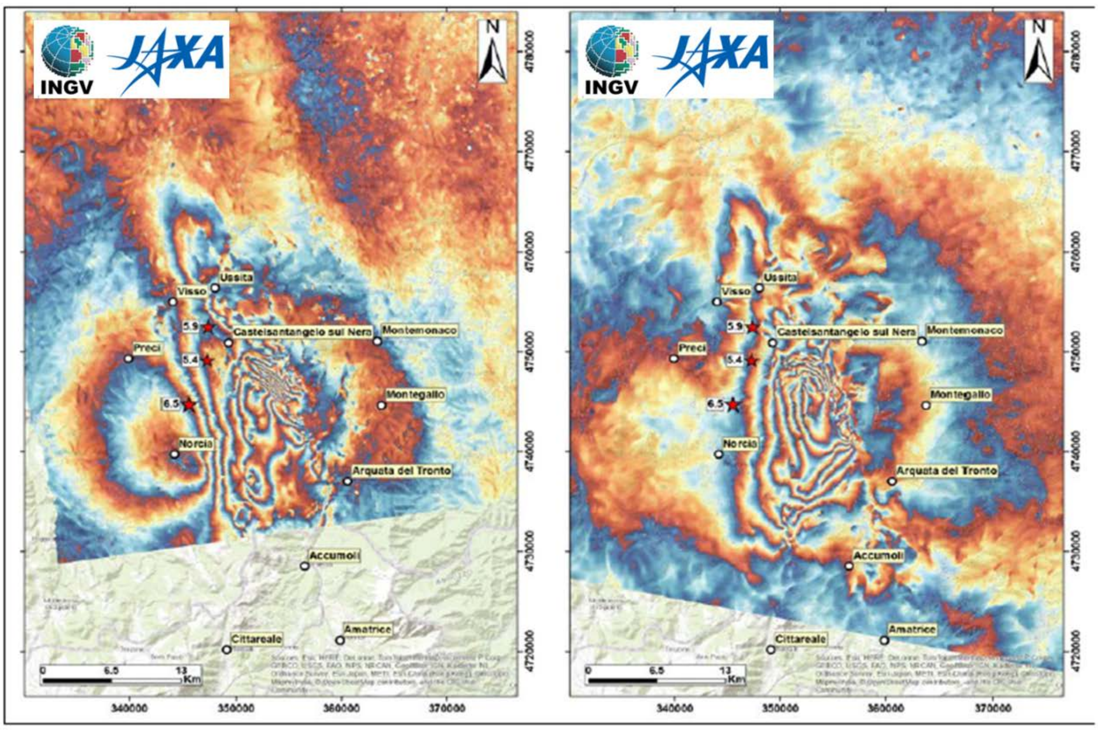


Figure 13 - ALOS 2 interferograms showing the cumulated ground deformation caused by the October 26 (Visso) and 30 (Norcia) earthquakes. The left image shows an ascending interferogram covering the period August 24 - November 02, 2016. The right image shows a descending interferogram covering the period August 31 - November 09. The main-shocks of October 26 and 30 are shown as red stars. Each colour fringe represents 12 cm of Line of Sight ground displacement. Credits: INGV, JAXA data provided by ASI.

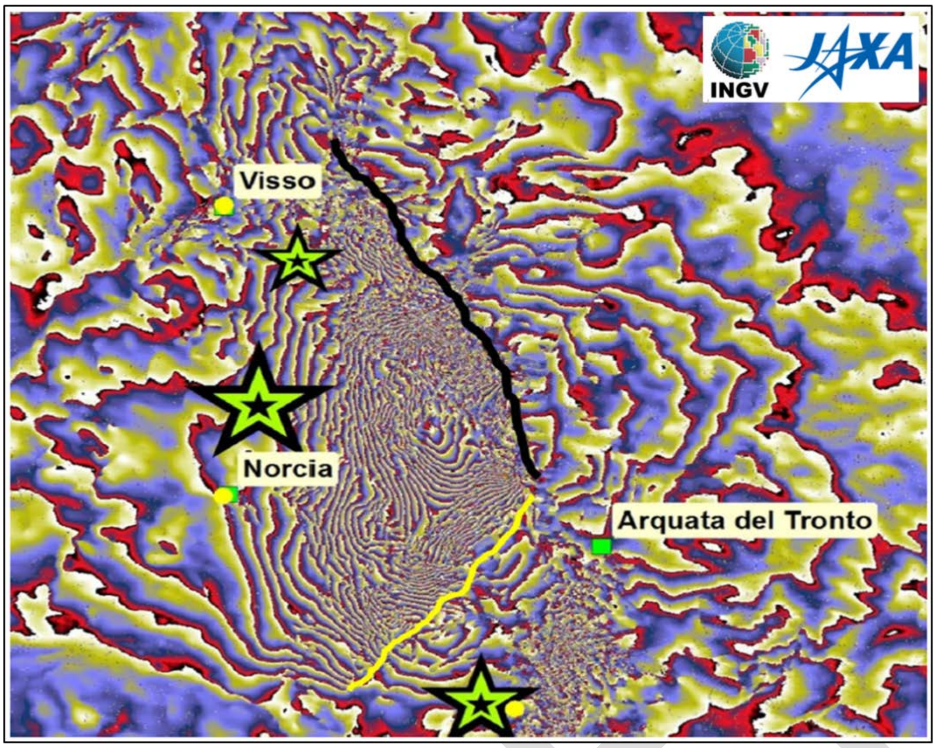


Figure 14 - A detail of the descending Sentinel 1 interferogram, showing the linear fringe discontinuities corresponding to ground breakage. The black line has been identified with a co-seismic scarp with 1-2 m displacement on the Monte Vettore fault (see photos in Figure 15). The yellow line has not been verified into the field but may represent the surface expression of a lateral fault which has been modeled by the inversion of InSAR data. Credits: INGV, JAXA data provided by ASI.

Figure 15 - Field photographs of the large normal fault scarp caused by the October 30 mainshock of Mw 6.5. The scarp corresponds to the fringe discontinuity mapped in all the interferograms. Credits: INGV.

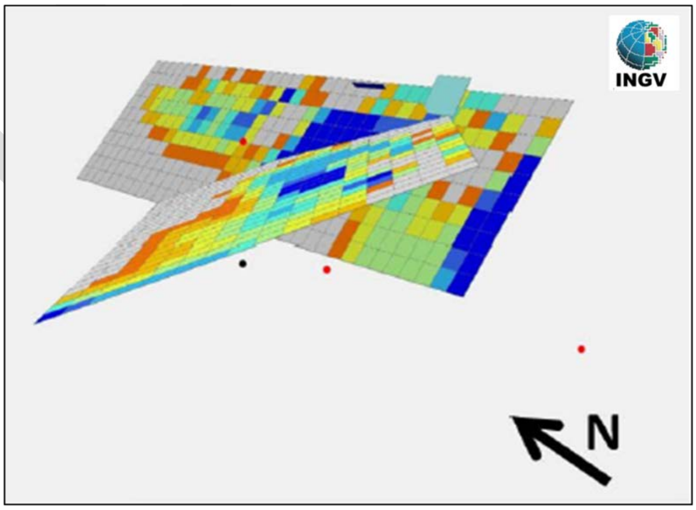


Figure 16 - The source model for the October 26 and 30 events. The main rupture occurred on the Monte Vettore-Monte Bove fault, extended NNW for over 25 km. Credits: INGV.

The April 2016 Ecuador earthquake: EO based products delivered by experts to national DRM authorities via the Italian DRM authorities.

The Institute for Electromagnetic Sensing of the Environment (CNR-IREA) contributes to the Seismic Hazard pilot and is Center of Competence (CoC) on DInSAR[1] for the Italian Civil Protection Department (DPC). In case of major (Mw >6) and shallow depth earthquakes occurring within the Italian territory, CNR-IREA has the mandate to rapidly provide the DPC with DInSAR Earth surface deformation maps, as soon as the first post-seismic SAR[2] acquisition is available.

DPC may also ask for displacement measurements related to earthquakes that occur abroad, in the framework of international collaborations with foreign authorities, as in the case of the earthquake that stroke Ecuador on 16 April 2016 (Figure 17).

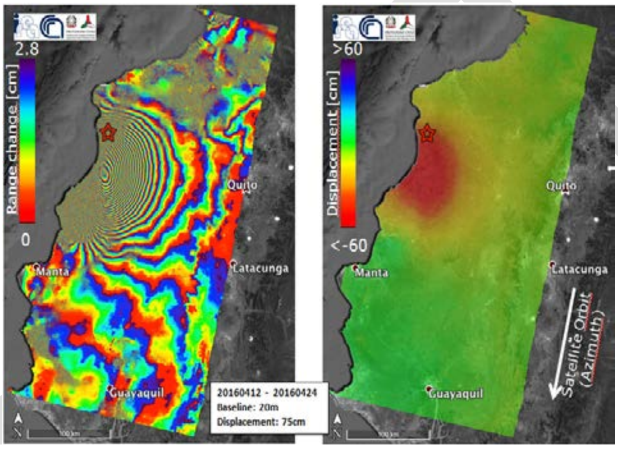


Figure 17. Interferogram and displacement map generated by CNR-IREA, exploiting two Copernicus Sentinel-1 acquisitions of 12 and 24 April 2016.

For this event, on April 17, 2016, the Ecuador government asked assistance to the Directorate-General Humanitarian Aid and Civil Protection of the European Commission. On this basis and under the coordination of the United Nations, Italy logistical support and technical experts to be provided for the evaluation of strategic buildings on site.

Within this frame, DPC asked CNR IREA a detailed report on the surface deformations due to the mainshock, which was also forwarded to the Ecuadorian authorities of civil protection. Through Objective C) of the CEOS Pilot, CNR IREA generated and shared results based on Sentinel-1 data. The deformation maps were used by DPC and other DPC CoCs to understand the extent of the area affected by displacements and better focus the DRM activities of decision makers. Moreover, these maps can be used to model the seismogenic fault in order to increase the knowledge on the earthquake and its causes.

[1] DInSAR : Differential SAR Interferometry
[2] SAR : Synthetic Aperture Radar

The 2015 Nepal Event Supersite: an international effort to better understand the impact of the Gorkha earthquake.

The area of Nepal deeply affected by the M7.9 earthquake of April 25, 2015, became an Event Supersite soon after the main shock, following requests from the geophysical scientific community to the Geohazard Supersite and Natural Laboratory initiative of GEO (www.earthobservations.org/gsnl_es_nepal.php).

Many CEOS agencies started to acquire satellite data over the Supersite, and ESA, ASI, CSA, DLR, NASA, USGS provided access at no-cost to GSNL users for these data. JAXA provided ALOS-2 data for the earthquake through the Seismic Hazards pilot Objective C. Data from ground networks were provided by UNAVCO and IRIS.

A number of scientific products were generated –among others- by INGV, NASA JPL, COMET, CNR-IREA and IPGP to measure the displacement and were combined with geological data to map the precise shape of the fault plane at depth and the amount of relative slip of the fault limbs.

The Event Supersite page provided reference to the data resources and also, for the first time, to several scientific products freely shared in digital form to allow re-use by scientists.

The data and the products were also provided to:

- end-users such as decision making bodies e.g. National Disaster Management Authority (NDMA) and National Emergency Operation Centre (NEOC)
- local scientific institutions in charge such as the National Society for Earthquake Technology (NSET) and other academic institutions
- the international scientific community, through scientific papers or web-stories.

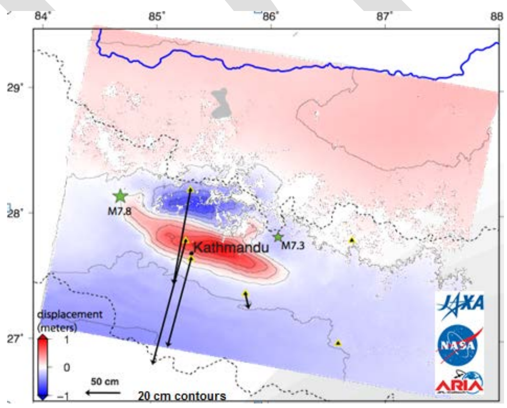


Figure 18. ALOS-2 deformation map generated by JPL NASA shows uplift and southward motion of central Nepal, including Kathmandu.

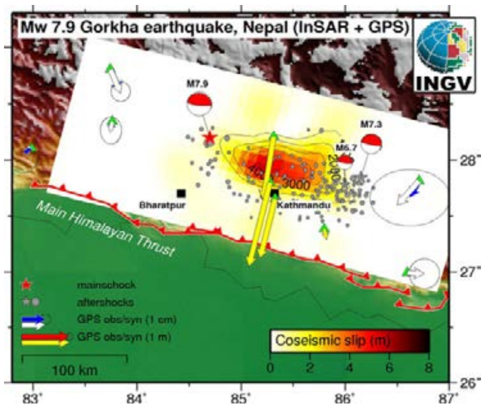


Figure 19. Source model from InSAR and GPS generated by INGV.

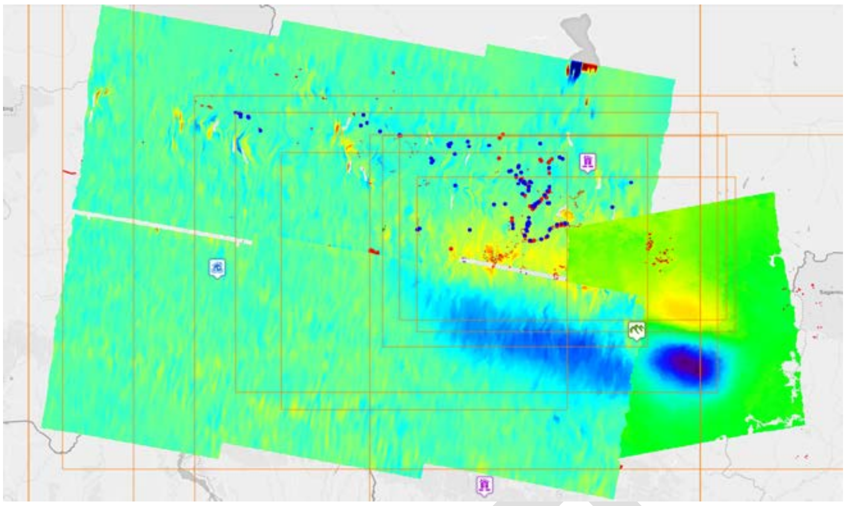


Figure 20.a: illustration of scientific products generated using or published by the precursor system GEP in the context of the 25 April Gorkha earthquake. Centre: displacement map generated by DLR using Sentinel-1 data acquired on 17 & 29 April 2015 (see 20.b); Right: displacement map generated by CNR IREA following the magnitude 7.3 aftershock of 12 May 2015; superimposed dots (blue and red): map of combined landslide features produced by an international team including British Geological Survey, Durham University, ICIMOD, MDA and NGA in spring 2015. Over the illustrated area four icons represent Charter activations over the last ten years including the activation about the Gorkha earthquake.

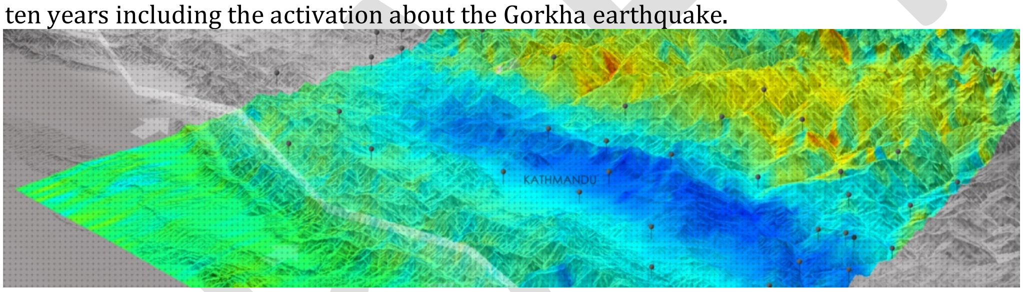


Figure 20.b: illustration of the Sentinel-1 based displacement map generated using pixel correlation and showing the large terrain motion induced by the Gorkha earthquake in Nepal. The map was delivered by DLR to ESA and published on the platform. Credits: DLR, ESA.

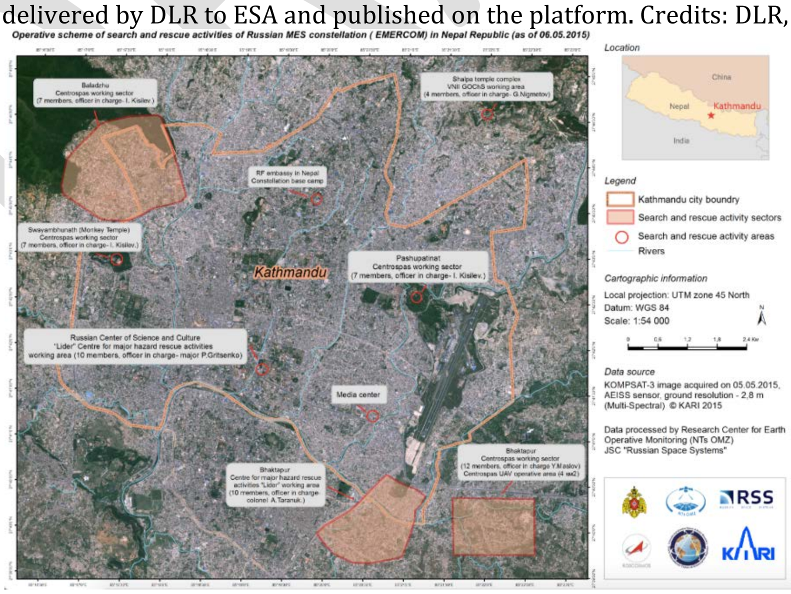


Figure 20.c: illustration of a satellite based Damage Mapping product generated in the context of the Charter activation 459 following the requests from the Disaster Management Support (DMS) Programme Office of the Indian Space Research Organisation (ISRO), UNITAR/UNOSAT on behalf of UNICEF. In parallel the Charter was triggered by the National Disaster Reduction Center of China (NDRCC). While the CEOS WG Disaster pilot activities concentrate on scientific products to

better characterize the hazard, the Charter activation provides support to assessment the hazard impact with Damage Mapping products.

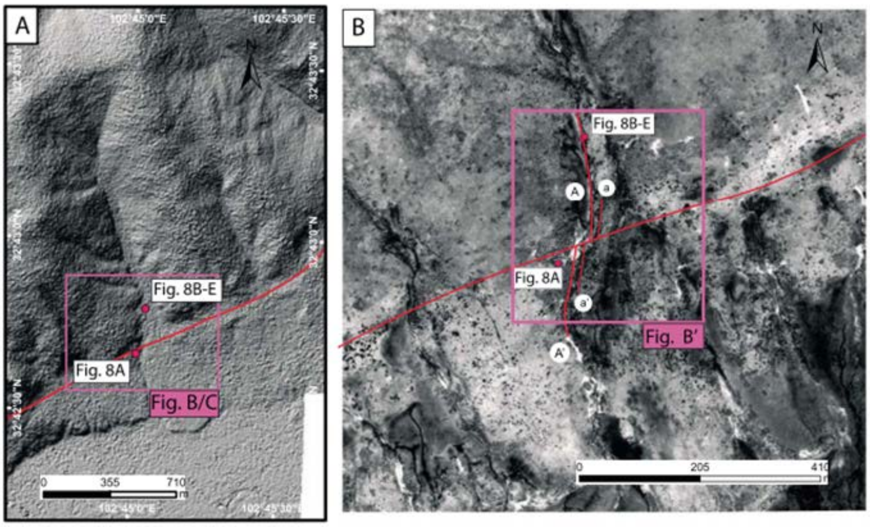


Figure 21: illustration of VHRO based analysis of active faults in the case of the Longriqu fault zone, eastern-Tibetan Plateau; Credits: Claire Ansberque, Olivier Bellier, Vincent Godard, Cécile Lasserre, Mingming Wang, et al.. The Longriqu fault zone, eastern Tibetan Plateau: Segmentation and Holocene behavior. Tectonics, American Geophysical Union (AGU), 2016, 35.

6. Taking lessons from precursor Seismic Hazards Pilot of the CEOS WG Disasters

The assessment of the impact and utility of CEOS WG Disasters activities relevant to the Seismic Hazards Consolidation Phase is related to the CEOS Seismic Hazards pilot and is described in the *Sustainability Report*.

7. Collaboration with EO based disaster response capabilities

Collaboration with the International Disasters Charter

A good example of the power—and potential of satellite EO —can be seen in the International Charter Space and Major Disasters (www.disastercharter.org), an international collaboration among space agencies that uses space technology to aid in response to disasters. When a disaster occurs, the International Charter grants access to satellite data at no cost and in a rapid fashion.

The Charter aims to help better organise and mobilise national disaster management resources during emergencies and the international relief community concerning situations where humanitarian assistance is required. The only users that can submit requests are Authorized Users, a predefined list of organisations with a mandate concerning disaster risk management.

The Charter is focused on hazards with rapid on-set scenarios, in the immediate response phase, and aims to service operational users, wherever a disaster occurs. Since its inception in 2000 it has delivered services 500+ times in 119 countries. To cite the Charter and its dramatic evolution over the last decade as progress toward EO-based risk assessment may be surprising, given the Charter's response-only focus. Yet the Charter remains a striking example of what space agencies working together can achieve. By raising the profile of satellites in disaster response, the Charter has greatly increased the DRM community's interest in EO satellite data and EO-based solutions.

Currently, the CEOS pilots have an agreement in place with the Charter for data sharing after a Charter activation. In July 2014, the Charter Board has communicated to the Chair of the CEOS WG Disaster following the request from CEOS to obtain access to data from the Charter for the purposes the DRM activities conducted by the CEOS Pilots. In July 2015, the Charter Board has communicated to the Chair of the CEOS WG Disaster with a procedure to implement this agreement.

In July 2015, the Charter Board has communicated to the CEOS Seismic Pilot Leads following the request to obtain support concerning the dissemination of CEOS Seismic Pilot results to appropriate users. In this official letter, the Charter agreed that products from the CEOS Seismic Pilot and the Geohazards Supersites (GSNL) can be shared with the Charter during an activation.

As a first priority, the CEOS WG Disasters activity intends to articulate with the Charter, make sure users are aware and use it. For seismic hazards, Authorized Users generally request a Charter activation and designate Charter End Users working with them; typically, they are recipient of data and specializing in hazard and risk analysis. In addition, a new activity is proposed in the CEOS context to complement the Charter data delivery with advanced tectonics products derived from InSAR processing to estimate terrain motion and model the earthquake source.

The Charter mandate is to provide EO data for the immediate response phase. In the case of earthquakes, as illustrated in Figure 25, specific tasking and data delivery are defined by the Charter in its so-called scenarios. These scenarios are focused on data supply (not value adding) and are dedicated to damage mapping (and not terrain motion mapping nor tectonic products).

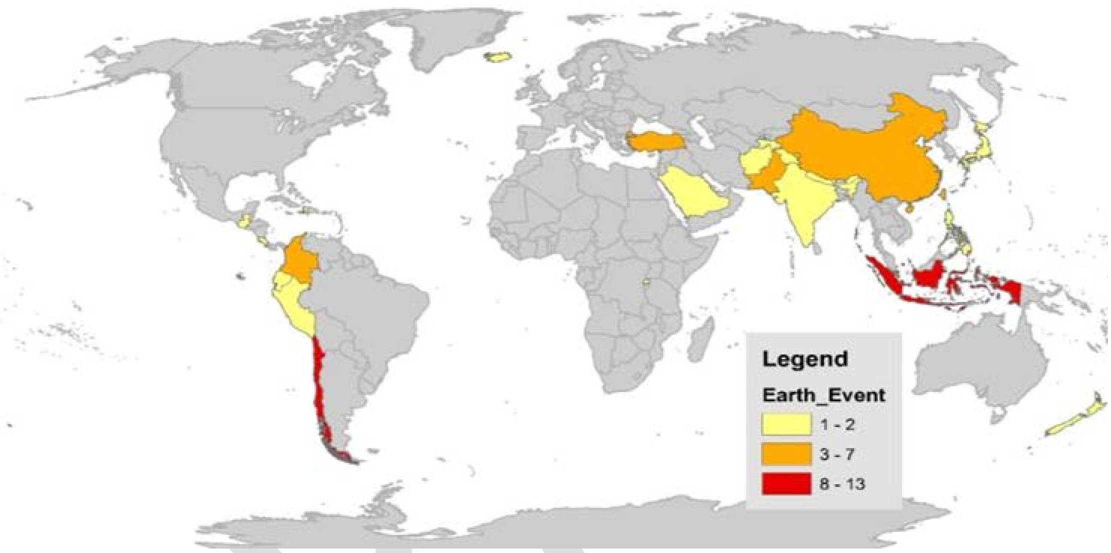


Figure 25: 2007-2015 Geographical distribution of Charter activations caused by solid earth related events (earthquake, tsunami, volcanic eruption, landslide caused by earthquake, subsidence); these events correspond to a third of the totality of Charter activations. Charter activations in geohazard themes represent 21% of Charter events and spread over 27 countries.

The collaboration with the Charter enables to complement the Charter disaster response activity with science products (e.g. advanced tectonic products) that are separate and complementary; they are not concerned with Damage Mapping (the main target of the Charter) but a better characterization of the hazard through scientific measurements exploited by specialist geoscience centres through a consensus product generation methodology to carefully generate advice from technical data. This may help DRM users in the decision-making process.

Therefore, the Charter activities and the Seismic Hazards Consolidation Phase activity would be aligned (not overlapping) and complementary (for the relevant hazard types):

- *On an emergency basis*: the activation is triggered by a Charter Authorized User and managed by the Charter and its PM; the Seismic Hazards Consolidation Phase is conducted in parallel and separate i.e. there is no interaction concerning operations; in particular, the Seismic Hazards Consolidation Phase is able to generate advanced products using open and free data such as Sentinel-1, Landsat-8 or Sentinel-2 collections (for

instance the precursor GEP is currently demonstrating these functions within the CEOS Seismic Pilot); other EO data sources may be exploited depending on the CEOS contribution agencies and through the Data Coordination Team (see section 6.3). As a baseline, the Seismic Hazards Consolidation Phase is not requesting data to the Charter during activations.
- *Not on an emergency basis*: a capacity development activity is conducted by the Seismic Hazards Consolidation Phase to promote the Charter and the Seismic Hazards Consolidation Phase and achieve better adoption by relevant DRM mandated users (the geoscience centres helping Charter AUs and involved as Charter End Users). Charter data can be accessed and exploited through the current Charter-CEOS WG Disasters agreement, that allows access to data from a Charter activation.

Connection between the Charter and the Seismic Hazards Consolidation Phase*:*

- There are no connections between the Charter and the Seismic Hazards Consolidation Phase concerning operations. The data access mechanism of the Seismic Hazards Consolidation Phase is the CEOS WG Disasters Data Coordination Team (DCT). After the Charter activation, Charter data can be accessed and exploited through the current Charter-CEOS WG Disasters agreement that allows access to data the Charter.
- The primary users of the Seismic Hazards Consolidation Phase are geoscience centres, they generally are not Civil Protection Agencies. They sometimes collaborate with DRM users that are Charter Authorized Users. They are able to provide scientific advice, this is separate from providing rapid mapping services, which anyway isn't the goal of the Seismic Hazards Consolidation Phase.
- The Seismic Hazards Consolidation Phase will clearly inform users that the measurements generated do not intend to substitute to end-to-end disaster response mapping service such as damage mapping products delivered in the context of the Charter, Sentinel Asia, the Copernicus EMS, etc.
- The type of geo-information provided by the Seismic Hazards Consolidation Phase does not concern Damage Mapping but advanced products. However, such products might be relevant in the context of Charter activations and, as a baseline, the measurements generated with the Seismic Hazards Consolidation Phase can be shared with the Charter.
- In the longer term the CEOS WG Disaster will take the opportunity of the Charter-CEOS agreement to explore options about sharing notifications of activities conducted by the Seismic Hazards Consolidation Phase and sharing measurements generated using the system.

Other EO based disaster response capabilities

Further to collaborating with the International Charter, as any CEOS WG Disasters activity, the Seismic Hazards Consolidation Phase intends to articulate with EO based disaster response capabilities such as the EMS and the Risk and Recovery services of the Copernicus program of the European Union, Sentinel

Asia, the UNITAR/UNOSAT and UN OOSA, etc. to make sure users are aware and use them. It is also anticipated to propose collaborations with these capabilities in the framework of the International Working Group on Satellite based Emergency Mapping (IWG-SEM).

The European COPERNICUS Emergency Management Service (COPERNICUS EMS http://emergency.copernicus.eu/) is active since 2005. It provides information for emergency response in relation to different types of disasters, including meteorological hazards, geophysical hazards, deliberate and accidental man-made disasters and other humanitarian disasters as well as prevention, preparedness, response and recovery activities. Copernicus EMS can be triggered by EU Member State civil protection agencies and several European Agencies. Mapping products are provided free of charge and generally full and open in access.

Sentinel Asia (SA https://www.aprsaf.org/initiatives/sentinel_asia/) is a space-based disaster management support system in the Asia-Pacific region (SA) under Asia-Pacific Regional Space Agency Forum (APRSAF), active since 2007. SA was established in 2005 as a voluntary collaboration between regional space agencies and disaster management agencies for humanitarian purposes. It covers not only response phase with satellite based emergency services but also mitigation preparedness phase with capacity building, early warning system for specific disasters using satellite-based data, and others. SA aims (a) to improve safety in society by Information and Communication Technology (ICT) and space technologies, (b) to improve the speed and accuracy of disaster preparedness and early warning and (c) to minimize the number of victims and social/economic losses.

8. Theme specific objectives of the seismic hazards community

The concrete targets defined in section 9 are associated to the objectives defined in section 2. Underlying the objectives described in section 2 the following is the synthesis of 'theme specific' objectives for seismic hazards. They are derived from the Memorandum of the International Forum on Satellite EO and Geohazards and the elaboration of precursor Pilots under the CEOS WG Disasters.

A. Support the generation of globally self-consistent strain rate estimates and the mapping of active faults at the global scale by providing EO InSAR and optical data and processing capacities to existing initiatives, such as the iGSRM [Wide extent satellite observations]; this is focusing on representative portions of the global seismic belt (Alpine-Himalayan Belt, and subduction zones of South America).

B. Pursue the GSNL for seismic hazards [Satellite observations focused on supersites]; access and use satellite EO and in situ data to better understand and monitor supersites.

C. Exploit EO data to derive advanced tectonic products for rapid earthquake response. [Observation of earthquakes with M>5.8]; access and use satellite EO to characterize earthquakes.

D. Make sure users access and use EO disaster response capabilities [Articulate relationship with Copernicus EMS, Charter and Sentinel-Asia, and role if any of CEOS]; explain and promote EO capabilities for damage mapping in the disaster response phase.

(http://esamultimedia.esa.int/docs/EarthObservation/Geohazards/esa-geo-hzrd-2012.pdf).

9. Targets of the Seismic Hazards Consolidation Phase activity

The concrete targets associated to the objectives defined in section 2 are described here below:

A.1) EO data to support global strain rate mapping (e.g. iGSRM) at regional and global scale:

- Wide extent and repeat InSAR data to build the global strain model (continuous observations over large areas using SAR data such as Sentinel-1, ALOS-2 and RCM) Coordination and sharing of data acquisition burden among SAR data providers
- Demonstration of EO-based strain rate measurements (over representative sites)
- Demonstration of methodologies and tools to produce large-area to global strain rate estimates
- Validation of these techniques to measure strain rates

A.2) EO data to support active fault mapping and fault reconnaissance mapping at regional and global scale:

- Wide extent and repeat InSAR and Optical ortho-rectified imagery to build regional or global maps of active visible fault (e.g. using Pléiades and other types of VHRO data ex archive) and to map deformations (combining with fresh acquisitions over hot spots)
- Fault mapping at a regional/global scale
- Risk assessment for urban faults over specific areas (mapping active urban faults)
- Ground displacement for historical events based on InSAR analysis and optical imagery when appropriate
- Study of past earthquakes during the satellite era using InSAR stacks and, when appropriate, optical data stacks
- Access to relevant Digital Elevation Models

A.3) Support the GSNL:

- While the Supersite EO data are obtained independently of the Seismic Hazards Consolidation Phase activities, the data will be (on request) hosted and/or distributed from the Geohazards Exploitation Platform, also part of the Geohazards Lab activity in a coordinated way with the other data distribution platforms/infrastructures which support the Supersites regionally (e.g. UNAVCO, EPOS, etc.)
- The GEP will provide access to tools for the GSNL users, who may also integrate and run online their tools.

The above shall be supported by the Seismic Hazards Consolidation Phase only if the Geohazards Lab activity is not approved by CEOS.

A.4) Collaboration and consensus methodology:

- Develop a collaborative framework with geoscience centres with or without EO expertise in order to ensure a consensus methodology for product generation is adopted and to demonstrate relevance of advanced EO products to a broader base of users (see Collaboration with the Charter); concerning geoscience centres typically are End Users and they have a role to do science as experts and, in some instances, to advise DRM authorities.
- Develop a procedure to exploit EO based data and derived products in accordance with the working practices of mandated users (in particular geoscience centres supporting End Users concerning geohazard risks).

B.1) EO data to support earthquake response:

- Ground displacement analysis using SAR and optical imagery
- (Semi-) automatic fault modelling, prediction of damage distribution, rapid calculation of Coulomb Stress changes on neighbouring faults (derived from above)
- Seismic source models
- Collection of InSAR data to support fundamental research on earthquake fault mechanics using observations of the early post-seismic phase. These observations (up to months after the event) are now possible thanks to the multiple sensors available through event supersites under the GSNL
- Maps of geological surface effects
- Post-seismic ground velocity maps

B.2) Collaboration with EO based disaster response capabilities:

- Awareness and promotion: Present and explain the contribution of EO based disaster response solutions and their complementarity with EO based solutions to support tectonics
- Awareness and promotion: Take the opportunity of international presence activities (events, working groups, etc.) to promote complementary EO based capabilities
- Collaboration with the Charter about accessing Charter data packages based on the current Charter-CEOS WG Disasters agreement; establish communications links to make the Charter aware of activities conducted by the Seismic Hazards Consolidation Phase that might be relevant to them; provide feedback to the Charter about EO data supplied by the Charter to users of the CEOS WG Disasters.

10. Milestones for the next three years

Milestones of the Seismic Hazards Consolidation Phase:

Q4 2017 - Required data volumes identified and agreed

Q3 2018 – Definition of procedures (for each agency, for some of the agencies this is not done yet) to ensure optimal data acquisition in case of earthquakes over a certain threshold.
Q4 2018 - Development of a procedure to make data available rapidly.
Q3 2019 - Develop a collaborative framework with geoscience centres and Coordinate with geoscience centres for bridging the gap to end users.
Q2 2020 - Help end users better understand advanced EO methods.
Q3 2020 - Demonstration of the generation of different products for 10-12 earthquakes per year.
Q3 2020 - Implementation of processing algorithms for rapid response products on the GEP.

11. Baseline data volumes

Based on the Sustainability Report of the Seismic pilot, possible yearly volumes of data required for 3 years for are described below. This concerns data collections to be downloaded by users.

Agency	ASI Cosmo-Skymed	CNES Pleiades	CSA RADARSAT	DLR TerraSAR-X	ESA Sentinel-1 & 2	JAXA ALOS-2
Number of Images per year for Seismic Hazards	200-400	50-100	50-100	100-200	open	50-100

Other EO data collections (SAR and Optical including VHRO) are intended to be exploited with processing without download (EO data are accessed by the processing environment but the user can only download the value adding product).

12. Conclusion

Currently, ESA and INGV are gathering contributions from CEOS space agencies and geoscience centres with EO expertise that have contributed to the precursor CEOS WG Disasters Seismic Hazards pilot activities. Also, they are approaching new geoscience centres in order to widen EO data exploitation, extend active fault mapping and fault reconnaissance mapping to a global basis, cover a larger number of seismic events per year and develop a methodology to provide consensus results to decision makers.

Annex 1 – Overview of international initiatives looking at satellite EO and DRM

Comparison with existing EO based DRM mechanisms

	Scope	Type	Provision	Phase of emergency management cycle	VA services	Activation	Disaster types covered
Seismic Hazards Consolidation Phase	Global	Best effort	Advanced science products (e.g. terrain motion products)	All phases	Internal	Predefined expert teams	Seismic hazards
Charter	Global	Best effort	EO data and VA products	Response	External	Authorized DRM organisations	Natural or man-made disasters
Copernicus	Global	Committed Service	VA products (Reference Maps, Delineation Maps and Grading Maps)	All phases	Internal	DRM organisations	Natural or man-made, emergency situations and humanitarian crises
Sentinel Asia	Asia-Pacific	Committed Service	VA products and information services	All phases	Internal	ADRC & JPT member countries	Natural disasters
UNOSAT	Global	Committed Service	Geo-spatial information based on field-collected, satellite & GIS data and web services	Response	Internal	UN decision makers, member states, international organizations and non-governmental organizations	Natural or man-made, emergency situations and humanitarian crises
Servir	Africa, Himalayas & SE Asia	Broad scope*	EO data, geospatial information, predictive models and science applications and tools	All phases	Internal	Auto-activation	Natural disasters, environmental changes and ecological threats

* Note: see https://servirglobal.net/about-Servir

Annex 2 – List of major international initiatives looking at satellite EO and DRM

The international Charter Space & Major Disasters:
Link: https://www.disasterscharter.org/web/guest/home

The Copernicus EMS and Risk & Recovery services:
Link: http://emergency.copernicus.eu/

The Sentinel Asia initiative:
Link: http://global.jaxa.jp/article/special/sentinel_asia/index_e.html

The Servir initiative of NASA and USAID:
Link: https://www.servirglobal.net/

The UNOSAT programme of UNITAR:
Link: https://www.unitar.org/unosat/maps

Other relevant EO based capabilities for DRM may have been omitted in this preliminary list.