GROUP ON
EARTH OBSERVATIONS

→ THE INTERNATIONAL FORUM ON SATELLITE EO AND GEOHAZARDS

The Santorini Conference
Santorini, Greece, 21–23 May 2012

Ph. BALLY (Editor)
ESA/ESRIN

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Preface

The European Space Agency (ESA) and the Group on Earth Observations (GEO) have worked together for several years on the specific topic of disasters and share, in particular, a deep interest in geohazards. This became more evident with the joint collaboration to host the International Forum on Satellite Earth Observations for Geohazards (the Santorini Conference) from 21-23 May, 2012 in Santorini, Greece.

Agence France Presse has reported that, in 2010, disaster events caused the death of almost 300 000 people, affected another 220 million and resulted in more than $120 billion of economic damages. While 2011 saw a drop in fatalities, the economic damages tripled to over $366 billion. The Japanese earthquake and tsunami of March 2011 alone accounted for over half of these damages. By 2050, the number of people exposed to storms and earthquakes in large cities could double, underlining the need for better geohazard-related information for improved disaster risk management (DRM).

Earth observation (EO) satellites have a major role to play in contributing to the understanding, mitigation, preparedness and management of geophysical risks. Working together with the research community and industry, ESA has a long history of science and application development using EO to support geohazard risk management. ESA is one of the founders of the International Charter Space and Major Disasters (the Charter) which since its inception in 2000 has been activated in response to over 330 major disasters in more than 120 countries. At the other end of the risk management cycle, ESA initiated a range of mitigation precursor projects looking at risk assessment to better characterize hazards and risks. These include supporting the development of sustainable services via nationally mandated organisations in Europe, such as the Terrafirma and Risk EOS actions of the Global Monitoring for Environment and Security (GMES) Service Element (GSE) programme. Such services contribute to the realisation of a GMES portfolio that the European Commission (EC) manages today. In Europe, GMES will provide the foundation for further development of geohazard services using satellite-based Earth observation. The new Sentinel missions, especially Sentinel-1 and 2, will form the backbone of GMES operational services to the geohazard community. The full implementation of the Sentinel programme, when used together with the capacities of existing national missions such as COSMO-SkyMed, TerraSAR-X, Pleiades, Radarsat-2 and the planned Radarsat Constellation Mission (RCM), will offer European and global users huge improvements in both temporal and spatial resolution, as well as geographic coverage.

On a global basis, ESA is collaborating with both the Committee on Earth Observation Satellites (CEOS), the space coordination arm of GEO, and GEO itself, to examine activities of member Agencies across a broad range of hydro-meteorological and geophysical hazards, covering the entire disaster cycle. The aim is to ensure more effective and balanced efforts among the agencies by assessing gaps and overlaps.

In 2007, ESA and GEO convened the 3rd International Workshop on Geohazards in Frascati, Italy, which addressed geophysical risks and the contribution of EO to geohazard research. As a result, the Geohazard Supersites and Natural Laboratories (GSNL) were created and remain the premier contribution of satellite EO to geohazard research. The GSNL are an initiative of the international geohazard scientific community, providing access to space-borne and in-situ geophysical data over selected sites prone to geohazards. In Europe, more than 50 geological surveys are committed to becoming users of EO-based terrain deformation services. In Italy, the government has purchased continuous InSAR coverage for the complete territory; the Swiss authorities have adopted EO as a method for monitoring landslide risks. Examples like this demonstrate that geohazards are also an area with a strongly developed user community. There is also ample evidence of this through the long-standing work of the Geohazard Community of Practice (GHCP) within GEO and within the more focused communities of the specific geohazards examined at the Santorini Conference: seismic hazards, volcanic hazards, landslide hazards, inactive mine hazards and coastal lowland subsidence hazards. The Santorini Conference provided the geohazard community with the opportunity to forge a vision and concrete objectives that will serve as the basis for agency planning in relation to investment on further use of EO. These objectives are captured in each of the thematic chapters addressed in the report.

The publication of this volume on the Santorini Conference marks a milestone in the international effort to apply satellite EO to geohazards, by defining clear objectives for each of the geohazard communities listed above, and charting a vision for the implementation of strategies to achieve these objectives. ESA and GEO are proud to have been the conveners of this important event. We believe the publication of this report will become a landmark in the improved application of satellite-EO to geohazard risk management for many years to come.

Volker Liebig
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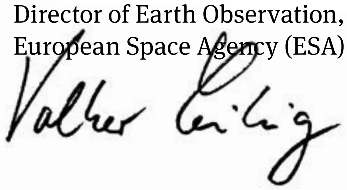

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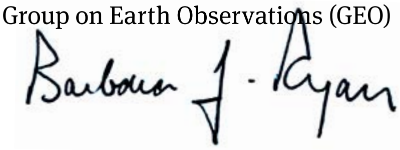

Contents

Executive Summary

Overview

The International Forum on Satellite Earth Observation and Geohazards (the Santorini Conference) was organised and chaired by ESA in association with the Group on Earth Observations (GEO). It gathered over 140 participants from 20 countries including European countries, the US, Canada, Japan and China. Over 70 organisations were represented, ranging from international organisations (e.g. World Bank) to public institutes, space agencies, universities and the private sector. From the private sector, 12 companies attended including non-EO service providers (e.g. Deltares) and sectoral users (e.g. Willis – global insurance broker). The Santorini Conference was an opportunity for users and practitioners of the geohazard community to come together and discuss the state-of-the-art in satellite-based Earth observations (EO) and objectives for the community over the coming 5 to 10 years. Sessions examined community papers drafted before the event covering five critical areas of application: volcanoes; landslides; seismic hazards; coastal subsidence and flood defence; and inactive mine hazards. Another session addressed industrial services presenting the current and immediate future plans for observations and issues and strategies to address emerging market opportunities. This report presents five community papers, developed for the Conference and revised and reviewed with thematic communities through an open review process. A paper on industrial perspectives and another on global perspectives are also included. Overall, communities have a range of information needs and concrete objectives concerning the role of newly available and planned EO missions data.

As far as the phases of risk management are concerned the assessment and discussions provided a focus on hazard identification, quantification and monitoring for prevention and preparedness, although emergency response and post disaster damage assessment were also discussed. In relation to disaster response, existing satellite EO capacities such as the International Charter were recognised as were the consultative processes through national risk management authorities and the international humanitarian community (e.g. within the UN). Similarly, other publications concerning satellite EO for exposure or asset mapping are available[1]. As a result, geohazard users and practitioners in Santorini focused their efforts on risk assessment needs, and addressed response and asset mapping needs only as a complement to existing capacities assumed to be perennial.

The report offers insight into the needs of the geohazard user community, a diverse group with varying objectives. Geohazard users include operational users with broad disaster or risk mandates such as civil protection agencies, but also operational users with a specific risk assessment focus, such as volcanic observatories or geological surveys. Users also include the research community in general, whether through institutes or academia. Finally, the user community is in close interaction with practitioners, who play a key role for acceptance of new techniques and more generally in encouraging the uptake of EO.

While many of the participants present stemmed from European organisations and programmes, the discussions held were rooted in a broader context, and aimed to ensure a global reach.

1. DEICHMANN, U., EHRLICH, D., SMALL, C. and ZEUG, G.,2011. Using high resolution satellite data for the identification of urban natural disaster risk. European Commission - Joint Research Centre, GFDRR, World Bank. gfdrr.org/gfdrr/ sites/gfdrr.org/files/publication/using_high_resolution_data.pdf.

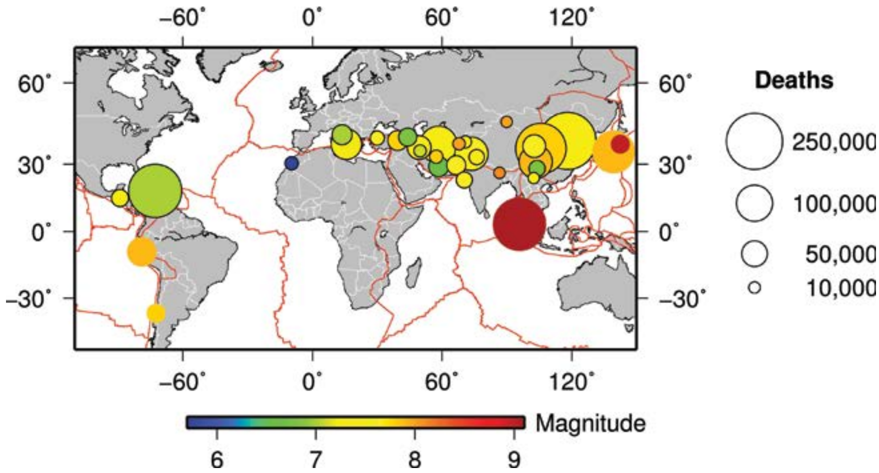

Figure 1. Earthquakes 1900-2012 killing more than 10 000 people (USGS); circle area proportional to deaths while colour shows earthquake magnitude. Circles with black rims show quakes not on plate boundaries. Adapted from England et al., 2011.

Seismic Hazards

Earthquakes are amongst the most deadly of natural hazards, especially in recent years. Of the 35 earthquakes since 1900 that have killed more than 10 000 people (Figure 1), seven occurred in the 21st century. These include the 2004 Indonesian earthquake and tsunami, and the 2010 Haiti earthquake, both of which killed more than 200 000 people. Large earthquakes have a major international economic and societal impact. As well as plunging Japan's economy into recession, the 2011 Tohoku-Oki mega-thrust earthquake caused a major shift in Germany's nuclear power policy, the shutdown of car production in Detroit due to lack of spare parts, and a global rise in insurance premiums.

Earthquakes cannot be prevented, and short-term prediction seems impossible. However, their impacts can be mitigated through improved understanding of the distribution of earthquake hazard and concerted actions by planners. California and Japan have invested heavily in both earthquake science and mitigation methods. As a result, the death toll from a future M~8 earthquake on the San Andreas Fault in southern California is estimated at only ~1800, while similar quakes caused ~30 000 deaths in Iran (M~6.5 Bam, 2003) and ~200 000 deaths in Haiti (M~7.0 Port-au-Prince, 2010). The death toll of the M~9.0 Tohoku-Oki event was only 10% of that in the 2004 Indonesian tsunami, despite their similar magnitudes and mechanisms. To achieve global risk reduction requires sustained effort in evaluating and monitoring seismic hazard, and in risk mitigation.

Community objectives for satellite EO

The seismic community has set out a vision of the EO contribution to an operational global seismic risk program. In 5 to 10 years' time, EO could provide fundamental new observations of the seismic belts - around 15% of the land surface – and improved understanding of seismic events through the work of the Geohazard Supersites and Natural Laboratories. This will enable:

1. Development of a high resolution global strain rate model at high spatial resolution incorporating deformation constraints from GNSS and InSAR. InSAR allows essentially continuous observations of the seismic belts worldwide with near-uniform quality.
2. New regional or global maps of active visible faults, incorporating the latest results from the geomorphological analysis of high resolution optical imagery and digital topography data.
3. The creation of a new global seismic hazard map based on 1 and 2.
4. To continue precise measurements, including frequent acquisitions with multiple SAR sensors, over geographically focused areas through the GSNL

to ensure strain rate measurements of unprecedented accuracy.

5. Rapid response to earthquakes, including:
   (a) Automatic rapid estimation of earthquake damage using high-resolution optical and radar imagery, and InSAR coherence using available capacities such as the Charter.
   (b) Automatic rapid creation and web-publication of co-seismic interferograms (wrapped and unwrapped) from all available sensors.
   (c) For non-specialist end users, products derived from the interferograms, such as phase gradient maps, combined with critical infrastructure data, could be produced.
   (d) (Semi-) automatic fault modelling – rapid production and web-publication of fault parameters using simple, consistent techniques.
   (e) Prediction of damage distribution using this fault model.
   (f) Rapid calculation of Coulomb Stress changes on neighbouring faults to assess likely locations of aftershocks or triggered earthquakes. The fault model in (d) would be used initially, along with any data on historical seismicity (e.g. from USGS archives).
   (g) Collection of InSAR data to support fundamental research on earthquake fault mechanics using observations of the early post-seismic phase. These observations (hours to days after the event) are now possible thanks to the multiple sensors available to the GSNL.
6. A long-term response to earthquakes that involves acquiring radar data for years to decades after an earthquake in order to measure post-seismic deformation.

It is apparent that while satellite EO will possibly never aid in the short-term prediction of earthquakes, new techniques and satellite systems would protect populations through improved mitigation initiatives. Sentinel-1 data and high resolution optical data such as those provided by Pleiades or US commercial systems are critical to achieving this.

Volcanoes

About 1500 volcanoes are known to have erupted in the last 12 000 years (the Holocene Era); about 700 of these, mostly subaerial, have erupted at least once in historical times (Siebert et al., 2010). Worldwide, about 100 volcanic unrests are observed yearly, and about a half of them become observable eruptions. It is estimated that less than 10% of active volcanoes are monitored on an on-going basis, meaning that about 90% of potential volcanic hazards do not have a dedicated observatory and are either monitored occasionally, or

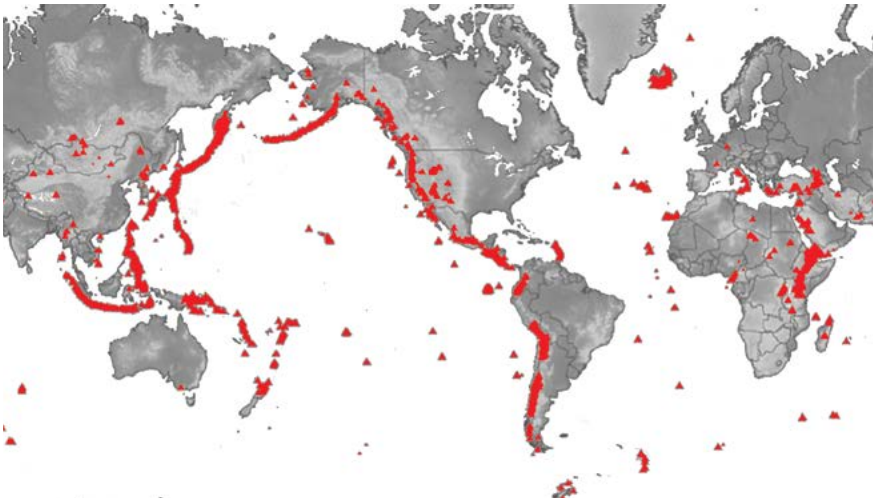

Figure 2. Holocene active volcanoes (Global Volcanism Program of the Smithsonian Institution, www.volcano.si.edu/world/find_regions.cfm).

not monitored at all. The number of active submarine volcanoes is larger than subaerial ones but the precise number is unknown. Almost all active volcanoes are associated with plate boundaries and hotspots, with particularly large numbers around the Pacific Rim.

The conversion of hazard to risk depends on the location of assets at risk, and their dependence on time. This leads to two risk terms, one related to geographically permanent exposures, such as cities and mega-cities at the foot of active volcanoes, and one transboundary, related to the emissions of volcanic ash and gases. Explosive eruptions produce ash and SO_2, which disperse in the troposphere and stratosphere, travelling large distances from their source.

Community objectives for satellite EO

To effectively use EO to monitor volcanoes requires a multi-parameter observation strategy in both real-time for monitoring and retrospectively for improved scientific understanding. This holds true for thermal features, ground deformation and gaseous emissions.
This strategy has six points to be realized within the next 5 to 10 years:

— Global systematic background observations: establish regularly refreshed baseline observations concerning ground deformation, thermal energy release and gas release at all 1500 Holocene Volcanoes, independently of the state of unrest.
— Increase systematic observation capability for early warning and alert: measure ground deformation, topography, thermal, ash and gas (where appropriate) weekly at all volcanoes that show signs of unrest. This represents approximately 100 volcanic unrests yearly.
— Detect, measure and track ash, measure thermal and gas parameters, for any eruption worldwide and at the appropriate spatial and temporal resolution at least daily; complemented with ground deformation measurements, morphology changes and assess post-eruption topography (DEM) as appropriate; improve the scientific understanding of eruption initiation and dynamics by frequent ground deformation measurements of volcanoes in severe unrest (InSAR observations of summit deformation before, during, and in between explosive eruption phases and of the initiation and propagation of dikes, as well as SAR backscatter analysis).
— Improve and/or develop the capability to carry out novel measurements, such as gas ratios, ash particle distribution, ash plume height, minor gases and ratios for gases in low quantities (HCL, H_2S, e.g.); extend the current capacity of measuring thermal and gas parameters to shallow submarine eruptions.
— Secure continuity and sustainability of all the above for 20 year horizon.
— Improve uptake of EO through training for end users.

EO is viewed as a critical tool to extend monitoring to unmonitored volcanoes. Resources available through the full implementation of the Sentinel programme, combined with an impressive array of national initiatives, would allow the implementation of the monitoring programme put forward above.

Landslides

Landslides represent one of the natural hazards that occur most frequently worldwide after hydro-meteorological events. The occurrence of landslides depends on complex interactions among a large number of partially interrelated factors, such as geologic setting, geomorphic features, seismicity, soil properties, land cover characteristics, hydrological and the effects and impacts of anthropogenic changes to the landscape. Natural triggers include

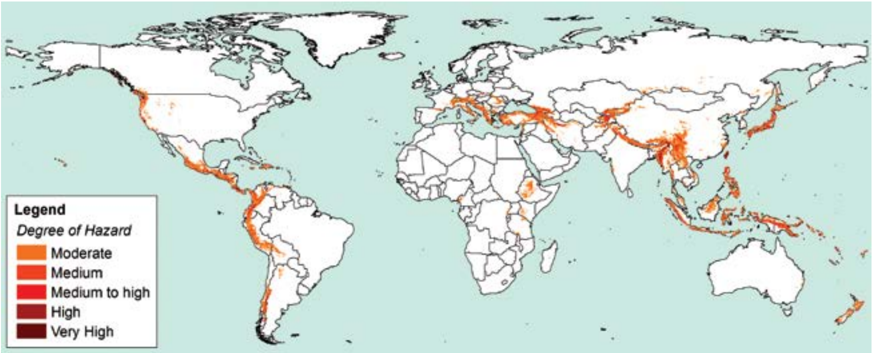

Figure 3. Global Landslide Hazard Distribution (GDLND), derived from the landslide hotspot map at global scale (Nadim et al., 2006) based on a heuristic landslide hazard model considering slope, lithology, soil moisture, precipitation, temperature and seismicity.

intense or prolonged rainfall, earthquakes, volcanic eruptions, rapid snowmelt and permafrost thawing, and slope undercutting by rivers or sea-waves. Other factors capable of acting as triggers for landslide failures are human activities such as slope excavation and loading, land use changes (e.g. deforestation), rapid reservoir drawdown, blasting vibrations, and water leakage from utilities. Earthquakes are notorious for triggering landslides. The Great Wenchuan earthquake in 2008 triggered more than 60 000 landslides. Slow-moving landslides such as those caused by subsidence and large scale slope deformation are other forms of landslides to be considered.

The combination of the landslide susceptibility map with the distribution and vulnerability of the elements at risk facilitates the understanding of the expected losses due to landslide occurrences. It provides an estimation of the number of people exposed to landslides. Different landslide susceptibilities have been produced at a global scale. They generally do not provide sufficient temporal perspective or information on the magnitude of expected events. They also fail to account for the distribution and vulnerability of all the elements at risk. Finally, there is no updated database of landslide occurrences at a global scale.

EO technologies already play a strong role in support of landslide hazard and risk applications, ranging from landslide mapping at the regional scale and monitoring of single slopes to modelling of landslide motion and correlation with triggering factors.

Community objectives for satellite EO

Over the next ten years, the landslide community aims to:

1. Develop comprehensive EO-based inventories of known landslide hazard areas currently unmapped or insufficiently mapped to better understand the extent of the hazard. This corresponds to more than 40% of the GDLND hazard global extent over the next ten years, with a priority focus on Philippines and Japan and in Central and South America along the Pacific Coast, as well as in south-eastern Asia, with medium to very high degree of hazard. For instance, in Europe, this concerns mainly Austria, Bulgaria, Romania, Serbia, Bosnia, Albania and Turkey. This represents an additional 25-30% of the European areas of interest.
2. Within priority areas above, monitor hotspots using regular satellite EO monitoring on a semestral to monthly basis, depending on the kinematic characteristics of the hotspot at hand, and by using both optical and radar imagery and derived products.
3. Develop outreach programs, capacity building and demonstration projects with national authorities to increase use of EO and promote acceptance of EO as a standard, as is currently done in several European countries (e.g. Switzerland, Italy).

EO satellite technologies are well suited to supporting both operational and scientific users in the process of landslide identification, mapping, characterization and monitoring, through timely sensing of wide areas at relatively low cost, detecting landslide-induced surface features and land motions, and providing long historical records globally. The main achievements of EO relate to the creation or updating of landslide maps at regional scale, and the long term monitoring of unstable slopes at local scale. EO data and EO-based services and applications need to address specific observational requirements to be able to support the identification, mapping and monitoring of landslide processes. With the full implementation of the Sentinel programme, users will have access to sufficient volumes of data to enable operational landslide services on a global basis, though the ability to use such services will depend on national and local constraints. Combined with higher resolution sensors such as COSMO-SkyMed and TerraSAR-X, the landslide community will use these critical data sets to support InSAR techniques for generating inventories of areas at risk.

Inactive Mine Hazards

Since the beginning of civilization, people have used stone, ceramics and, later, metals found on or close to the earth's surface. Mining is the extraction of valuable minerals or other geological materials from the earth, from an ore body, vein or seam, including the removal of soil. Materials recovered by mining include base metals, precious metals, iron, uranium, coal, diamonds, limestone, oil shale, rock salt and potash. Today, active and abandoned mining areas are widely spread all over the world (Figure 4) and represent a possible subsidence hazard.

Every mining activity impacts the nearby environment, whether open pit mining or underground mining, small scale mining or large operations. Active mining operations are mostly well monitored by mining authorities with, however, different standards of quality and quantity depending on the legal regulations within each country. When a mine site is abandoned, the awareness of previous mining activities decreases quickly. Former mine shafts and underground cavities, re-filled open pits, tailings and dumping sites exist. Even when the former mine sites have been secured, depending on the knowledge and standards at the time of abandoning in the different countries, hidden legacies can represent a hazard. Typical hazards include: collapses migrating to the ground surface and sinkholes; slope instabilities and collapses; collapse of spoil heaps; subsidence or uplift of the ground surface; pollution to air, soil, and water by toxic waste from mining; initiation of small earthquakes.

Most mining authorities have similar information needs. The common steps to evaluating the risk are identifying the sites posing a potential risk; mapping and assessing the hazard; identifying the exposure of people and infrastructure; and monitoring the hazard with a frequency dependent on the magnitude of the hazard and the risk posed.

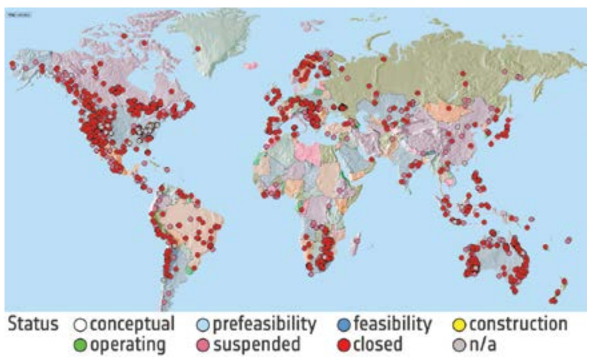

Figure 4. Inactive Mines of the world (Source: Raw Material Group 2012, www.rmg.se).

It is clear that satellite EO can make a meaningful contribution to quantifying and evaluating the global inactive mining hazard, and InSAR using data from the Sentinel-1 mission in particular can meet the global requirement for hazard inventory purposes and for on-going monitoring. Sentinel-2 and other higher resolution optical missions can provide relevant background imagery.

Coastal Subsidence and Flood Defence

Issues of subsidence are generally associated with protection of critical infrastructures and damage to built-up areas. However, when rapid rates of subsidence are seen in coastal areas, the problem is augmented by the increased risk of flooding, compounding damages and extending the impact to large populations. According to the Worldwatch Institute, 24 of the world's 33 major river deltas are sinking due to flood-control efforts and other human-caused changes to the river systems. The combination of sinking deltas and rising seas will increase the damage caused by hurricanes and other flooding events in the future, according to Syvitski et al. (2009). The study estimates that the area vulnerable to flooding could increase by 50% worldwide. An estimated 500 million people live in river deltas, hence the focus of this chapter on coastal lowlands, especially deltas. While sea level rise is a factor, it is usually estimated in centimetres, while subsidence in some coastal areas can be measured in tens of centimetres and, in some cases, metres over decades. Understanding the relative impact of subsidence is critical to properly estimate coastal flood risk. An OECD study attempts to quantify the impact of climate change and subsidence on populations and infrastructure. "By the 2070s, total population exposed could grow more than threefold to around 150 million people due to the combined effects of climate change (sea-level rise and increased storminess), subsidence, population growth and urbanisation." It is clear from the study that subsidence will be a major factor for determining risk exposure in coastal mega-cities, especially in Asia, as evidenced in Figure 5.

Satellite EO can make a meaningful contribution to subsidence monitoring using new data sets made available from Sentinel-1 and techniques such as InSAR.

Community objectives for satellite EO

The community has identified three objectives over the next five to ten years:

1. Develop historical terrain deformation maps over known areas of subsidence and flood defence structures where stability needs to be assessed. This is of particular concern for urban resilience linked to flooding and storm surges in coastal areas. Even when subsidence is slight, the cumulative effect over decades may dramatically increase exposure of populations to flooding. This

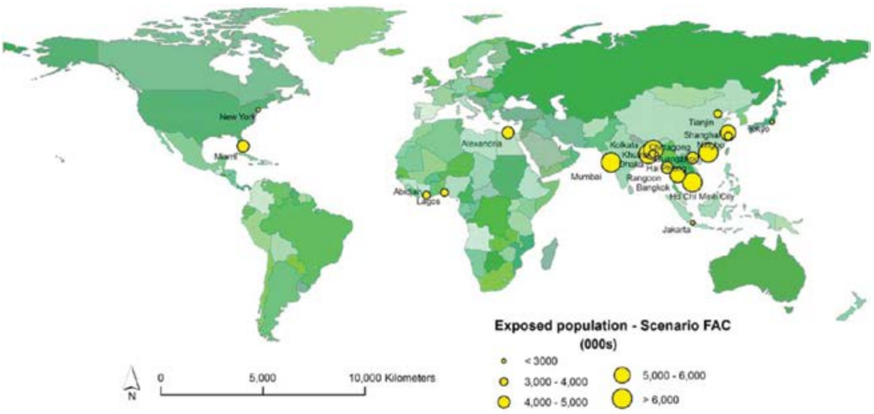

Figure 5. Top 20 cities for coastal flood risk by exposed population in 2070 (Source: Nicholls et al (2007), OECD, Paris).

involves mapping all coastal flood risk areas of the world prone to subsidence over the next 5 years, and updating these maps regularly (e.g. every five years).

2. Establish on-going monitoring of critical areas 1) where subsidence greatly increases exposure to coastal flooding; 2) where stability of flood defence structures is critical to population safety. The need is evident for example in Asian megacities. On-going monitoring of critical areas also allows one to measure the impact of mitigation policies on a local scale.
3. Within 10 years, enable the combined use of terrain deformation and flooding information to support risk management authorities in coastal lowlands. This requires direct real-time access to terrain deformation and flooding data and information products.

It is apparent that satellite-based InSAR will be a key means to map and monitor rates of subsidence in rapidly changing coastal areas with high populations and rapid growth; overall, terrain motion services can play a key role in the context of flood risk management concerning megacities with subsidence problems and when there is a need to monitor the stability of flood defence systems.

Industrial and Global Perspectives

In addressing the way forward for industrial services, the Santorini Conference participants considered four fundamental questions:

— What needs to be delivered over the next 5 to 10 years?
— What factors can accelerate the realization of these objectives?
— What organisations are involved?
— What about other users not using Satellite EO?

As users considered these questions, it was in the context of the full implementation of the Sentinel programme. Missions such as Sentinel-1 will provide large volumes of data over geohazard risk areas, enabling new applications. EO users need to collectively address the challenges associated with their stated objectives, considering the role of mandated organisations, international organisations and industry and possible new partnerships.

The process of looking at what factors – technological, R&D, operational and organisational – can accelerate the realization of the objectives of geohazard communities is reflected in the thematic chapters of this report. It has to take into account the role of mandated organisations, international organisations, and industry, and assess whether new partnerships are needed.

Awareness remains a critical hurdle. Globally, many users are not aware of what is available, are not able to take full benefit from existing systems or cannot afford space technologies.

Feedback from the users of industrial services provides an assessment of the relative success achieved to date and the need for further progress. At the Santorini Conference, two user groups were well represented: the insurance sector – represented by a global insurance broker Willis - the international development sector – represented by World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR). Both of these user groups can be considered to be new to the use of EO, and to be at early stages in their EO use. Both sectors show strong long-term promise for uptake of EO data and information products.

The key areas where satellite EO products have been successfully applied to insurance applications are exposure mapping and classification; post event monitoring and damage assessment; environmental monitoring and risk parameterisation; and hazard model calibration and validation.

For the insurance sector, EO-based applications, products and services remain a pilot effort, aimed at determining to what extent the tools and data

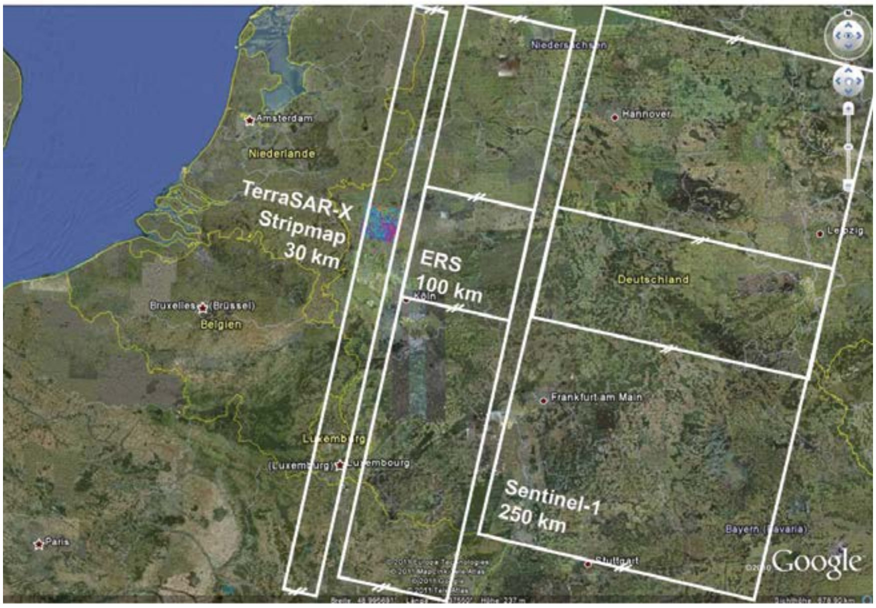

Figure 6. One pass coverage of Sentinel-1, ERS and TerraSAR-X compared. Source: ESA.

available today can meet the needs of the community. Key issues identified to improve uptake were the simplification of sources of supply for processed data/information; the speed of access to the information; entry cost; and appropriate license terms.

The international development community recognises that EO, combined with other data sources, can be a powerful tool, with important opportunities to support risk management. While some EO data helps derive hazard information, the main attention within the development community has focused on the ability of EO to provide exposure information relating to assets and vulnerability. There are entire EO-based applications that, for the development community, remain uncovered or under developed. Upcoming missions should open new areas for investigation, given the large amount of available data and open data policies of Sentinel-1 and 2 in particular. The issues of cost, continuity and sustainability must be carefully considered when considering applications in developing countries. These remain hurdles, but once addressed, EO may be a much needed catalyst in work on improving data preparedness. Improved data preparedness will result in accelerated risk assessment, which will assist in targeting in-country capacity development.

There is already, in orbit and planned, a substantial space capability including C, X and L-band SARs, optical very high resolution satellites and high resolution satellites, and many others. The collective capability offers high revisit and wide area synoptic coverage. There is some concern today that planned resources will not be fully exploited due to insufficient user capacity, underdeveloped value-adding segments or missed opportunities. This is however based on projections of existing use, which remains embryonic. Most of the large users of data are in fact working in the context of pilots that aim to validate a much broader application of the resources. Further investment may be required for new user communities and to support emerging partnerships.

Indeed, services already exist that serve users and have demonstrated the cost-benefit of risk assessment based on satellite EO data. The R&D for these services is completed and the services are mature, precise and documented. Communicating this success remains a challenge. Service provision today in the EO value added sector remains product focused and EO-driven. What remains is for EO requirements to be integrated into a non-satellite centric vision of the end-to-end service, using the established successes of the GMES Emergency Management Service, Terrafirma, EVOSS, DORIS, and other precursor projects to firmly root the new services. Niche services such as precision terrain motion, asset and exposure mapping and rapid damage mapping are soon to be followed by emerging services requested by geohazard risk management users such as thermal anomaly detection, or atmospheric constituents monitoring.

Hurdles remain to making the use of satellite EO fully operational. These hurdles are both technological in some cases and organisational in others. Services providers must specifically identify the authorities that manage the thematic issues in their target markets, and convince them on a case-by-case basis of the merits of adopting a satellite EO-based approach. Ensuring these technology developments take place and encouraging business to pursue a collaborative approach with national authorities are critical steps to ensuring success over the coming years. Global development actors could and should play a critical role as catalysts to bring these technologies to the developing world by working within user communities to develop capacity and raise awareness.

Sustainable services can be created if value-adding companies (VACs) have a reliable and robust space segment, an effective and efficient ground segment, and a reasonable data cost. This should be the main role of space agencies. VACs are like engines. They need fuel (i.e. satellite data) to work. VACs, on the other hand, should provide end users with high quality products, integrated when necessary with other data sources. VACs also need to ensure users have the capacity to understand and use SAR data. VACs and space agencies should continue investing in educating future clients and users. VACs, research institutes and space agencies can make others aware that some EO products and services are no longer R&D exercises but are standard services available now from different providers. In the end, the largest barrier towards progress in the uptake of EO-based solutions remains lack of awareness of what is available, what has been accomplished and how this contributes to the benefits expected by the user.

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Alors dist Pantagruel: «Si les signes vous faschent, ô quant vous fascheront les choses signifiées» *Rabelais, Le Tiers Livre*

Methodology

Purpose, context and heritage

The purpose of this document is to provide the result of the assessment and discussions concerning the contribution of satellite EO in the area of geohazard risk management. The document is a Scientific and Technical Memorandum produced by ESA in association with GEO, in which the opinions and conclusions reflect the outcome of a two-fold process i) the publication of five community papers issued for review in April 2012; and ii) the discussions held at the Santorini Conference jointly convened by ESA and GEO in May 2012. The Community Papers looked at seismic hazards, volcanic hazards, landslides, inactive mines and coastal lowland subsidence and flood defence. Chapters have been added on industrial and global perspectives based on Santorini discussions, independent studies on the state and health of the EO sector and a compilation of international activity in the geohazard area over the past decade. Finally, the report includes a listing of key R&D issues to be considered by the community, elaborated by the authors and circulated within the geohazard and value-adding community for review.

The Santorini Conference was a continuation of a series of international workshops such as those organized by the Geohazards Theme of the Integrated Global Observing Strategy (IGOS) Partnership. The last event was the 3rd International Geohazards Workshop, which took place in 2007 in Frascati, Italy. The Workshop adopted the Frascati Declaration which among others things recommended the creation of the Geohazard Supersites, now Geohazard Supersites and Natural Laboratories (GSNL). For the supersite areas, the GSNL promote free exchange of all relevant data, including in situ, airborne, and space-borne observations, and the availability of the data for scientific studies. The Conference also built on previous scientific workshops with satellite EO themes, in particular, "Understanding Extreme Geohazards: The Science of the Disaster Risk Management Cycle" - a European Science Foundation (ESF) sponsored meeting in northern Spain, in November 2011.

Overview

The conference gathered over 140 participants from 20 countries including European countries, the US, Canada, Japan and China. Over 70 organisations were represented, ranging from international organisations (e.g. World Bank) to public institutes, space agencies, universities and the private sector. From the private sector, 12 companies attended including non-EO service providers (e.g. Deltares and Fugro) and sectoral users (e.g. Willis - insurance). The conference comprised five thematic sessions and an industry session focused on industrial services for the geohazard sector. Invited speakers at the Conference presented their experience and expertise concerning the use of satellite EO with the aim of contributing to the understanding and management of geophysical risks and launching discussions with the participants. Each session concluded with a discussion period focused on challenges and opportunities for EO. While many of the participants present stemmed from European organisations and programmes, the discussions held were rooted in a broader context, and aimed to ensure a global reach. The Conference concluded with a general wrap-up session.

National and international users

The report offers insight into the needs of the geohazard user community, a diverse group with varying objectives. Geohazard users include operational users with broad disaster or risk mandates such as civil protection agencies, but also operational users with a specific risk assessment focus, such as volcanic observatories or geological surveys. Users also include the research community in general, whether through institutes or academia. Finally, the user community is in close interaction with practitioners, who play a key role for acceptance of new techniques and more generally in encouraging the uptake of EO.

For risk management it is worth noting that decisions are taken at the local level, or through the impetus of a national initiative or legislation. The risk management user community is composed of users at a local/national level and users at an international level. There are different categories of user organizations at the local/national level: policy decision bodies such as national-level authorities in charge of civil protection and risk prevention policies and sub-national authorities, which have a large decision power, at their territorial level, in risk management policy implementation and have operational responsibilities (coordination, decision-making); risk prevention services, the institutional services in charge of the risk analysis and risk prevention policies; risk anticipation/forecasting services, the institutional services in charge of the risk anticipation and forecasting; rescue management services, the local, regional and national (and sometimes supra-national e.g. EC level in Europe) Civil Protection and rescue services that are in charge of overall response management. In addition there are researchers, advisors on risk exposure and mitigation and communicators fit into another, important, category of individual or group users who may be involved in the management of geohazard risk, at different stages and with different roles.

At the international level most 'users' are in fact stakeholders, introducing policy initiatives but not directly responsible for disaster risk reduction or disaster management per se and are from either the international humanitarian community (with a focus on Disaster Response) or the international development community (with a focus on Disaster Risk Reduction). The international community has undertaken a variety of initiatives on monitoring hazards, populations, and prevailing environmental conditions, to assist the most vulnerable nations to devise appropriate prevention and mitigation measures prior to emergencies. This is reflecting the strategic guidelines of the UN Hyogo Framework for Action. Examples include: the United Nations and other international organisations, specifically the agencies that have mandates related to disaster risk reduction (e.g. UNISDR, UNDP, UNEP, UNESCO, WMO, etc.); donor governments (including governmental agencies); international/regional development banks, International Financial Institutions such as the World Bank; the World Bank/ISDR Global Facility for Disaster Reduction and Recovery (GFDRR), the Inter-American Development Bank (IADB), Asian Development Bank (ADB), etc.; non-governmental organisations (NGOs), both national and international, including associations of NGOs (e.g. International Federation of Red Cross and Red Crescent Societies (IFRC), VOICE, CARE, etc.); private sector companies (e.g. insurance sector as an end user, or value adding sector as intermediary user).

Thematic scope

As far as the phases of risk management are concerned the assessment and discussions provided a focus on hazard identification, quantification and monitoring for prevention and preparedness, although emergency response and post disaster damage assessment were also discussed. In relation to disaster response, existing satellite EO capacities such as the International Charter were recognised as were the consultative processes through national risk management authorities and the international humanitarian community (e.g. within the UN). Similarly, other publications concerning satellite EO for exposure or asset mapping are available[1]. As a result, geohazard users and practitioners in Santorini focused their efforts on risk assessment needs, and addressed response and asset mapping needs only as a complement to existing capacities assumed to be perennial.

EO capacity and services

The Conference presented the global capacity provided by EO mission owners and operators, the services provided by the International Charter and the GMES Emergency Management Services (EMS) and the offerings from the EO service sector. Much of the discussion focused around existing and planned SAR missions (COSMO-SkyMed, TerraSAR-x, Radarsat-2; Sentinel-1, RCM, ALOS-2, etc.). The discussion was more limited concerning Very High Resolution Optical sensors for which no mission owner from the US attended, although the French space agency CNES (Centre national d'études spatiales) was present, representing Pleiades.

A broad range of EO-based techniques relevant to geohazards were presented and discussed such as precise terrain motion mapping using interferometry, image correlation, etc.; monitoring using thermal imagery; monitoring using atmospheric sensors; and, to a lesser extent, EO-based reference mapping and crisis/damage mapping. A substantial portion of the users and practitioners were concerned with more than one EO technique. Many of the experts were particularly focused on precise terrain motion monitoring using interferometry and the expectations and community objectives relating to interferometry are present in detail in each of the five thematic chapters.

Outcome

The Conference drew from a range of thematic experts to build a common vision for the sustained provision of satellite EO information on geological hazards in order to address society's needs for risk mitigation and management. The five thematic papers circulated prior to the conference were discussed in detail at each of the thematic sessions, and comments continued to be received on-line. The reworked community papers form the core of this report, and include, inter alia: information needs from users and practitioners; geographic priorities by theme; relevance of current EO missions to geohazard user needs and requirements for EO data to support future geohazard applications; a 5 to 10-year vision outlining objectives; a listing of factors that may accelerate uptake of EO in relation to these objectives; results of the scientific exchange and dialogue fostered between researchers, users and practitioners at the Conference.

1. DEICHMANN, U., EHRLICH, D., SMALL, C. and ZEUG, G.,2011. Using high resolution satellite data for the identification of urban natural disaster risk. European Commission - Joint Research Centre, GFDRR, World Bank. gfdrr.org/gfdrr/ sites/gfdrr.org/files/publication/using_high_resolution_data.pdf.

January 15, 2010 - View of Port-au-Prince, Haiti, after a magnitude 7 earthquake hit the country on January 12, 2010.

1. Perspectives Concerning Satellite EO and Geohazard Risk Management: seismic hazards

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1.1 Scope

This chapter presents perspectives concerning how satellite EO can contribute to geohazard and disaster risk reduction in seismic hazards. Its primary focus is on management and user organizations with an operational mandate in seismic risk such as national and regional civil protection organisations, seismological centres, and a range of other actors including non-governmental organizations, academic institutions and international organisations. The authors outline a 5 to 10-year vision for the seismic risk community, based on the assessment of state of the art research and the application of EO in seismic hazard and seismic risk management. This chapter aims to achieve a shared view of the community of geoscience users involved with seismic risk mitigation using satellite EO. It aims to define the issues and opportunities associated with the use of satellite data to support science users and operational users in seismic risk management in the context of newly available and planned EO missions that will supply large volumes of observations. This raises issues relating to the capacity of EO missions, the position of mission operators and data owners and the acceptance and level of uptake from risk management authorities concerning the exploitation of EO-based geo-information products and services.

It should be noted that the seismic hazard community does not think of a seismic risk monitoring programme in the same way as, for example, a volcanic risk monitoring programme. There are no reliable precursors for earthquakes and no EO solutions are expected to provide short-term earthquake warnings. However, EO does have a critical role to play in the estimation of long-term

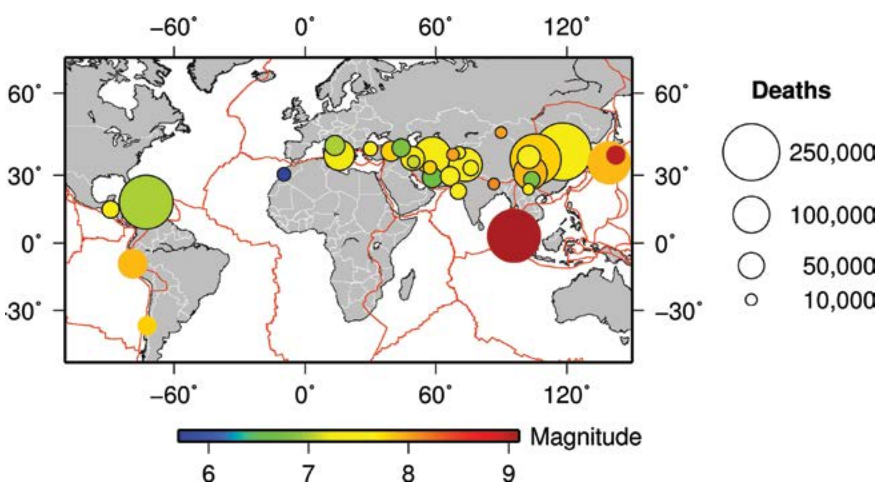

Figure 1. Earthquakes 1900-2012 killing more than 10 000 people (USGS); circle area proportional to deaths while colour shows earthquake magnitude. Circles with black rims show quakes not on plate boundaries. Adapted from England et al., 2011.

seismic risk, in the rapid response to earthquakes, and in providing data vital for furthering scientific understanding of these events.

1.2 Seismic hazards and global exposure

Earthquakes are amongst the most deadly of natural hazards, especially in recent years. Of the 35 earthquakes since 1900 that have killed more than 10 000 people (Figure 1), seven occurred in the 21st century. These include the 2004 Indonesian earthquake and tsunami, and the 2010 Haiti earthquake, both of which killed more than 200 000 people. Large earthquakes have a major international economic and societal impact. As well as plunging Japan's economy into recession, the 2011 Tohoku-Oki mega-thrust earthquake caused a major shift in Germany's nuclear power policy, the shutdown of car production

Seismic Hazard Assessment from Tectonic Strain

Typically, seismic hazard is assessed through analysis of the historic and instrumental earthquake record – areas that have experienced strong shaking in the past are likely to experience it again (*e.g. Aki, 1988*). Additional constraints come from the mapped locations and measured slip rates of known active faults. These methods break down when earthquakes are infrequent or faults have not been identified (*e.g. Ward, 1998*). For example, the Bam earthquake (*M6.5, Iran, 2003*) occurred on a fault that was not and probably could not have been identified prior to the earthquake, in a city that had not experienced strong shaking for at least 2000 years (*Jackson et al., 2006*).

Although earthquakes do not appear to have recognisable short-term precursors, all are preceded by the steady accumulation of seismic strain over decades to millennia. Short-term measurements of this strain accumulation offer an alternative method for assessing seismic hazard that is not biased by the brevity of the instrumental record (*e.g. Kostrov, 1974*). Even with existing measures of strain (*Kreemer et al., 2003*), which are derived from ground-based observations of surface motions that are often sparse, the relationship between measured strain and earthquake hazard is strong (Figure 2). Few earthquakes occur in regions where the magnitude of strain is lower than 1×10^{-8} yr^{-1} (or 1 mm/yr over 100 km length scales).

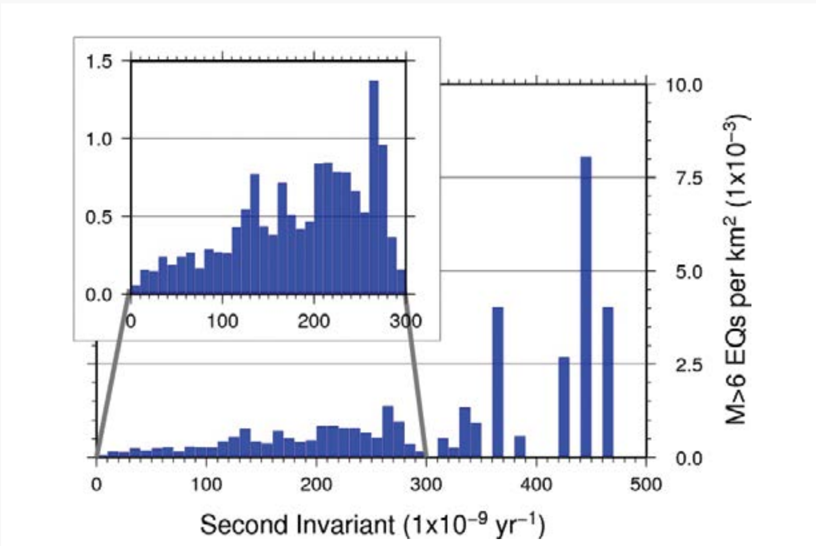

Figure 2. Number of earthquakes per square kilometre (M>6 from the ISC catalogue 1964-2010) as a function of the magnitude of tectonic strain (second invariant of strain tensor from Kreemer et al. (2003)).

Recently, *Bird et al. (2010)* proposed a formal method for utilising geodetic strain data to provide a long-term forecast of shallow seismicity. They tested the method using strain data from the Global Strain Rate Model (GSRM) of *Kreemer et al. (2003)* and some simple assumptions about the style of earthquakes occurring in each region to forecast shallow seismicity rates. For continental regions, they found good agreement between the observed seismicity rates for the past 30 years and those predicted by the model, without any requirement for adjustment factors.

However, the GSRM is constrained in the continents primarily by ground-based GPS data. In many countries with hazardous faults, GPS data are sparse if they exist at all. As such, any forecast based primarily on the GSRM can only hope to capture a broad overview of the potential seismic hazard of a region. Dense geodetic observations are required before further progress can be made. Satellite EO can potentially provide these observations. Recently, *Wang and Wright (2012)* showed that InSAR and GPS could be combined to produce dense geodetic observations over broad regions. With data from future satellite missions, this method has the potential to map tectonic strain at the required accuracy and resolution for all the seismic belts (see Figure 4), with reasonably uniform quality.

in Detroit due to lack of spare parts, and a global rise in insurance premiums.

Earthquakes cannot be prevented, and short-term prediction seems impossible. However, their impacts can be mitigated through improved understanding of the distribution of earthquake hazard and concerted actions by planners. California and Japan have invested heavily in both earthquake science and mitigation methods. As a result, the death toll from a future M~8 earthquake on the San Andreas Fault in southern California is estimated at only ~1800 (Jones et al., 2008), while similar quakes caused ~30 000 deaths in Iran (M~6.5 Bam, 2003) and ~200 000 deaths in Haiti (M~7.0 Port-au-Prince, 2010). The death toll of the M~9.0 Tohoku-Oki event was only 10% of that in the 2004 Indonesian tsunami, despite their similar magnitudes and mechanisms.

Understanding and modelling the strain that causes seismic activity is critical to improved mitigation. The 'straining belts' represent about 15% of the earth's surface, as seen in Figure 3. To achieve global risk reduction requires sustained effort in evaluating and monitoring seismic hazard, and in risk mitigation. Satellite EO can make an exceptional contribution to an operational global seismic risk programme.

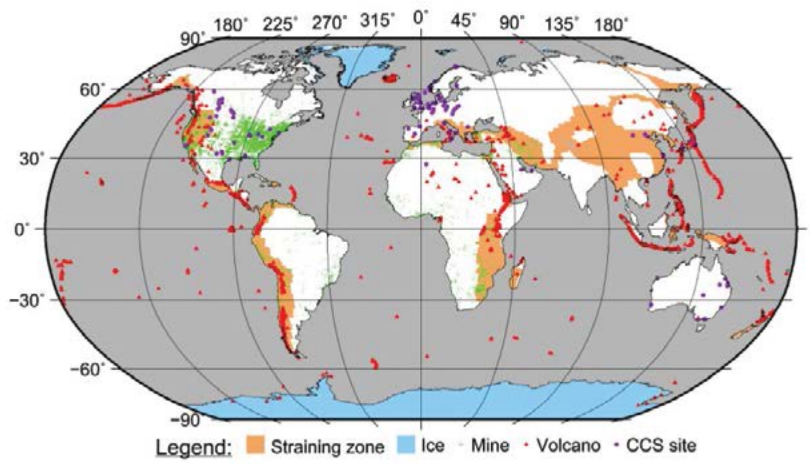

Figure 3. Straining areas (seismic belts) and volcanoes of the world (Kreemer et al., 2003). Figure from the GSNL Strategic Plan 2012.

1.3 Users and their information needs with regards to seismic risk

National and regional civil protection agencies, seismological centres and national and local authorities in charge of seismic risk management activities are all concerned with the phases of preparedness/mitigation, early warning, response, recovery, rehabilitation and reconstruction. The insurance and re-insurance industries also have a strong interest in quantifying seismic risk. Beyond operational users with a mandate in seismic risk management, there is a range of geoscience users focused on the scientific use of data with the main goal of understanding the physics of earthquakes thereby improving our ability to characterize, understand, and model seismic risk.

The needs of these user groups can be broken into the following three categories of activity: (i) long-term seismic risk estimation; (ii) emergency response, and (iii) scientific research. Below, we describe the needs in these different areas, and the potential contribution of information from EO.

Long-term seismic risk estimation

This activity has two components. The first is assessing the likely seismic hazard, using the latest scientific information from a variety of sources including records of historical seismicity, instrumental seismicity rates, information on fault locations, slip rates on those faults, and tectonic strain rate, as well as the local site response. The second is acquiring the most accurate knowledge of exposure (including population density, building stock, and the location of key infrastructure) and vulnerability (including construction type, building heights, and the response to past events) to map hazard into risk. Some, but not all, of these key data sets can be sourced from EO.

In terms of the hazard, high-resolution optical satellite imagery and digital elevation models can be used to map the location of faults. In some cases, where the fault trace at the surface is clear, this is a relatively straightforward task. In others, where faulting is 'blind', EO data can be used to identify tell-tale signatures of faulting in the landscape (see section 'Scientific Research' described overpage). EO data can be used to identify surface offsets across faults, which can then be targeted for ground-based dating studies; together, these provide information on fault slip rates. Slip rates on faults can also be estimated using targeted geodetic studies of known faults. This can be achieved with ground-based GNSS[1] observations, or with Interferometric Synthetic Aperture Radar (InSAR). Many earthquakes in the continents occur on faults that were unknown, or whose hazard had previously been underestimated (e.g. England and Jackson, 2011). Mapping regional tectonic strain (Figure 2) using GNSS and/or InSAR has the potential to dramatically improve our understanding of this poorly quantified component of seismic hazard (e.g. Wang and Wright, 2012). EO data on land cover can also provide some useful, if crude, information for assessing local site response (Yong et al., 2008).

Much of the information required for accurate estimates of exposure and vulnerability can only come from detailed ground-based surveys. However, EO data can provide useful proxies for some key parameters. For example, various EO data sets, including night-time lights, were combined with census data (Dobson et al., 2000) to produce a global population database. High-resolution

1. Global Navigation Satellite System. Although in practice, most current GNSS observations are made using the Global Positioning System (GPS), the next 10 years should see increasing use of the European Galileo system, as well as systems from Russia and China.

optical imagery can be used to assess building stock and the location of key infrastructure. Some information on construction type and building heights can also be estimated from high-resolution EO data. A full evaluation of seismic risk requires the integration of information on hazard, exposure and vulnerability. EO data are an important part of this picture. They are particularly valuable in developing countries where reliable ground-based information can be sparse.

The Earthquake Loading Cycle

In the Earth's upper, seismogenic crust, typically 10-15 km thick, tectonic forces cause stresses to slowly accumulate until they are sufficiently high to overcome frictional resistance on a fault plane. At this point, one side of the fault starts to slide past the other. Because the dynamic coefficient of friction is usually lower than the static one, fault slip accelerates catastrophically. The result is an earthquake.

During the build-up to an earthquake, the *inter-seismic* period, the tectonic stresses cause the rocks around the fault to strain as they accumulate elastic energy (Figure 4a,b). In the earthquake itself, the *co-seismic* period, most of that elastic energy is released, as the rocks spring back (Figure 4b,c). In the immediate aftermath of an earthquake, a period of accelerated *post-seismic* deformation also often occurs, as stresses are redistributed on and around the fault plane. By making precise measurements of surface deformation during the *inter-seismic*, *co-seismic*, and *post-seismic* phases of the earthquake cycle with satellite geodesy, scientists can estimate the mechanical properties of the crust. In addition, earthquake slip models derived from observations of *co-seismic* deformation can be used to forecast the likely locations of aftershocks and triggered earthquakes.

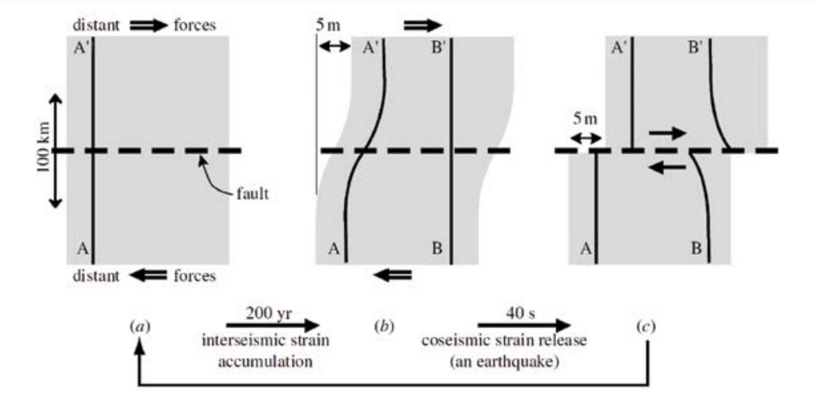

Figure 4. Simplified earthquake loading model.

A simplified earthquake loading cycle model, after (Reid, 1910), redrafted from (Wright, 2002). (a) Map view of area spanning a hypothetical fault, in the instant after the last earthquake. (b) The same area, 200 years later. The profile A-A', straight at the beginning of the cycle, has become curved. This is known as *inter-seismic* strain accumulation. Note that the magnitude of the warping is vastly exaggerated in this diagram. (c) 40 s later, after an earthquake. A-A' is once more a straight line, but this time with a 5 m step at the fault. B-B', straight immediately before the earthquake, is now curved with an offset of 5 m at the fault, decaying with large distances from the fault. The timings and displacements are representative of a typical earthquake with horizontal (strike-slip) motions, such as the 1999 Izmit (M~7.6, Turkey) earthquake. The cartoon does not include the accelerated period of *post-seismic* deformation often observed after large earthquakes.

Emergency Response

This activity is concerned with the operational response to major seismic events, and needs data and information products in near-real time geared towards damage analysis and situational awareness. Information from EO that could be useful includes the extent of damage, either through direct mapping or through models based on accurate knowledge of the extent of the fault rupture, and information on the probable magnitudes and locations of future aftershocks.

Direct estimates of damage can be made by manual or automatic analysis of high-resolution optical and/or radar imagery (e.g. Stramondo et al., 2006, Adams et al., 2004, Gokon and Koshimura, 2012). An alternative approach is to estimate the damage distribution indirectly using a model of the earthquake. For example, the USGS PAGER system (Jaiswal et al., 2011) provides a very rapid estimate of the area and extent of damage (quantified in both deaths and dollars) based on the predicted shaking (initially a function of earthquake epicentre and magnitude), along with estimates of population exposure and vulnerability. Satellite observations of co-seismic deformation (Figure 4, The Earthquake Loading Cycle) from InSAR can be used to determine the precise location and distribution of slip on the earthquake fault. As well as being more accurate than seismic source locations (e.g. Weston et al., 2011), the InSAR-derived models describe the full extent of the fault plane: for a M7+ earthquake, faults are typically 100 km long or more. Distance from this extended source is a more reliable predictor of damage than distance from the single point epicentre provided by seismology.

One of the most significant breakthroughs in the past 20 years of earthquake research has been the realisation that the distribution of earthquake aftershocks and triggered earthquakes is controlled by the static stress changes induced by the main shock (e.g. Stein, 1999). Where Coulomb stresses are elevated (typically, but not exclusively, around the tips of faults), the likelihood of future seismic activity is raised. Where the stresses are lowered, often parallel to the fault that slipped, aftershocks and triggered earthquakes are much less likely. In principle, static stress calculations can be performed in near-real time, but they are currently limited by the reliability of rapid earthquake source models. As discussed above, InSAR-derived source models are the most accurate available for continental earthquakes. With future satellite systems, there is the potential to provide them in near-real time. If this was possible, the predictions of the resultant stress calculations could provide emergency responders with valuable, reliable information on the areas that are most and least at risk from aftershocks and future seismic activity.

Scientific Research

The scientific user community is engaged in a wide range of activities with the aim of improving understanding of the fundamental physics and phenomenology of earthquakes and tectonics, and of improving the ability of users to perform 'Long-term seismic risk estimation' and 'Emergency response' tasks, described above. EO can provide useful data in a number of areas, but, of most relevance here, particular progress has been made in mapping and modelling deformation associated with the earthquake loading cycle (Figure 4), and in identifying tell-tale signatures of active faults in the landscape (tectonic geomorphology).

The proliferation of satellite geodetic observations of the earthquake loading cycle from GNSS and InSAR in the last 20 years has dramatically increased the quantity and quality of observations of the inter-seismic, co-seismic, and post-seismic phases of the earthquake loading cycle[2]. While this is a vast improvement on the situation 20 years ago, geodetic solutions for earthquakes are still dramatically outnumbered by seismic solutions over the same period. Many faults lack detailed inter-seismic observations and the number of post-seismic observations is too small to draw clear conclusions about any spatial variations in the physical properties of the crust and mantle. There is a clear need for a global, systematic acquisition of SAR data that would allow small rates of tectonic strain to be mapped in all fault zones. In addition, many of these geodetic data sets have been analysed in different ways with different assumptions by different groups. There would be considerable benefits to a systematic analysis of each and every earthquake, for example, that could provide a consistent set of geodetic source models, at least for shallow continental earthquakes. Similarly, significant effort is required in modelling the results. In most cases, it is not possible to observe all three phases of the earthquake cycle in one location; models that fit post-seismic deformation may not also satisfy constraints from inter-seismic deformation late in the earthquake loading cycle.

Tectonic geomorphology has also advanced dramatically in the past 20-30 years (e.g. Burbank and Anderson, 2012). Scientists are now able to read the tell-tale signatures in the landscape due to buried (blind) faulting. The increased availability of very high resolution optical imagery and digital topography data means that much analysis can be conducted remotely, with fieldwork only required for validating the EO results, and for obtaining age constraints that allow rates to be calculated, for example. The need of this community is for increased availability of affordable high resolution imagery and topography. Because active faults can be distributed over vast areas, the imagery and topography needs to be acquired for the entire planet. This is ideally suited to satellite observations.

1.4 The European case

In Europe, most of the seismic regions are concentrated in the areas around the Mediterranean Sea. Moderate to strong seismicity is present from Spain and Portugal in the west through Italy, Greece, and the Balkan Peninsula, to Turkey further east. Based on the surface extent of seismically prone areas globally, the European risk represents about 11% of the extent of seismic risk areas in the world. The North Anatolian Fault Zone (NAFZ) that cuts Turkey from East to West along 1200 km is, along with the San Andreas Fault in California, one of the longest and deadliest strike-slip fault systems in the world. The NAFZ is characterized by frequent seismicity: a sequence of 9 M7+ earthquakes that began in 1939 culminated with two large earthquakes in 1999, the August 17 M7.6 Izmit earthquake followed on November 12th by the Magnitude 7.2 Düzce earthquake to the east. Together, these earthquakes killed more than 30 000 people. A major seismic gap on the NAFZ south of Istanbul remains a significant concern. Rapid population growth (10-fold in the last 50 years) in Istanbul has resulted in hastily constructed new building stock that often does not comply with required standards. About 65% of the total building stock does not satisfy current codes.

From a seismological perspective all the main types of faulting are present in Europe and all have been responsible for major disasters. Normal (extensional)

2. In a recent compilation of geodetic observations, Wright et al. (2012, in review) found 78 earthquake source mechanisms for continental earthquakes derived from satellite geodesy, 187 measurements of inter-seismic strain accumulation around locked faults, and 23 earthquakes (or sequences) for which post-seismic deformation had been observed.

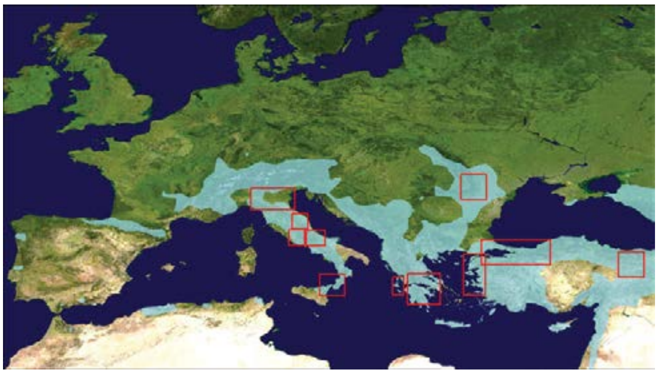

Figure 5. Priority area surface coverage of EO-based tectonic services of Terrafirma. This comprises the mapping activities conducted at national level and the pre-operational service deliveries of European projects (2009-2012). Semi-transparent blue mask is an indication of risk prone areas based on mortality and economic loss risk derived from Natural Disaster Hotspots: a global risk analysis (CIESIN, World Bank).

faulting occurs along the spine of Italy, in Greece and Western Turkey for example; major strike-slip structures are found in Turkey; the Hellenic arc is a well-known example of thrust faulting, and has caused significant tsunamis in historical times. The tectonic services of Terrafirma cover a portion of the most seismic areas in Europe. In particular the case studies are Istanbul Metropolitan area and the NAFS (North Anatolia Fault System) in Turkey, the Messina Strait (Italy), the Ionian Islands and the Corinth-Thessaly-Athens region in Greece (see Figure 5).

Large efforts have been made in the coordination of research infrastructures at the European scale. A Collaborative Project in the Cooperation programme of the Seventh Framework Programme of the European Commission (FP7), SHARE started in 2009 to provide a community-based seismic hazard model for the Euro-Mediterranean region with update mechanisms. The project aims to establish new standards in Probabilistic Seismic Hazard Assessment (PSHA) practice by a close cooperation of leading European geologists, seismologists and engineers.

SHARE is a Regional Programme of the Global Earthquake Model (GEM) (http://www.globalquakemodel.org/) providing essential input and feedback on all hazard assessment procedures and standards in Europe. SHARE and GEM are working together in the development of a computational infrastructure for open-source probabilistic seismic hazard assessment. Further activities are ongoing concerning the management of earthquake crises. Among them are REAKT (Strategies and tools for Real time EArthquake risK reduction looking at real time seismic risk reduction methodologies stemming from probability models), NERA (Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation), VERCE (Virtual Earthquake and seismology Research Community in Europe e-science environment), EUDAT (EUropean DATa).

Since 2002 ESFRI (European Strategy Forum on Research Infrastructure) has been leading the strategic plan and further initiatives have been derived from it at National and European scale. Moreover it led to the start of the strategic project EPOS (European Plate Observing System) coordinated from Italy through the Istituto Nazionale di Geofisica e Vulcanologia (INGV). EPOS is aimed at coordinating Research Infrastructure and e-science for Data and Observatories on Earthquakes, Volcanoes, Surface Dynamics and Tectonics. Originally, the EPOS project was limited to using in situ data. More recently, the need to augment these data with valuable satellite EO has been recognized. The working group WG8 ‘Satellite Information Data’ is the link between the EO data community, composed of the EO data providers and EO product providers, and the in situ data community.

1.5 Current state of Satellite EO-based applications & services

Satellite EO-based applications and services for seismic risk fall under three categories of activity: (i) long-term seismic risk estimation; (ii) emergency response, and (iii) scientific research. The potential applications and services that could be offered based on state-of-the-art current research are also described.

Long-term seismic risk estimation

EO has a significant role to play in the estimation and mapping of both seismic hazard and the resulting risk. For estimating hazard, satellite geodetic techniques (InSAR, GPS) have the potential to map tectonic strain (Figure 2, seismic hazard assessment from tectonic strain), and high resolution optical and digital topographic data sets derived from satellite observations can be used to identify active faults, often 'blind' at the surface. For converting the hazard into risk, some data on exposure and vulnerability can also be derived from EO data. In both cases, the potential impact of the EO data sets is greatest in developing countries, where ground-based observations are sparse.

Despite this strong potential, relatively few applications and services exist to provide end users with EO data or derived products designed for seismic hazard or risk. The Terrafirma project (http://www.terrafirma.eu.com), a Pan-European ground motion information service funded by the EU Global Monitoring for Environment and Security (GMES) programme, is one exception. The Terrafirma project calculates and disseminates PSI[3] motion estimates (e.g. Ferretti et al., 2001) to end users for target areas throughout Europe. Since phase three of Terrafirma began in 2009, tectonics and crustal deformation have been included as one of three themes. The specific aim is to deliver information on crustal faults, including their slip rates and locking depths, to end users in Italy, Greece, and Turkey, where the seismic hazard is high. Because tectonic strains are often distributed over many tens of kilometres (cf. box 1), this service has necessitated the development of new wide-area processing techniques, which allow PSI results from multiple SAR tracks to be combined into a single product. Further research is required to compare the results of such methods with alternative approaches that rely on the combination of conventional InSAR results with ground-based GNSS data (e.g. Wang and Wright, 2012). Tools and data sets that exist today, or will come on stream in the next 5 to 10 years, will allow EO to be much more widely used in estimating seismic hazard and risk (cf. section 1.6).

Emergency response

Several active projects and initiatives around the world use EO data in the response phase to emergencies. In Europe, the EU Framework programs have supported several important projects on emergency response, which are now integrated as part of GMES. Until 1st April 2012, the pre-operational emergency management service of GMES was provided through the EU-funded project SAFER. On 1st April 2012, the mapping component of the GMES Emergency

3. PSI (Persistent Scatterer Interferometry) is a technique that calculates interferometric time series for point targets selected on the basis of amplitude and phase stability, and spatial and temporal coherence.

Management Service entered into Initial Operations (GIO EMS – Mapping: http://portal.ems-gmes.eu). This is the first implemented Service of the GMES Initial Operations programme 2011-2013 (GIO). The GIO Emergency Management Service has worldwide coverage. It can provide data in "rush mode", which covers the on-demand and fast provision of geo-spatial information supporting authorities in charge of crisis management immediately following natural or man-made disasters, including earthquakes. Products include reference maps based on archived EO data and damage delineation and grading maps derived from EO data acquired immediately after the event.

Globally, the main mechanism to exploit space technology concerning the response phase is the International Charter (http://www.disasterscharter.org). With 14 members today, the Charter is able to provide rapid access to data from a virtual constellation of satellites, both optical and SAR, tasked in rush mode to help disaster management centres in relief actions in the response phase. This activity is focused on hazards with rapid on-set scenarios, on the hazard impact, and aims to service operational users, not science users. In practice, this means that raw data are provided to value-adding companies, who then create products that are of practical use to operational users on the ground. EO data provided by the International Charter was invaluable for the emergency response and situational awareness during the 2010 Haiti earthquake, for example, because there was little seismic infrastructure before the earthquake. Existing services are focused on providing simple mapping products and direct estimates of damage distribution. Further work could focus on the rapid and automated production of earthquake displacement maps and source models. These could be used to improve the accuracy of predicted damage distributions, and for forecasting the likely distribution of aftershocks and triggered earthquakes.

Scientific research

EO data are used widely in scientific research into seismic hazard. For deformation work, much progress has been made possible by the decision of space agencies to task their radar satellites through background missions. In particular, a large archive of radar data from ERS-1, ERS-2, Envisat and Radarsat-1 and 2 acquired over the past 20 years is an invaluable resource.

Perhaps the most important scientific development for EO data has been the GSNL initiative (http://supersites.earthobservations.org/). The GSNL provide access to space-borne and in-situ geophysical data of selected sites prone to earthquake, volcano or other hazards. The GSNL are supported by numerous partners including GEO, ESA, JAXA, NASA, DLR, ASI, CSA, NSF, UNAVCO and EPOS. Earthquake supersites exist in Istanbul (Turkey), Tokyo (Japan), Los Angeles (USA), Vancouver/Seattle (Canada/USA) and Hawaii (USA). In addition, "event supersites" have been established after significant earthquakes. The GSNL were selected for scientific reasons but also to maximize the visibility of the project. They are not intended to be global in their reach, but to provide data for type examples of hazardous systems or natural laboratories.

A number of scientific projects and laboratories provide ad hoc earthquake source mechanisms from EO data. None, at present, would claim to provide an operational service, with the aim of investigating every single earthquake. Similarly, a number of groups have been using InSAR to map strain, and optical and topographic data to find hidden faults. Again, none of these groups are at the stage of providing operational services. However, the methodologies employed by these researchers are now reaching maturity. Operational services could be provided in the next 5 to 10 years.

In order to achieve the objectives outlined in section 1.6, below, the ideal satellite mission would measure tectonic strain (Figure 2) with InSAR at surface velocity gradients of 1mm/yr over 100 km length scales (strain rates of 10-8 yr-1) in the east-west, north-south and vertical dimensions (Wright et al, Santorini Workshop 2012). Coherent interferograms would always be possible. To meet these criteria and also respond rapidly to earthquakes would require:

1. A SAR satellite or series of SAR satellites with rapid revisit times (6-12 days) to increase the number of observations (to reduce noise), maximise coherence, and to ensure that data are available quickly after an event. It is unlikely that this could be achieved without a constellation of satellites, but these would not necessarily have to be from the same satellite provider.
2. A SAR satellite that is always on when over tectonic areas to maximise the number of observations and increase coherence. In other words, a dedicated observation strategy aimed at creating a large database of images over the Earth's tectonic zones.
3. A sensor that is capable of obtaining spatially dense measurements. For tectonic strain and earthquake response, very high resolution is not necessarily required.
4. A satellite that allows measurements of motion in at least three disparate directions to obtain three dimensions of surface displacement observations (note that most polar orbiting systems including Sentinel-1 can only obtain 2D deformation from ascending and descending combinations; methods for obtaining displacements in the azimuth direction exist, but are currently significantly less accurate than interferometric measurements of range change).
5. L-band. The coherence at L-band (~20cm wavelength) is dramatically better than at C-band and the longer wavelength also simplifies phase unwrapping. Ionospheric noise is worse, but that can be dealt with if there is sufficient band width for split-band processing.
6. Data available in near-real time and free of charge, to maximize chances of early response to events.
7. Wide swaths: to capture long-wavelength inter/post-seismic deformation and co-seismic deformation from large earthquakes.

No single current or planned mission meets all of these requirements. However, through the combined application of currently planned missions such as Sentinel-1, the Radarsat Constellation Mission (RCM) and ALOS-2, it may be possible to meet the stated requirements.

1.6 The way forward

There are four fundamental questions that concern the use of satellite EO to support the seismic hazard risk management community:

- What objectives does this community need to achieve over the next 5 to 10 years?
- What factors can accelerate the realization of these objectives?
- Is the international community ready to collectively address the challenges associated with these objectives?
- What about other users not using Satellite EO?

What objectives does this community need to achieve over the next 5 to 10 years?

The seismic community has set out a vision of the EO contribution to an operational global seismic risk program. In 5 to 10 years' time, EO could provide fundamental new observations of the seismic belts - around 15% of the land surface – and improved understanding of seismic events through the work of the GSNL.

This will enable:

1. Development of a high resolution global strain rate model at high spatial resolution incorporating deformation constraints from GNSS and InSAR. InSAR allows essentially continuous observations of the seismic belts worldwide with near-uniform quality.
2. New regional or global maps of active visible faults, incorporating the latest results from the geomorphological analysis of high resolution optical imagery and digital topography data.
3. The creation of a new global seismic hazard map based on 1 and 2.
4. To continue precise measurements, including frequent acquisitions with multiple SAR sensors, over geographically focused areas through the GSNL to ensure strain rate measurements of unprecedented accuracy.
5. Rapid response to earthquakes, including:

   (a) Automatic rapid estimation of earthquake damage using high-resolution optical and radar imagery, and InSAR coherence using available capacities such as the Charter.
   (b) Automatic rapid creation and web-publication of co-seismic interferograms (wrapped and unwrapped) from all available sensors.
   (c) For non-specialist end users, products derived from the interferograms, such as phase gradient maps, combined with critical infrastructure data, could be produced.
   (d) (Semi-) automatic fault modelling – rapid production and web-publication of fault parameters using simple, consistent techniques.
   (e) Prediction of damage distribution using this fault model.
   (f) Rapid calculation of Coulomb Stress changes on neighbouring faults to assess likely locations of aftershocks or triggered earthquakes. The fault model in (d) would be used initially, along with any data on historical seismicity (e.g. from USGS archives).
   (g) Collection of InSAR data to support fundamental research on earthquake fault mechanics using observations of the early post-seismic phase. These observations (hours to days after the event) are now possible thanks to the multiple sensors available to the GSNL.

6. A long-term response to earthquakes that involves acquiring radar data for years to decades after an earthquake in order to measure post-seismic deformation.

What factors can accelerate the realization of these objectives?

To meet the ambitious vision outlined on a 5 to 10 year time scale requires a concerted effort from both EO data providers and scientists or value adding companies developing tools to exploit the EO data. The initiative should be user-driven to ensure that the results provided are utilised to increase resilience to earthquake hazards.

Requirements for EO data providers

The main areas of the 5 to 10 year vision where activities are critically dependent on EO data providers are for the goals of mapping tectonic strain, mapping faults, and for rapid response to earthquakes. Specific recommendations include:

For mapping strain: Mapping tectonic strain with the required accuracy to be useful for seismic hazard estimation (Figure 2) requires regular repeated radar acquisitions over long time periods, ideally in several different viewing geometries. No single planned mission meets all the requirements, but upcoming missions, notably Sentinel-1A/B, ALOS-2 and the RCM, have the potential to collectively fulfil the objective. In order to achieve this:

— Planned radar missions should acquire data as often as possible in the world's seismic belts (Figure 3). The surface area with strain rates higher than 10-8 yr-1 is ~3.55% of the imageable Earth surface (between +/-80 degrees). The entire seismic belts, including the lower straining areas, cover ~15% of the earth's land surface.
— Radar missions should build uniform catalogues in single modes of acquisition for long periods of time. Missions should have background missions that build up large, uniform catalogues over the seismic belts. This will ensure accurate deformation rates can be recovered.
— Radar missions should acquire data with multiple viewing geometries (ascending and descending). To ensure that faults with all geometries can be viewed, single missions (e.g. Sentinel-1A/B) should acquire data in ascending and descending modes. Space agencies should coordinate efforts to ensure a range of viewing geometries are acquired in the future.
— Data should be made available for this task. Ideally, satellites should have a free and open data policy that would allow multiple users to work on this task. Multi-sensor imagery should be available with unified metadata through a convenient e-infrastructure following the example of the GSNL to facilitate joint analysis of thousands of radar data.

For global fault mapping: Mapping faults using EO data requires high resolution optical imagery and digital topography. Specifically:

— High-resolution (1 m or better) optical imagery should be made available at reasonable cost for all tectonic zones for the purposes of seismic hazard investigation. Currently the costs for finding faults across large regions using tectonic geomorphology from EO data are prohibitive for individual scientists or civil protection agencies.
— High-resolution (10 m or better) digital topography should be made available at reasonable cost for all tectonic zones for the purposes of seismic hazard investigation. New missions are capable of producing high resolution topographic models using optical stereo matching or InSAR. Space agencies should consider making these available at reasonable cost for large regions for investigations into seismic hazard.

For rapid response to earthquakes: The rapid acquisition of post-event data is critical. The impact of EO data for damage assessment is highest in the immediate aftermath of an earthquake, and its use would be facilitated by:

— Immediate tasking of radar and optical satellites for acquisition of post-event data. In some cases this will require special intervention to ensure imagery is acquired. In others, with suitable background missions, this objective should be straightforward to meet.
— Opening of archive data for the area of the earthquake. For change detection work using optical or radar data, pre-event imagery is as critical as post-event imagery.
— Rapid delivery of EO products to all potential users. This could be facilitated through "event supersites", for example, to ensure that all potential users of the EO data have rapid access to the best possible pre- and post-event data.

Requirements from scientists, civil protection agencies and value adding companies

To meet the objectives, considerable effort is required on the part of scientists, civil protection agencies and value adding companies. Specifically, the following tasks are required:

For strain mapping:

- Further development and optimisation of automated time series methods. To map strain using InSAR first requires producing the best possible deformation maps for individual radar tracks. If we are to achieve this regionally or even globally, considerable effort will be required in automating this process and conducting quality control with existing methods. Particular attention will need to be paid to phase unwrapping errors, orbital errors, corrections for tropospheric and ionospheric noise, and other geophysical corrections (such as earth tides). These are particularly important at the long spatial scales (~100 km) that are required for mapping tectonic strain.
- Testing and further development of methods for integrating GNSS and InSAR to map strain over large regions. Integrating observations from multiple satellites with different viewing geometries with ground-based GNSS observations is critical for producing a uniform product comparable to the existing, low resolution global strain rate map, derived from GNSS. Further work is required to test and improve on existing algorithms.
- Organisation and planning is required if this task is to be completed. The processing involved represents a considerable task, which should not be underestimated. It will require dedicated operational staff and computing resources.

For mapping active faults:

- Further development of observational strategies. Mapping tectonic faults using EO data, particularly those that are blind at the surface, is becoming more routine, but methods are developing all the time. Further research is required in this area. Training of scientists and civil protection agencies is needed. Mapping faults across large regions or even globally would require a huge effort. Many of the methods used in tectonic geomorphology for identifying faults are now fairly routine, but specialist training is required to roll out these methods to a wider range of scientists in research establishments or civil protection agencies.
- Organisation and planning is required if this task is to be completed. Like strain mapping, this is a considerable task that would require some central coordination if a uniform global product is to be produced.

For mapping seismic hazard:

- Development and testing of methods for incorporating tectonic strain into seismic hazard maps. Methods have been proposed but need further testing and development.

For rapid response to earthquakes:

- Development and testing of methods for automatic rapid damage assessment using optical and/or radar imagery. Considerable progress has been made in this area, but further work is required to refine and automate existing algorithms.
- Development of automated algorithms and systems for rapid production and web delivery of co-seismic interferograms and derived products. At present, co-seismic interferograms and derived products are produced by the community and posted on 'event supersites' after significant events. This could be automated and products could be delivered via, for example, the USGS earthquake portal.
- Development and testing of automated geodetic source modelling routines. Numerous inversion schemes exist that are capable of creating source models after earthquakes. Few of these are automated, but there are no real barriers to this.
- Development of derived products from geodetic source models. Once the geodetic source models exist, creating derived products, such as predicted damage distributions or stress change maps, is relatively straightforward.

Nevertheless, effort is required in developing, testing and automating these methods.

For advancement of earthquake science:
The goals in earthquake science are too numerous to list here, but one issue merits highlighting: modelling. In the past 20 years, data have outstripped model development when it comes to the earthquake loading cycle. There is not a self-consistent model that can explain co-seismic, post-seismic, and inter-seismic deformation that is accepted by the community, and this goal may be years away, in stark contrast with the climate community for example. Huge effort is required to support the modelling of geodetic data in order to better understand the physics of earthquakes.

Is the international community ready to collectively address the challenges associated with these objectives?

To achieve the ambitious objectives set out will require considerable coordination and focused effort from the international community currently engaged in the use of EO for seismic risk. One of the challenges is that many scientific users of EO have, to date, been primarily focused on using EO for furthering understanding of the fundamental processes associated with earthquakes, rather than in creating new products or services that could have immediate practical implementation. These scientists need to be engaged with value-added companies and end users to deliver the services described here.

It is likely that some funding would be required to ensure that the community is able to respond to the challenge in a coordinated fashion. The organisation of any community effort could be conducted through existing organisations, such as the GSNL initiative, or the GEM. The Geohazards Event Supersites have shown the value of free and open access to pre- and post-event imagery. Value can be added by multiple, independent teams from around the world, without restriction. Providing open and free access to pre- and post-event imagery, perhaps via the Geohazards portal, would increase the value of input from a range of different organisations.

What about other users not using satellite EO?

Products and services derived from EO will only ever be one component of an array of tools and data sets available to those responsible for managing seismic risk. The authors of this chapter believe there is scope for increasing the uptake and effective use of EO by the end user community and have highlighted several issues that need addressing:

— Lack of acceptance of EO data. Many of the technologies used in creating EO products that could be used by seismic risk practitioners are relatively new. Although methods have been validated in numerous scientific studies, further work is required in demonstrating the validity of products derived from EO, and in delivering robust uncertainty estimates.
— Lack of expertise. Most end users are not experts in EO data processing and interpretation. Considerable effort is required in creating products and services that are straightforward to use, and in building EO analysis capacity through targeted training to end users.
— High cost of many data products. Many civil protection agencies, particularly in developing countries, cannot afford to purchase EO-derived products, such as PSI deformation maps. Alternative funding models need to be considered if such products are to be widely used.

Volcanic Ash cloud from erupting Klyuchevskoy Volcano in northern Kamchatka. Photograph taken from the space shuttle; courtesy of NASA.

2. Perspectives Concerning Satellite EO and Geohazard Risk Management: volcanic hazards

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2.1 Scope

This chapter presents the perspectives on the contribution of satellite EO to volcanic and volcano-related hazards, and the associated risk and disaster impact mitigation. Taking into account the current state and expected evolution of applications and services, their realistic level of usage and the achievable needs expressed by qualified end users, the document attempts to broaden the view to provide a global perspective. The chapter outlines a 5 to 10-year vision for the volcanic hazard community, based on the assessment of state of the art research. It composes of a set of possible outcomes including analysis of how to strengthen and consolidate the applications and to focus, orient and improve competitiveness of volcanic risk related EO services.

2.2 Volcanic Hazards and Volcanic Risk exposure

About 1500 volcanoes are known to have erupted in the last 12 000 years (the Holocene Era); about 700 of these, mostly subaerial, have erupted at least once in historical times (Siebert et al., 2010). Worldwide, about 100 volcanic unrests are observed yearly, and about a half of them become observable eruptions. It is estimated that less than 10% of active volcanoes are monitored on an on-going basis, meaning that about 90% of potential volcanic hazards do not have a

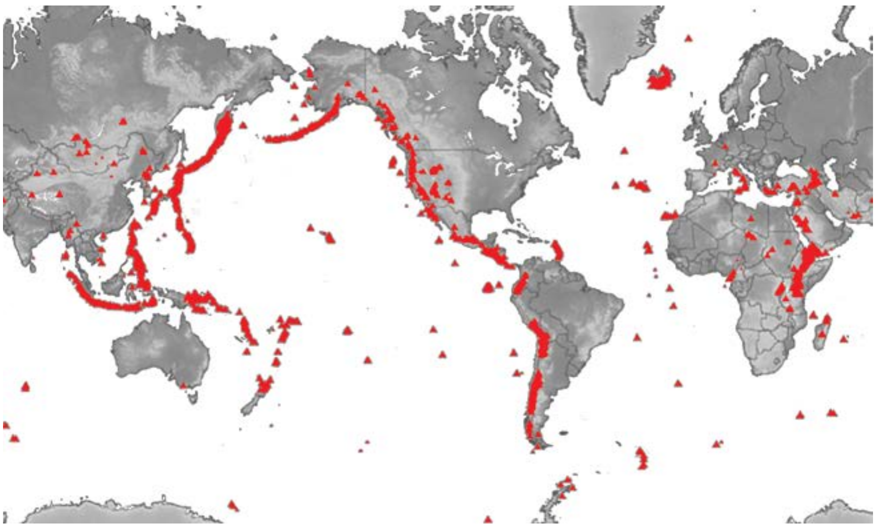

Figure 1. Holocene active volcanoes (Global Volcanism Program of the Smithsonian Institution, www.volcano.si.edu/world/find_regions.cfm).

dedicated observatory and are either monitored occasionally, or not monitored at all. The number of active submarine volcanoes is larger than subaerial ones but the precise number is unknown. Almost all active volcanoes are associated with plate boundaries and hotspots, with particularly large numbers around the Pacific Rim (Figure 1).

The conversion of hazard to risk depends on the location of people and assets at risk, and their dependence on time. This leads to two risk terms, one related to geographically permanent exposures, such as cities and mega-cities at the foot of active volcanoes[1], and one that is transboundary, related to the emissions of volcanic ash and gases.

The dramatic impact of transboundary emissions is well known to travellers. On April 14, 2010, the moderate eruption of the Icelandic volcano Eyjafjallajökull - which began one month earlier - suddenly turned into phreato-magmatic explosive activity. The resulting closure of north and central European airspace between April 14 and 20 led to the cancellation of ~100 000 flights and the stranding of ~10 million passengers (about half of the world's air traffic). Oxford Economics (2010) estimated that the 2010 Eyjafjallajökull eruption had a total global economic impact of ~5bn€ and the International Air Transport Association (IATA) stated that the total loss for the airline industry was close to 1.5bn€. Another 0.2bn€ was claimed by the Airport Operators Association (AOA) as the major hubs of London, Amsterdam, Paris and Frankfurt were virtually shut down by the effects of the ash clouds.

Eruptive styles generally correlate with viscosity and temperature of magmas[2]. The driving force for explosive eruptions, the products of which are ash and SO_2, is provided by dissolved gas in viscous magmas: the resulting clouds can disperse in the troposphere and stratosphere, travelling very large distances (~1000's km) from the eruption source.

Lava flows, the non-turbulent fluid product of effusive eruptions, may travel long distances on land at velocities modulated by instantaneous effusion rates, terrain slopes and viscosity. Velocities are typically much less than 0.3 ms^{-1}, and flow lengths are on the order of a few kilometres; noteworthy cases include flow lengths of a few tens of kilometres (Nabro 2011, e.g.) and an exceptional velocity of ~3 ms^{-1} observed once at Mauna Loa (Hawaii) in 1950. In a few cases worldwide, persistent molten 'lava lakes' may form if a dynamic equilibrium is reached between the magma load, its volatile content and the pressure in the underlying shallow plumbing system. Among the more or less long-lived lava lakes, that at Nyiragongo (Congo) is peculiar as it is less than 20 km away from and about 2000 m above the crowded city of Goma, which underwent a major volcano emergency and humanitarian crisis in 2002.

Still on land, 'pyroclastic flows' are hot (~ 1100 K), fast moving (~200 ms^{-1}) horizontal and vertical streams of fragmented rocks and superheated gases. Originating from the gravitational collapse of "Plinian" columns[3], or from the collapse of spines of very viscous lavas at "dome forming" volcanoes (e.g. Mt. Pelée 1902, Montserrat 1995-2010). These are the most destructive features associated with volcanic eruptions in general.

1 In Italy, Japan, Iceland, western central and southern Americas, northern-western USA and Alaska, Kamchatka, Indonesia, Philippines, Hawaii, Lesser Antilles, Azores, Canarias, Congo, etc.

2 In essence, high-viscosity magmas display high-Silica content (typically >60%) and relatively low-temperature (typically <1000°C). They are associated with 'explosive' volcanism as highly viscous lavas tend to retain high-temperature volcanic gases, such as water vapour, carbon dioxide and sulphur dioxide, which form vesicles within the entrapping matrix. Conversely, magmas with relatively low silica content (in the order of 50%), low-viscosity and temperatures typically over 1000°C, give rise to 'effusive' eruptions with limited or no explosive activity as gases migrate through and escape, without major build-up of internal pressure.

3 After the famed Pompeii disaster of Mt. Vesuvius, Naples, 79 AD.

Three final hazardous elements are the expected length of flows, the duration of unrests, and the impact of both on the management of territory and air space. Forecasting the extent of flows over time is important to prepare the operational response, and to constrain time, location, type and extent of civil protection activities. It is generally agreed that the effusion rate is the lead factor among the many parameters (e.g. terrain slope, viscosity, yield strength, total volume, mass, effusion rate) to determine lava flow length. In explosive eruptions, where ultrafast development of climaxes does not allow a timely response on land, all prevention measures –mostly involving evacuation of people and displacement of activities to safer places– should be taken well in advance, before the onset of the crisis. In general, however, the ability to take decisions is affected by the lack of knowledge concerning two crucial questions: when the first breakout will happen, and when the eruption –or the eruptive cycle– will come to an end. Recent major worldwide[4] crises illustrate that we can usually only answer the first question, and then only with large uncertainty.

In highly explosive eruptions, the turbulent 'jet' composed of rock fragments and super-heated gas heats the troposphere and rises fast and high by convective thrust. The ceiling of such explosive eruptive columns depends on the difference in temperature between the 'jet' and the surrounding atmosphere, and the fourth root of the actual mass eruption rate. For ordinary mass eruption rates (below 8-10 m^3 s^{-1}), ash can be injected into the upper troposphere and propagate even at distances of several hundred kilometres before being diluted to non-dangerous concentrations. The response of a jet engine to volcanic ash depends on a number of variables, including the ambient ash concentration and composition (which influences the melting point), time of exposure and engine type and thrust settings. Flying across a high ash concentration or flying a long time along an unnoticeable low-concentration ash plume may result in severe engine damage including engine failure and severe sandblasting of exposed surfaces.

2.3 Users and their information needs

Conceptually, the monitoring of volcano dynamics is dealt with by volcano observatories which operate arrays of instruments and carry out multi-parameter networked measurements for constraining deformation, mass, geometry, magnetism and chemical and gas parameters in time and space. As volcano assessment and forecasting are supervised, an important part of monitoring relies upon visual observation and terrain inspection.

By nature, a volcanic eruption is a local event that may turn into a transboundary one. Consequently, there are two categories of major, potential, systematic users of space-borne information on volcanic activity (monitoring and early warning) and volcanic hazards in general (risk exposure assessment and mapping):

(1) the first category is national, and is selected on a case-by-case basis by those responsible for disaster and risk management, or for giving scientific advice to those who make decisions to protect lives and property. Typically, the former is a Ministry or a mandated National Agency, whereas the latter is a volcano observatory, a geological survey or their equivalent;

(2) the second category is transnational and, as such, has no authority over the territory containing the volcano. It is typically a Volcanic Ash Advisory centre (VAAC) within a Meteorological Watch Office (MWO), an intermediate link between the World Meteorological Organisation (WMO), the International Civil Aviation Organization (ICAO) and individual airlines. Timely warnings from

4 In particular: St. Helens 1980-1991, Campi Flegrei 1982-84, Rabaul 1982-2012, Pinatubo 1991, Etna 1991-93, Montserrat 1995-2010, Eyjafjallajökull 2010.

Feature	Need	Resolution	Observable	Required	Payload (2012)	Mission (2012)
Magma at surface	Detection and Location	High temporal	Radiance	TIR, MIR, SWIR	SEVIRI, Imager, JAMI, MODIS, AVHRR, VIIRS	MSG, GOES, MTSAT-2, Terra, Aqua, NPP
Lava flows	Flow mapping (topography and volume	High spatial	Radiance ** Amplitude, phase **	SWIR, NIR SAR	ETM+, HRVIR, HRG, AL, LISS-IIII C-band, X-band Radar	Landsat-7, SPOT-4*, SPOT-5, EO-1, IRS-P6 Radarsat, TerraSAR-X, COSMO-SkyMed/ 1-4
	Effusion rate monitoring	High temporal	Radiance **	TIR, MIR, SWIR	SEVIRI, JAMI, MODIS, VIIRS	MSG, MTSAT-2, Terra, Aqua, NPP
Pyroclastic flows	Flow mapping	High spatial	Radiance	TIR	ETM+ , HRVIR, HRG, ALI, LISS-III	Landsat-7, SPOT-4 and 5, EO-1 IRS-P6
Active domes	Detection, Mapping	Moderate temporal High spatial	Radiance	TIR, MIR TIR, SWIR, NIR	MODIS, VIIRS, AVHRR ETM+, LISS-III, HRVIR, HRG, ALI	Terra, Aqua, NPP, NOAA, MetOp-A/B Landsat-7, SPOT-5, EO, IRS-P6
Fumarole fields	Detection, Monitoring	High spatial	Radiance	TIR	ETM+	Landsat-7
Eruptive columns, Ash	Detection, Location	High temporal	Radiance	TIR, MIR, SWIR, NIR, Visible	SEVIRI, Imager, JAMI, AIRS, MODIS, AVHRR, VIIRS, IASI	MSG, GOES, MTSAT-2, Terra, Aqua, NOAA, NPP, MetOp-A/B
Ash dispersal (atmosphere)	Monitoring	High temporal	Radiance **	MIR, TIR, LiDAR	SEVIRI, Imager, JAMI, MODIS, AIRS, AVHRR, VIIRS, IASI, CALIOP	MSG, GOES, MTSAT-2, Terra, Aqua, NOAA, NPP, MetOp-A/B, CALIPSO
SO_2 concentrations	Detection, Monitoring	Low spatial, High temporal	Radiance **	UV, TIR, MIR	OMI, IASI, GOME-2, AIRS, MODIS, VIIRS, SEVIRI , SCIAMACHY*	Aura, MetOp-A/B, Terra, Aqua, NOAA, NPP, MSG, ENVISAT*
CO_2 concentrations	Detection, Mapping	Low spatial, Low temporal	Radiance **	UV to TIR	TANSO-CAI, TANSO-FTS	GOSAT
Topography	DEM	High spatial	Interferometric phase ** Stereoscopy **	SAR Visible, NIR	C-band, X-band Radar ASTER GDEM, SPOT DEM	Envisat*, Radarsat, COSMO-SkyMed/1-4, Tandem-X Terra, SPOT-4*
Ground deformation	Detection, Location, Monitoring	High spatial, Low temporal	Interferometric phase change **	SAR	L-band, C-band, X-band Radar	ALOS*, Envisat*, Radarsat, COSMO-SkyMed/1-4, TerraSAR-X
Ash dispersal (ground)	Mapping	High spatial, Low temporal	(Reflectance) Radiance **	Visible, NIR, SWIR	ETM+, HRVIR, HRG, MODIS, VIIRS. LISS-III	Landsat-7, SPOT-4*, SPOT-5, IRS-P6, Terra, Aqua, NPP
Morphology changes	Detection, Location, Mapping	High spatial	Amplitude, phase (coherence, reflectivity) Radiance (Reflectance) changes)	SAR Visible, NIR, SWIR	C-band, X-band Radar Pleiades, GeoEye-1, Ikonos, WorldView-1/2, QuickBird-2, Kompsat-2	Radarsat-2, COSMO-SkyMed/1-4, TerraSAR-X Pleiades, GeoEye-1, Ikonos, WorldView-1/2, QuickBird-2, Kompsat-2

Table 1. * ceased operations during 2012 ** advanced post-processing required

volcano observatories –where they do exist– on major ash and gas emissions are required.

Table 1. Most major observation needs can be satisfied remote-sensing. In 2012 only, 4 passive geostationary payloads, 12 passive polar orbiting payloads and 7 SAR payloads were systematically exploited for the provision of volcanic observation services - at various levels of timeliness, and for research - worldwide.

Researchers, advisors on risk exposure and mitigation and communicators fit into a third, important, category of individual or group users who may or may not be involved in the management of volcanic risk, at different stages and with different roles.

Most monitoring relies on visual observation and terrain inspection. Less than a hundred observatories worldwide follow activity in the 10% of volcanoes that are monitored. Table 1 summarizes volcano observation needs where EO is relevant.

A key use for EO data is at volcanoes where little or no ground-based monitoring exists. This includes (a) large-scale InSAR surveys that look for signs of unrest at volcanoes without any seismic monitoring stations, (b) thermal studies that look for the first sign of magma close to the surface, and (c) tracking large ash clouds following eruptions. Given the transboundary nature of volcanic hazards, it is vital that volcanoes can be studied free of political restrictions and national boundaries and also in remote or inhospitable locations. This capability is unique to EO.

Having carried out a review of user needs based on major crises worldwide and various projects in remote sensing, several distinct groups of users and needs have been identified. Observational needs are broadly divided into those related to ground features and atmospheric features and can be used for either crisis management or in strategic activities for hazard assessment and risk reduction. To date, the prevalent demand in EO from volcano observatories is centred on pre-eruptive and syn-eruptive stages, with requested refresh rates of information strongly varying as a function of both the activity to deal with, and the parameters monitored. This overview of user needs relies on 20 years of co-operative volcanology and remote sensing research undertakings[5], and over 10 years of the International Charter on Space and Major Disasters[6]. The Charter provides access to data from a virtual constellation of EO missions that works on a reactive basis in the immediate disaster response phase. To be effective, EO response requires operational systems. In the case of volcanic hazards, scientific users play a critical role by advancing science to better understand and put into context observed phenomena.

Following the 2010 Eyjafjallajökull eruption, the user needs of the volcanic ash community have been particularly clearly defined. The community interested in following volcanic activity on the ground is separate from the atmospheric community interested in tracking and quantifying volcanic ash and gas emissions. A broad community of end users composed of aviation regulators, policy makers, engine manufacturers and representatives of commercial airlines have agreed upon three levels of ash concentration thresholds[7]. As these ash concentration levels are «Forecast» and not «Observed», this puts a heavy burden on the achievement of an all-weather quantitative observation capacity, as well as the ability of atmospheric dispersion models to make accurate forecasts reliably fitting the actual concentration and location of ash clouds.

The current needs consist in the timely provision (refresh rates in the order of minutes) of: (i) detection, location and quantitative characterization of the active volcanic source on ground; (ii) detection, accurate 3-D location and

5 E.g. the European Laboratory Volcanoes, supported by the European Commission in its 4th and 5th Framework Programmes.

6 *http://www.disasterscharter.org/home*. As of 2012, the Charter was triggered 18 times between 2001-2012 on: Etna (2001), Nyiragongo (2002), Stromboli (2003), Soufriere Hills (2003 and 2008), Galeras (2004), Karthala (2005), Merapi (2006 and 2010), Nevado del Huila (2007 and 2009), Tungurahua and Michamahuida (2008), Chaitén (2009), Eyjafjallajökull (2010), Hudson and Puyehue (2011), and Fuego (2012).

7 These thresholds range from «safe to fly» (below 200 µg m-3) to «special safety procedures» (between 200 and 2000 µg m-3): beyond 2000 µg m-3, the airspace becomes «no-fly zone».

Figure 2. Mediterranean volcanoes.

concentration imaging of the volcanic ash cloud, and (iii) forecast of the cloud dynamics in concentration, space and time, since timeliness and complete temporal coverage (day and night) are needed. The end users for these data are essentially the airline industry, but the data pass through several filters, including third party EO data product providers, advisory and warning centres (e.g. VAACs), official channels (e.g. MWOs) and aviation stakeholders, such as airport authorities, airlines, air-freight companies, private and commercial business jet operators and defence agencies.

2.4 The European case

Looking at volcanic hazards from the European standpoint, one should consider at least three different cases that imply a need for different risk management policies:

— *Active volcanoes in Greater Europe*[8], which directly threaten cities of variable size, vital services and strategic infrastructures, are all located in the Mediterranean. Vesuvius and Campi Flegrei bind the megacity of Naples (over 2 million people)[9], while Mt. Etna towers over Catania (ca. 900 000 people in the region).

— *Active volcanic areas located in EU territories worldwide* - excluding the above - are the European islands in the Lesser Antilles (Caribbean), the Azores and the Canary Islands archipelago in the northern Atlantic Ocean, and Reunion Island in the Indian Ocean. The picture is completed by Tristan da Cunha and the South Sandwich Islands in the southern Atlantic.

— *Volcanic threats to European land from non-EU volcanoes* mostly relate to volcanic aerosols (ash, SO_2) in high concentrations. Iceland, with 18 historically active volcanoes, and 29 eruptions in the last fifty years, is the major source of local hazard (e.g. Jökulhaups) and to both continental and insular Europe. In the Indian Ocean, Mayotte is threatened by Karthala, Grand Comore, Comoros archipelago. New Caledonia and the Society Islands do not host active subaerial volcanoes, but can be threatened by major explosive eruptions or by volcano-engendered tsunamis in the southern Pacific.

2.5 Current state of satellite EO services & applications

Satellite EO data are used for different facets of risk management concerning volcanic hazards. Whereas historical analysis using EO data can help

8 Ischia, Stromboli, Vulcano, Lipari, Pantelleria, Nysiros, Santorini, Mt. Etna, Mt. Vesuvius and Campi Flegrei.

9 Emergency plans drawn to deal with future occurrences of volcanic unrests present complexities associated with the need to displace between 500 000 and 700 000 from Vesuvius and nearby, or from the western suburbs of Naples, with little advance notice, for a period of a decade or more.

Figure 3. Very high resolution image of the volcano Vesuvius acquired on 18th June 2012 by the Pléaides-1A satellite
© CNES 2012 - distribution Astrium Geo Information Services / SpotImage.

identify and characterise eruption types and document their past occurrence, EO-based monitoring is ideally suited (see Table 1) to support the characterisation of the current state of a volcano. Infrared sensors have proved crucial, or even unique in measuring thermal outputs, constraining heights and movement of eruptive columns and ash clouds, estimating gas and aerosol concentration and composition. Space-borne InSAR is a recognized technique for the early detection of possible magma injections, for monitoring the stability of volcanic edifices, and for creating 3D digital elevation models (DEMs) anywhere on Earth. Allied to these automatic and semi-automatic quantitative techniques is a range of single-view and stereoscopic optical and radar imagery that can provide valuable information via supervised processing, interpretation and analysis.

Main EO capacities used or in development

While most volcanoes in the world have been observed and measured from space at least once, a few volcanoes[10] have been the subject of dozens of investigations both during unrest and in quiet times. Notwithstanding many convincing demonstrations, however, satellite EO is not exploited in a structured manner at a sufficient number of volcanoes worldwide[11]. Indeed, with the exception of the remote sensing of volcanic clouds –which is done continuously at a supra-continental scale and offers a significant contribution to the VAAC interface to aviation– volcanic EO of ground parameters is principally called on when a volcanic crisis is at an advanced or even at eruptive stages, and usually relaxed when activity declines. There are six sectors relevant for EO of volcanic, and volcano related hazards:

10 Such as for instance Campi Flegrei, Etna, Iceland, Kilauea, Nyiragongo, Okmok and Piton de la Fournaise.

11 In the US, for example, there are 169 potentially active volcanoes within the USGS area of responsibility, and satellite remote sensing has been used at many of them for mapping volcanic deposits in order to produce hazard assessments, for assessing surface changes during volcanic unrest, for detecting the onset of eruption, and for assessing deposits and morphological changes during and following an eruption. The Volcanic Hazards Program utilizes a variety of data sources and techniques to this end, including frequent low-spatial resolution weather satellite data (mainly Alaska, Northern Mariana, and Hawaii), moderate-spatial resolution mid- and thermal-infrared data (until 2012, primarily ASTER and Landsat; from 2013, LDCM), SAR (mainly Radarsat) for InSAR deformation mapping and analysis of surface change, and high-spatial resolution commercial electro-optical satellite data (such as Worldview, Quickbird, etc).

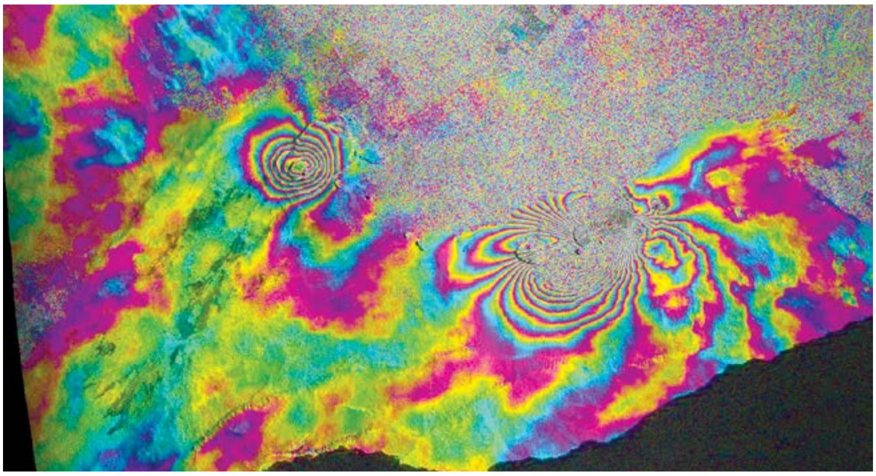

Figure 4. Relative deformation of Earth's surface at Kilauea between Feb. 11, 2011 and March 7, 2011 – two days following the start of the eruption on March 5, 2011 – imaged by radar interferometry using COSMO-SkyMed. Fringes mirror surface motion with 1.5 cm steps. Left: the circular pattern of concentric fringes represents deflation of the magma source beneath Kilauea. Right: the pattern represents the deformation caused by volcanic dike intrusion and subsequent fissure eruption taking place (P. Lundgren, NASA - JPL).

Space-borne SAR Interferometry

This technique has been used continuously from ERS-1 in 1992, to present-day, including with very-high resolution systems (TerraSAR-X and COSMO-SkyMed (Fig.4)). Science and technique have developed in parallel, relying upon the systematic availability of long series of comparable images of steadily high quality in most areas of the world. The forthcoming Sentinel-1 twinned mission builds on the successes of almost 20 years of C-band SAR missions (ERS-1 and -2, Envisat, Radarsat-1 and -2).

Interferometric techniques have evolved from the measurements of a DEM or of a single deformation map, to the study of the temporal evolution of complex 3-D displacements. Many contemporary studies explore the integration of satellite and ground-based geodetic measurements in volcanic and other settings. One of the main limitations of satellite based systems was the near-monthly revisit, leading to temporal decorrelation, including problems of vegetation-related coherence. Further difficulties in repeat pass interferometry are range errors caused by atmospheric changes and stratification effects. The estimation and compensation of such effects has made great progress in recent years. Decorrelation is also now mostly overcome by revisit intervals for new sensors ranging from none (TanDEM-X) to 1-8 days (COSMO-SkyMed constellation of four, Sentinel-1A/B and the forthcoming RCM). This outstanding technical performance has already led to a better understanding of transient volcano deformations of all magnitudes.

Moderate-to-High Resolution SAR Interferometry (from about 100 m and 20 m pixels, ScanSAR to Stripmap modes, to exploit large swaths in survey mode) looks appropriate for hazard inventory purposes, to include reconstruction of broad deformation patterns with time or to define deformation baselines to actual unrests. In many cases, a combination of ascending and descending data is required to derive 2D or even 3D displacement vectors from 1D radar interferometric observations. For monitoring of sustained unrests, conversely, a high revisit frequency is essential to avoid the temporal decorrelation – on the one hand – and aliasing in the deformation series, on the other. In this case, Very High Resolution SAR Interferometry (Stripmap to Spotlight modes) is appropriate for advanced monitoring purposes and support to crisis management (e.g. active volcanoes exhibiting severe unrest) as the increase in spatial resolution and the inherent decrease in swath-width will be compensated by improved knowledge of the spatial location, pattern and extent of deformation. Ideally, this function is to be fulfilled with the best descending and ascending repeat coverage allowed by the acquisition configuration.

Accounting for the expected, fast deformation rates with respect to available payloads, very-high resolution data should be considered not only for interferometry but also to detect, characterize and map ground features, thus exploiting the radar's cloud penetrating capability.

Operationally, while the value of this technique is recognised, its use is uneven. In the US for example, the USGS monitors about 130-140 volcanic systems using InSAR throughout the year, compared to daily observations of about 75 volcanoes using weather satellites. Resources permitting, more use of this technique is planned.

High-temperature thermal anomalies on the ground, at high spatial resolution.

Upon termination of the exceptional, 1983-2011 mission of Landsat 5-TM, and of the SWIR part of the ASTER mission, the sector currently relies only upon the SPOT-5 HRG and EO-ALI missions, which operate with day-time only acquisitions. From 2013, routine observation for science will be undertaken with the NASA-USGS Landsat Data Continuity Mission (LDCM) to provide 15-100 m resolution images in visible, NIR, SWIR plus one TIR channel to detect cirrus clouds, on 16-day revisits, and the twinned ESA Sentinel-2A/B mission. The latter is provided with 13 visible-NIR-SWIR spectral bands (four at 10 m, six at 20 m and three at 60 m) and has typically a 5-day revisit interval in the daytime only.

Considering the future acquisition capacity of Sentinel-2A/B, in combination with the current observing capacity of SPOT-5, it should be noted that that they do not fly TIR payloads and are not planned to acquire during the night time.

In order to maximize the advantage of the availability of multi-platform (three) multi-payload (five) multispectral EO, overpasses should ideally be phased to obtain at least one day-time observation every two days, on every priority area defined in section 2.2, and on erupting volcanoes.

As for TIR, observations at high-spatial resolution of low integrated temperature anomalies (typically, $350\ K > T_i > 300\ K$) are crucial for the detection of thermal precursory phenomena, the efficient monitoring of unrests building-up from mild stages to pre-eruptive, the monitoring of active domes, and the detection of dike emplacements before breakout. This minimized capacity will be soon fulfilled only by the split-window TIR on LDCM, at a bi-monthly repetition rate or less.

Finally, the offering of visible-NIR payloads with metre resolution is already broad (e.g. GeoEye-1, WorldView-1 and -2, Ikonos, QuickBird, Kompsat-2) and is

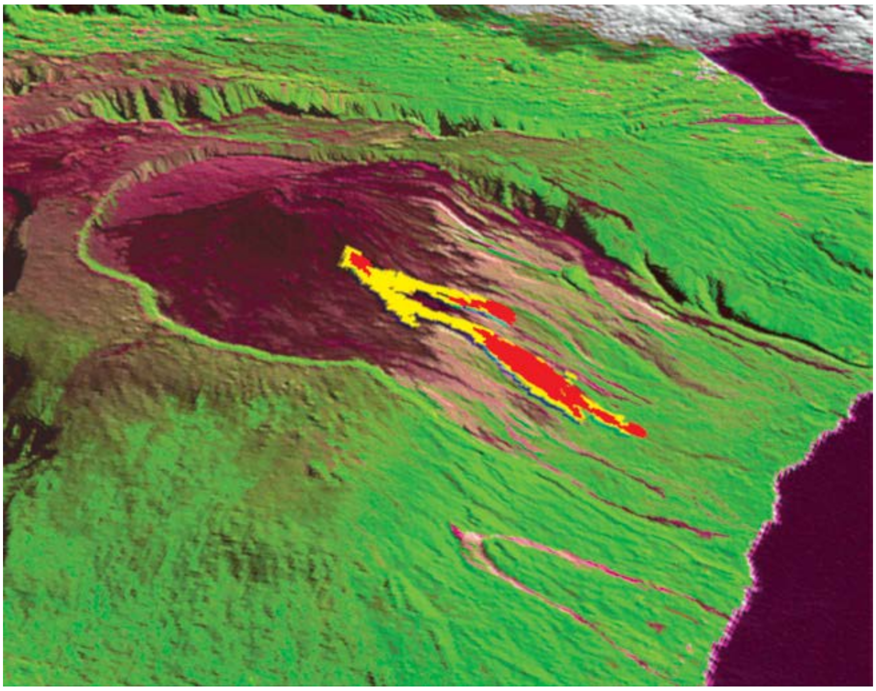

Figure 5. Reunion Island, France. Lava flowing on the SE flank of Piton de la Fournaise on November 8, 2000, imaged by the multispectral V-NIR-SWIR-TIR radiometer ASTER onboard EOS-Terra. Red: active flows (SWIR radiances). Yellow: cooling flows. Started on June 23rd, the lava flow finished on November 13, 2000. Flows overlayed on a 1-2-3 Landsat-7 ETM+ image draped on a 30m DEM. (B. Hirn, b.hirn@iesconsulting.net).

undergoing further, major improvements with the French constellation Pleiades. This type of EO is seldom used for quantitative volcano assessment, mainly because of lesser swaths and obscuring by clouds, steam, ash, SO_2 and even jet contrails.

High-temperature, thermal anomalies on the ground, at high temporal resolution

Hot-Spot pixels relating to magmatic or fire events at the surface, detected daily with polar orbiting MODIS (on Terra and Aqua) worldwide and shown with daily delay, and with geostationary GOES (11-12-13-15) in near-real time, are arranged in an all-public, semi-qualitative information service run since the late 1990s by the Hawai'i Institute of Geophysics and Planetology (http://hotspot.higp.hawaii.edu/). A step beyond, radiant fluxes, cloud cover and, where appropriate, effusion rates are analytically computed in real-time using SEVIRI for volcanoes within its "disk", in the framework of the GMES-EC project EVOSS. Estimates of SO_2 quantitative information are distributed in real-time via a proprietary portal to a community of stakeholders in areas where there is no volcano observatory, or as was the case during the 2011-2012 eruption of Nyamulagira (Congo), when the volcano observatory cannot function.

SEVIRI onboard MSG-1, -2 and now -3, is increasingly exploited for all-time detection, quantitative evaluation and tracking of volcanic features both in the atmosphere and on ground. Its 15-minute rate of observation is optimal, and the combination SEVIRI-MODIS has proved to be effective for resolving both types of volcanic features. The natural drawback in geostationary observation is the spreading of pixels from the nadir outwards towards the disk border, where the SEVIRI multispectral pixels exceed 50 km^2 and must be complemented or replaced by the 1 km^2 pixels of MODIS. Using MODIS does drop the revisit from 96 to two times daily per satellite, at low latitudes, but allows covering the polar regions up to sixteen times daily.

As for the quantitative use of polar orbiting instruments for volcano observation, the AVHRR datasets are less effective because of the limited number of bands (only five) and the early saturation of a crucial band (MIR) at temperatures as low as 330 K. The datasets from ATSR/ATSR-2/AATSR Infrared bands which did not suffer the early saturation drawback are complete from 1992 primarily for the SWIR channel at 1.6μm. The MODIS dataset is complete for all bands from 2000, and SEVIRI's archive is complete from 2004.

Volcanic Aerosols, in particular, Sulphur dioxide SO_2

Measurable in UV, MIR and TIR, and eventually SWIR, SO_2 is primarily a proxy for the amount of all magmatic gases that are being erupted, hence a marker of the magma masses available in the shallow plumbing system: conversely, SO_2 is a loose marker of ash as different dilution, weight, and chemical combination in the atmosphere lead to different fates of ash and SO_2 at distance.

Today, there are four[12] LEO very-low to low spatial resolution and half-daily to daily revisit instruments:

- the Global Ozone Monitoring Experiment (GOME-2) onboard MetOp-A and, soon, MetOp-B;
- the Ozone Monitoring Instrument (OMI) onboard AURA, the Ozone Mapper and Profile Suite(OMPS) followed soon by TROPOMI to fly on ESA's Sentinel-5 Precursor, scheduled for launch in 2014;

12 SCIAMACHY (Scanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY instrument) onboard Envisat, ceased operations on April 8, 2012. Its large spectral range had allowed observing many atmospheric trace gases (O_3, NO_2, BrO, SO_2, HCHO, CHOCHO, OClO, H_2O, CH_4, CO, CO_2)

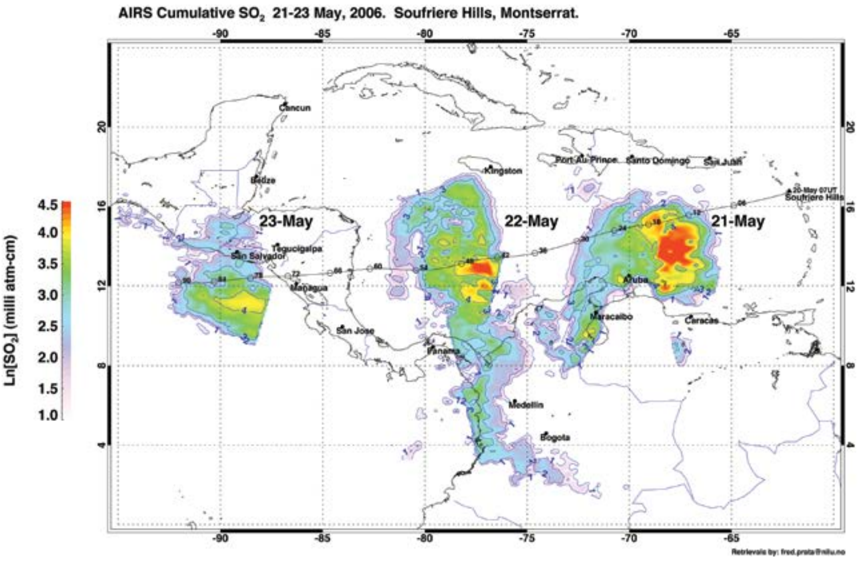

Figure 6. Soufrière Hills volcano, Montserrat, following the eruption of 20 May, 2006. The image shows SO_2 retrievals on 7 consecutive days, from the Atmospheric Infrared Sounder (AIRS on board EOS-Aqua), to measure atmospheric profiles of temperature, moisture and trace gases for climate and weather prediction applications. Trajectories from an atmospheric dispersion model overlaid on the plot confirmed a high, stratospheric SO_2 cloud. Cloud behaviour was monitored every 15 minutes using MSG-SEVIRI data. (F. Prata).

— two UV-SWIR hyperspectral payloads: IASI-Infrared Atmospheric Sounding Interferometer onboard MetOp-A, and AIRS-Atmospheric Infrared Sounder onboard Aqua (Figure 6).

Volcanic Aerosols, in particular, volcanic ash

Information provision services on volcanic ash and SO_2 are already launched, in ESA's VAST and Support to Aviation Control Service or SACS projects, based both on geostationary (high refresh rate products by EUMETSAT and ESA, involving SEVIRI) and polar orbiting satellites (moderate refresh rates, involving all available UV and IR payloads: GOME-2, SCIAMACHY, OMI, IASI and AIRS). A particularly promising instrument here is IASI onboard MetOp-A. The progress and the state-of-the-art concerning EO techniques to monitor volcanic aerosols is described in detail in the Proceedings of the ESA-EUMETSAT workshop on the 2010 eruption at the Eyjafjallajökull volcano, held in Frascati, Italy, from 26-27 May 2010.[13]

Emerging Research

The use of EO data for volcanic ash, although quite mature, can be enhanced by some targeted approaches using existing space-based assets and also by planning for systems that fill the gaps. Some areas where improvements can be made include:

— targeted EO aviation products, such as dosage rates, probabilistic measures, error bounds, concentration charts, hazard indices and risk prone airspace maps;
— improvement in the vertical sampling of EO data, specifically better spatial-temporal coverage from space-based LiDAR systems;
— improved compatibility between EO products and model-based data, specifically in the case of aviation for systems that permit assimilation of EO data into models, and use of quantitative satellite retrievals in inversion schemes leading to improvements in ash forecasting;
— improved vertical resolution in the EO-constrained ash plumes.

Advanced research has moved into the pre-operational domain recently, proving that geosynchronous observations by payloads provided with an

13 ESA-Publication STM-280. doi:10.5270/atmch-10-01, C. Zehner, Ed.,2010

adequate number of infrared channels and acquisition rates in the order of minutes, are already effective in dealing with source-and-plume monitoring, simultaneously on land and in the atmosphere. Indeed, thanks to the synergetic combination of advanced payload technology, robust theory and efficient processing, it is now possible to operate with detection thresholds as low as 0.1 GW for radiant fluxes on ground (corresponding to lava effusion rates theoretically lower than 1 $m^3 s^{-1}$, which would be difficult to measure even on the ground) and ash mass loadings as low as 0.2 g m^{-2} (meaning that concentrations lower than 200 μg m^{-3} can be determined in 1-km thick ash clouds with no obscuring water vapour).

These quantitative approaches are complementary, and remain such also in the presence of obscuring features, once the ash eruption is in progress and the plumes of ash and SO_2 are emitted in sufficient concentration. In the short term, an effective step forward would be that of a constructive fusion of ground-focused and atmosphere-focused methods. If the magmatic source on the ground is hindered by ash or clouds, an inversion scheme for the dispersion model and the eruption source parameters may allow model inference of the eruptive column; whereas, if the ash plume is embedded in clouds and the volcanic source on the ground is visible, measured mass eruption rates may allow model inferences of the jet, thus of the eruptive column and the altitude of the buoyant ash plume.

Geostationary observations by the current SEVIRI on MSG, the forthcoming Advanced Baseline Imager onboard GOES-R (2016) and the Flexible Combined Imager onboard MTG (2017), represent a sustainable global capacity of dealing with multiple eruptions at least to 2030. Thanks to greatly improved spectral and spatial resolutions these meteorological payloads are expected to improve global volcano monitoring, just as SEVIRI marked the turning point from strategic to tactical radiance EO monitoring of eruptions.

The primary need for operational volcano monitoring is all-weather, continuous EO in regions where observation is systematically hindered by clouds (in particular, tropical regions and high-latitude regions in winter) and can only be resolved by SAR. There is in fact a broad field of civil applications of non-interferometric SAR, which may take advantage of the capacity of recognising not only individual patterns and objects, but fuzzy and ever-changing "patterns of patterns" that can be revealed by the SAR's day and night vision at high and ultra-high resolutions. A striking example of the value of SAR for crisis monitoring is the 2010 eruption of Merapi volcano in Indonesia. SAR imagery (provided by the Charter) detected major changes in the volcano's summit area which led to the evacuation of ~320 000 residents prior to the arrival of unusually large pyroclastic flows.

The availability of medium and high, and sometimes ultra-high resolutions in polar orbiting satellites and constellations (Envisat, TerraSAR-X, COSMO-SkyMed, Radarsat-2, and the forthcoming Sentinel-1 and RCM) indicates that systematic homogenization and harmonisation of results appears to be a priority for transforming huge data archives into extensive knowledge of volcano behaviour, in terms of strain and stress.

In the case of effusive eruptions, EO data can be employed in lava flow hazard assessment thanks to the functional integration of satellite-derived effusion rate and physics-based flow models for lava flow path simulations. Several physical models and numerical methods have been applied to simulate lava flow paths under some simplified assumptions, based on the concept of maximum slope and stochastic perturbation of topography, Cellular Nonlinear Networks, Automated Neural Networks or Cellular Automata.

Sensitivity analysis of physical and rheological parameters that control the evolution of models confirm that DEMs and effusion rates or more generally eruption rates, have great influence on the results of modelling, where it is preferable to exploit near-continuous discharge rates, even with controlled errors, rather than sparse and accurate measurements as is usually done in the past. Emerging research in this field is expected to bring strong operational clues on mass (melt and gas) involved in the development of the various families of eruptive columns, their jets and the altitude for ash buoyancy and spreading.

2.6 The way forward

In the near term, EO for volcanoes needs to be developed in two complementary directions: i) quantitative integration of ground based and space-borne information, to constrain the multiple parameters within a complex environment such as an erupting volcano; ii) expansion of the scope of volcano monitoring beyond a few existing volcano observatories to offer a global perspective on all phases of activity from unrest, precursory activity to eruption and post-eruption with uniform frequency and appropriate resolution.

The GSNL initiative offers an appropriate framework for the first of these targets. To effectively use EO to monitor volcanoes requires a multi-parameter observation strategy in both real-time for monitoring and retrospectively for improved scientific understanding. This holds true for thermal features, ground deformation and gaseous emissions.

This strategy has six points to be realized within the next 5 to 10 years:

— Global systematic background observations: establish regularly refreshed baseline observations concerning ground deformation, thermal energy release and gas release at all 1500 Holocene Volcanoes, independently of the state of unrest.
— Increase systematic observation capability for early warning and alert: measure ground deformation, topography, thermal, ash and gas (where appropriate) weekly at all volcanoes that show signs of unrest. This represents approximately 100 volcanic unrests yearly.
— Detect, measure and track ash, measure thermal and gas parameters, for any eruption worldwide and at the appropriate spatial and temporal resolution at least daily; complemented with ground deformation measurements, morphology changes and assess post-eruption topography (DEM) as appropriate; improve the scientific understanding of eruption initiation and dynamics by frequent ground deformation measurements of volcanoes in severe unrest (InSAR observations of summit deformation before, during, and in between explosive eruption phases and of the initiation and propagation of dikes, as well as SAR backscatter analysis).
— Improve and/or develop the capability to carry out novel measurements, such as gas ratios, ash particle distribution, ash plume height, minor gases and ratios for gases in low quantities (HCL, H_2S, e.g.); extend the current capacity of measuring thermal and gas parameters to shallow submarine eruptions.
— Secure continuity and sustainability of all the above for 20 year horizon.
— Improve uptake of EO through training for end users.

ESA and the European Commission could be strong partners in such efforts, which would also involve international associations of volcanology (IAVCEI) and geophysics (IUGG), along with the World Organisation of Volcano Observatories (WOVO), the Global Earth Observation System of Systems (GEOSS), meteorological regulator authorities (ICAO, WMO) and national entities dealing with volcanic risk. The GSNL are an integral component of the observation strategy. They allow integration of data from multiple satellite resources with different wavelengths, resolution and revisiting times, as well as in-situ and other data sets. The GSNL are focused on science with in-depth monitoring with a clear and limited geographic focus. A comprehensive monitoring approach, particularly for severe volcanic unrest and eruptions, requires all available sensors collectively offering daily or even sub-daily observations (e.g. using meteorological missions data) of progressing volcanic crises, irrespective of geographical location.

The report of the USGS National Volcano Early Warning System recommends[14] that all high- and very high-threat US volcanoes be monitored with robust remote sensing methods. To this end, improvements in acquiring SAR data from high-resolution, C-band and X-band sources such as Radarsat-2, TerraSAR-X/TanDEM-X and COSMO-SkyMed would greatly aid their use. They can contribute with rapid tasking, processing, and delivery during crisis response, whereas sustainability issues in particular for long-lasting crises (years) call for a modulated, acceptable reduction in the cost of the data. In addition, continuation of moderate-spatial resolution mid- and thermal infrared missions are vital. Current access to weather satellite and high-spatial resolution EO data is adequate.

Factors that can accelerate the realization of these objectives belong to three main categories: technology and services, science, and users.

Technology & services

As the current evolution is towards two major families of EO, one dealing with large swaths and frequent refresh, and one focused on image sizes of a few hundred square kilometres at most, there is a need to readily redirect scientists (or value adding companies) from large to narrow swath views without loss of resources and time. A focused Change Detection Tool on low-to-mid, and mid-to-high resolution features would be essential for improving productivity and minimizing quantitative pre-browsing of all sort of scenes and imagery. Indeed, saving time is essential in view of the dramatic increase in data volumes already experienced.

Future improvements in SAR interferometry are not expected to be in the direction of improving resolution, but rather to minimize the temporal aliasing. Ad hoc attempts at exploiting redundancy in telecommunication sources in geosynchronous orbits that continuously transmit in the C, X and $K_{a,u}$ bands of the microwaves and their “8-shaped analemma” path to make the antenna synthesis are promising. However, further science and engineering efforts are required before interferometry from geostationary platforms becomes feasible.

Concerning integration. The wide spectrum of currently operating and planned EO techniques begs the question of how to integrate them with ground based systems into an effective, efficient global monitoring system. The last decade saw the emergence of several new approaches to integrating SAR and optical data with ground based geodetic data. Integration between satellite and ground based thermal data is still at an early stage, while there have been attempts to integrate ground and satellite based measurements of volcanic gases (e.g. SO_2) at some volcanoes.

Concerning validation. On multispectral high resolution images, validation of results relies on multi-parametric “ground truthing”. Processing of TM or ETM+ images, for example, could be validated against a few radiometers situated on the ground in specific pixels. With sub-resolutions, and the awareness that the transfer function in the atmosphere and its multi-temporal heterogeneity are drawbacks to validation. With the current availability of multi-payload/platform observation at dramatically increased refresh rates, “validation” scenarios have changed. Traditional validation may only apply to a few cases. For most EO applications, it would be worth considering almost continuous validation, which might come from ground data, if they are simultaneously available for the imaged area, or from one or more different payloads simultaneously observing the same parameters. A good example is provided by thermal sub-resolutions, where radiant fluxes obtained every 15 minutes at an assigned volcano by the geostationary SEVIRI (9 km^2 pixel at nadir, one MIR and two TIR bands), through the Dual Band or the

14 http://pubs.usgs.gov/sir/2008/5114/

Three-Component method, are systematically validated by radiant fluxes measured at almost the same minute and by the same methods run on data acquired by the near-polar orbiting MODIS payload (1 km^2 pixel, one MIR and two TIR bands). Scaling up in resolution, the same could have been applied to the pair MODIS-ASTER on the Terra platform. Regarding InSAR interferometry, in-depth validation programs have been conducted in recent years to better characterise the technique and its performance (e.g.Valproj Campaign in Terrafirma).

Science

Merging the needs expressed from users involved in the management of volcanic crises on the ground and in the atmosphere, the research agenda that will be followed in the coming years will be one of a variety of approaches of data fusion with modelling activities.

The generation of spatially and temporally dense deformation maps and time series through integration of data from different satellite platforms will help in better constraining volcano deformation models and, hence, in improving the understanding of mechanisms responsible for volcanic unrest. Currently, the availability of (i) InSAR data, capable of observing deformation patterns at a spatial resolutions unachievable with other sparse geodetic measurements, (ii) ground-based geophysical data, able to provide further constraints on sources and to reduce interpretative ambiguity of geophysical methods, and (iii) numerical modelling procedures, appropriate to describe complex volcanic processes, offers the opportunity to explore more realistic models to quantify the time-dependent volcanic processes and to gain insights on the volcano's level of activity, with obvious implications for the volcanic hazard assessment.

The integration of satellite data and numerical modelling represents a step toward the next generation of EO-based hazard assessment in volcanic areas. The key innovation is to solve the scientific challenge of developing numerical models, in which the output from numerical predictions are compared with observations to investigate the role of relevant factors affecting volcano unrest, to provide a quantitative estimate of the volcano internal state, and to identify the critical conditions making the volcano erupt.

Both EO data analyses and modelling procedures can be largely automated by taking advantage of modern computer technology. These will undoubtedly include, but may not be limited to, inversion, assimilation and ensemble modelling, as well as multi-parameter tomography and direct modelling of flows and eruptive columns.

Future systems should be able to diagnose a suite of gases, rather than only SO_2, with an improved capacity in discriminating and measuring CO_2 and H_2O, which intervene significantly in the magma ascent dynamics and in the eruptive dynamics. This requires improvements in temporal resolutions and in spectral resolutions for discriminating the signature of atmospheric components from those of volcanic products more effectively than what can be achieved today. These improvements would lead to a better knowledge of the volcanic source and of the propagation environment, given the critical role played by volcano dynamics in volcanic science.

Concerning science and education. Science and Higher Education institutions play a crucial role in the entire process of better understanding how volcanoes work and the overall capability to forecast a phenomenon on the basis of fundamental knowledge. In the last three decades, progress in all fields of geophysics has had an impact on the way volcanologists work, transforming their actions both in the field and in the laboratory. The fundamentals of physics and chemistry are increasingly present in the models describing volcano activities and in models designed to forecast the activity.

It is crucial to provide scientists and students easy access to a full range of data from volcanoes, from the ground and from the space. Easy and free access to all available data from volcanoes would increase basic knowledge of volcanism and boost the capability of volcano observatories to perform their fundamental work of informing the final users and authorities in an efficient manner.

Furthermore, scientists play a key role in education and the diffusion of information to the public. An important aspect of supporting the quality of research and innovation (and its operational use in the observatories) is the existence of long time series of data from ground and space, over years and decades which are at the time scales of the phenomena under investigation. For this reason, sensors on the ground and in space must be planned for long term continuity.

Users and Practitioners

As far as the community dealing with volcanoes is concerned, the user can be institutional (volcano observatories, or an equivalent mandated entity), academic (research centre, university, both crucial for innovation in technology and science and for the improvement of the hazard assessment) or designated by and representing a very broad community of users (the VAAC, for instance). It is worth noting that as a function of which part of the community is dealt with, there is a significant difference in the requirements towards EO, and a variable technical and scientific feeling about what EO can offer in general.

Concerning organization. Volcano observatories, and/or volcano observing and alerting capacity are heterogeneously distributed worldwide. Volcanoes in European countries, North America and Japan are generally well-monitored with well-organized volcano alert systems and well-established procedures regulating the communications between the observatories, the science community and the end users. In other parts of the world, where the largest part of active volcanoes is located (South America, Indonesia, Philippines), volcano observatories are more disperse and not as well-equipped.

Concerning users. End users, in particular those who have little or no quantitative information from the field, must understand the content of information in EO data (post-processed at various levels of sophistication) conveyed to them. In particular, it is important for the EO community to evaluate collections of users' requirements with a critical eye, avoiding personal bias or individual expectations. Realistic expectations regarding exploitation of information are critical to the success of EO, as well as ensuring accurate results. Therefore, systematic involvement of users in advanced training is necessary.

The Lumnez valley, located in the Canton of Grisons is one of the most active landslide zones in the built-up areas of the Swiss territory. Credits: Hugo Raetzo, FOEN.

3. Perspectives Concerning Satellite EO and Geohazard Risk Management: landslide hazards.

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3.1 Scope

This chapter presents the perspectives concerning how satellite EO can contribute to geohazard and disaster risk reduction in landslide-prone and landslide-affected areas. It is addressed to both the operational and the scientific users of the landslide community, and considers the state-of-the-art concerning EO data-based landslide research, applications and services, starting from the situation in Europe and expanding to provide a global perspective. The current status of landslide applications based on EO data is tackled through some case studies and goals achieved over the last decade in a range of activities identified by the contributors to this document, focussing initially on the European context, and broadened to address global landslide hazards. The chapter examines how to consolidate landslide applications and services to achieve benefits expected from their users. Particular reference is made to the forthcoming availability of large volumes of imagery from new satellite missions and the consequent need for effective, standardized and widely-accepted methodologies, as well as national and international capacities for the integration of EO data into everyday practices for landslide risk management; the final objective is the provision of support for landslide prevention, preparedness and emergency response, as well as post-emergency and recovery activities, and mitigation strategies. The community outlines a 5 to 10-year vision, based on the assessment of state of the art research and the application of EO for landslide risk management.

3.2 Landslide risk and exposure

Landslides, as a major type of geological hazard, represent one of the natural events that occur most frequently worldwide after hydro-meteorological events. The occurrence of landslides depends on complex interactions among a large number of partially interrelated factors, such as geological setting, geomorphic features, seismicity, soil properties, land cover characteristics, hydrological and the effects and impacts of anthropogenic changes to the landscape. Landslide predisposing or preparatory variables making the slopes susceptible to failure include soil and rock geo-mechanical properties, slope

Figure 1. Rainfall induced rock fall/ rock slide in the Tramuntana range, Majorca, Spain.

gradient and aspect, elevation, land cover, lithology and drainage patterns; triggering or dynamic factors are those initiating landslide movements, and might be either natural or human-induced, or even any combination of both (Dai and Lee, 2002). Natural triggers include intense or prolonged rainfall, earthquakes, volcanic eruptions, rapid snowmelt and permafrost thawing, and slope undercutting by rivers or sea waves. Other factors capable of acting as triggers for landslide failures are human activities such as slope excavation and loading, land use changes (e.g. deforestation), rapid reservoir drawdown, blasting vibrations, and water leakage from utilities. Earthquakes are notorious for triggering landslides. The Great Wenchuan earthquake in 2008 triggered more than 60 000 landslides (Gorum et al., 2011). Slow-moving landslides such as those caused by subsidence and large scale slope deformation are other forms of landslides to be considered.

Landslides represent a main hazard in mountainous and hilly regions as well as along steep riverbanks and coastlines, and their impacts depend largely on the area and volume involved, the motion velocity and intensity, number and distribution of elements at risk, their vulnerability and their exposure value. Data collected by the International Landslide Centre at Durham University (UK) indicate that in 2003 the death toll from landslides exceeded 2000 people globally (http://www.landslidecentre.org/).[1]

In order to represent landslide risk on a global scale, a few attempts have been made to assess susceptibility, hazard and risk, with uncertain degrees of accuracy. Recent studies such as those by Nadim et al. (2006) and Hong et al. (2007) show the hazardous areas are mainly concentrated in the Philippines and Japan and in Central and South America along the Pacific Coast, as well as in south-eastern Asia, with a medium to very high degree of hazard (cf. Figure 2).[2]

Many factors contribute to landslide risk, including topography, soil type and climate; for example, areas with coarse and relatively bare soil types and rainfall-affected areas are more susceptible to landslide processes. As a consequence, the hazard of rainfall-induced landslides tends to be much greater in tropical mountainous areas like the Philippines, Central and South America, and south-eastern Asia, with susceptibility indexes up to 5 (highest susceptibility level)[3]. The combination of the landslide susceptibility map with the distribution and vulnerability of the elements at risk facilitates the understanding of the expected losses due to landslide occurrences. It provides an estimation of the number of people exposed to landslides. Different landslide susceptibilities have been produced at a global scale. They generally do not provide sufficient temporal perspective or information on the magnitude of expected events. They also fail to account for the distribution and vulnerability of all the elements at risk. Finally, there is no updated database of landslide occurrences at a global scale.

1 This is probably an underestimate. In Italy, a country for which a detailed record of landslide and flood mortality exists, in the 52-year period between 1960 and 2011, 789 landslide events have caused 3417 deaths, 15 missing persons and at least 1940 injured people in 522 municipalities (Salvati et al., 2010).

2 Other important landslide-affected areas are found in the Himalayas (India, Nepal), in the European Alps (Italy) and Balkan regions (Albania, Greece), in the Middle East (Turkey, Georgia, Azerbaijan, Iran), in the Rocky and Appalachian Mountains (USA and Canada), and in some regions of Africa (Ethiopia, Kenya, Tanzania, Cameroon).

3 Other landslide-prone regions shown on the landslide susceptibility map by Hong et al. (2007) include the Pacific Rim, the Himalayas and South Asia, the Rocky and Appalachian Mountains, the Alps, and parts of the Middle East and Africa. India, China, Nepal, Japan, the USA, and Peru include wide landslide-prone areas as well.

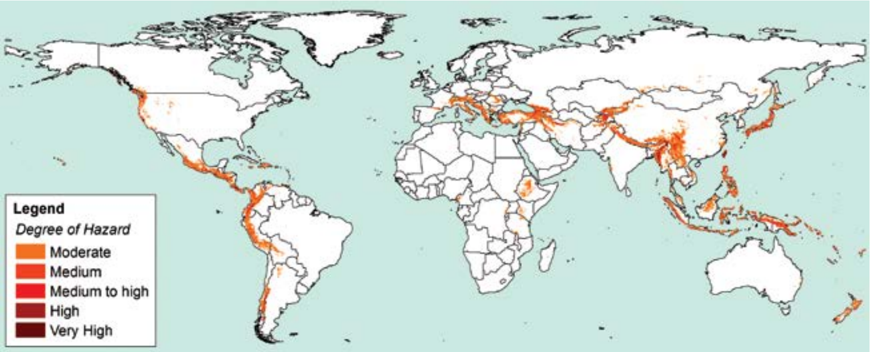

Figure 2. Global Landslide Hazard Distribution (GDLND), derived from the landslide hotspot map at global scale (Nadim et al., 2006) based on a heuristic landslide hazard model considering slope, lithology, soil moisture, precipitation, temperature and seismicity.

3.3 Users and their information needs

The EO perspectives on landslide hazard assessment and risk reduction rely on synergic linkages between the different actors involved in the process of landslide risk management. It is important to engage a large variety of users from both private and public sectors, from industry and the scientific community, government and research departments, from local to international levels, and to provide them with easily accessible, continuous, accurate and consistent information. Citizens represent the ultimate users of landslide risk management services, as they are affected by risk and can benefit from proper strategies of landslide risk mitigation, or suffer the consequences of inappropriate policies and actions. Both operational and scientific users of the landslide community benefit from EO satellite support, but their needs and requirements depend on their role within risk management process (cf. Table 1 and Table 2). A distinction can be made between activities performed in real (and near-real) time and those in deferred time. During 'real time' (measurable in hours, days or months) the performed emergency activities include urgent, immediate actions such as event now-casting, containment of effects, counter measures for risk mitigation and restoration previous living conditions. On the other hand, study, forecasting and prediction aimed at guaranteeing permanent safeguard of human lives and properties over the long term are carried out in 'deferred time' (measurable in years or decades). From a disaster risk management point of view, this is the distinction between response and recovery activities, and longer-term recovery and mitigation or preparedness activities.

Operational users from the landslide community include civil protection agencies, decision makers and stakeholders. They are often in charge of emergencies related to the occurrence of ground movements threatening populated areas and are asked to manage the impacts of landslide hazards on society during both real and deferred times. Populations are increasing, especially in developing countries, and landslide impacts are growing. Effective mitigation requires knowledge of location, extent, typology, intensity, style and state of activity of landslide processes.

Civil Protection Authorities: include all the structures and activities put in place by governments to safeguard the integrity of life, goods, buildings, cultural heritage and the environment from any damage arising from natural disasters, catastrophes and any other hazardous event. In joint collaboration with the scientific community, the civil protection agencies coordinate and manage forecasting of landslide risk scenarios, monitoring and early warning systems, prevention activities aimed at minimizing damage, relief operations (rescuing people, ensuring early assistance to the population affected by disasters), as well as training activities to ensure citizen preparedness. Civil protection emergency management and support have demanding needs; resources (e.g. computing, data, services, knowledge and expertise) need to be shared in a coordinated, effective and timely fashion (simple and clear procedures); information including rapid identification of affected areas need to be frequently updated. This user group is of crucial importance for successful landslide risk mitigation, as it represents the contact point with local authorities, and provides them with direct suggestions and recommendations during landslide emergencies.

Policy makers and planners: include a wide range of elected government officials at the national, regional or local level, politicians, administrators, land use planners and all those authorities taking part in the selection of the best actions to be performed among several alternative scenarios. Decision makers are interested in simple long-term effective information on geohazards, to support their role in hazard mitigation (e.g. through stabilization and remediation works) and risk management (e.g. implementation of land use planning strategies, regulation and controls driven by clear and firm laws). Their information needs include identification, mapping and classification of areas with present or past ground instability, e.g. location, areal extent, volume of displaced material, kinematic behaviour and evolution of the phenomenon in space and time. During and after emergencies, real-time information includes mainly monitoring activities (continuous stream of information to remote control stations and alert systems), residual risk mapping (identification of affected areas and residual risk zonation) and analysis of stability of surrounding areas (selection of safe areas where affected population can be relocated).

Other end-users: include a wide range of end-users including insurance companies, engineering and construction companies, environmental groups, transport officials, infrastructure operators and land owners. They should be considered during the land use planning phase and decision making processes in a truly participatory risk management process.

Citizens: the ultimate beneficiaries of geohazard-related strategies, citizens need to be informed on where, when and to what extent the ground may become unstable. Correct and thorough knowledge of a phenomenon is the first step towards understanding it and preventing disaster. One of the most important duties of the scientific community and responsible authorities is to make the population aware of procedures to adopt if a landslide occurs, by leading awareness and preparedness campaigns, and establishing simple rules on how to prevent or minimize damage from landslides.

Scientific users of the landslide community include universities, geoscience research departments, environmental agencies, national geological surveys and, generally, those institutes dealing with slope instability and working on the prediction, monitoring and supervision of the various types of landslide processes. Their main goals are the collection of satellite EO data validation through on site measurements and their integration into geotechnical, hydrogeological and deformation models, as well as development and testing of better data analysis techniques to extract from EO data the information which is relevant for landslide investigations. The quality and appropriateness of the validation dataset and the eventual systems for retrieval are particularly important for regular landslide monitoring. Geological surveys are involved in both education and capacity building activities and actions, as well as in risk assessment. They regularly deal with long-term monitoring of geohazards, collection and analysis of data and information related to natural hazards. They are primary providers of information products supporting decision makers, local and regional/county authorities, and populations when landslides occur, straddling both scientific and operational roles. The scientific community carries out prediction and prevention research activities for knowledge development on landslides, and collaborates at both functional and operative levels with the responsible authorities to develop monitoring, surveillance and alert systems for hydro-geological risk, mainly in deferred time and, partially, in near-real time. Its activities include technical-scientific training and assistance for civil protection agencies and local authorities. This happens in the framework of simulated events, as well as through the development of methodologies for the identification of landslide triggers and forecasting models. The community also leads the assessment of hydrological thresholds and dangerousness of landslide processes, and the definition of operative procedures and protocols for the identification of risk scenarios, in concert with national and/or local authorities.

Taking into account the different objectives, tasks and responsibilities of the operational and scientific landslide community in deferred, near-real and real time (Table 1 and Table 2), the information needs of the landslide community can be summarized as follows:

— Regularly updated landslide maps (susceptibility, hazard and risk maps) and landslide inventories, including location, type, area, volume, intensity, state and style of activity of observed phenomena; updated distribution of landslide-affected areas help understanding ongoing and future instability.
— Long-term monitoring of areas at higher risk, with regularity and consistency of observation, to improve the understanding of landslide kinematics and facilitate the assessment of their future evolution; site-specific information on the instability conditions are needed to associate the identified motions with causative factors and triggers, and analyse zones with different susceptibility to landslides.
— Post-event motion and damage assessment, mapping of affected areas and identification of safe zones for relocation of elements at risk; residual hazard and risk zonation.
— Landslide vulnerability assessment and modelling; forecasting and early warning.

Table 1. User capacity and needs for landslide-related hazards in deferred, near-real and real time.

		Deferred time		**Near-real and Real time**
Scientific community	ACTIONS	• Technical/scientific training and assistance • Research on prediction and prevention • Analysis of past ground movements • Development of data analysis tools • Delivering of EO-based services	ACTIONS	• Monitoring and surveillance • Emergency support • Daily bulletins • Daily severity maps
	NEEDS	• Access to scientific information • Collection of accurate raw EO data • Feedback about delivered product	NEEDS	• Easily accessible information • Updated EO data • Direct contact with EO segment
Civil Protection Agencies	ACTIONS	• Prediction and prevention activities • Protection of environmental resources • Implementation of early warning systems	ACTIONS	• Emergency management • Updating risk scenarios • Relief operations
	NEEDS	• Accuracy-based products • Easily access to scientific information • Sharing of knowledge	NEEDS	• Real time observation tools • Clear procedures and methods • Timely products
Policy makers and planners	ACTIONS	• Urban and land use planning • Risk mitigation strategies • Clear and firm laws	ACTIONS	• Emergency management • Relocation
	NEEDS	• Long-term information on geohazards • Timely updated thematic maps • Large area coverage, simple, effective, standardized, reliable information	NEEDS	• Monitoring data • Rapid mapping (rush mode products) • Residual risk zonation • Detection of safe areas
Other end-users	Ask for truly participatory risk management processes			
Citizens	NEEDS	• Awareness and preparedness	NEEDS	• Simple and standardized advices of proper behaviour in case of events

	Scientific Users	Operational Users
Deferred time	· Mapping and long-term monitoring · Typology and kinematics · Modelling and prediction · Vulnerability assessment and modelling	· Inventory (location, type, area) · State and style of activity · Magnitude (intensity, volume) · Monitoring of areas at higher risk · Forecasting
Near-real and Real time	· Mapping landslide events and their consequences · Statistics of landslide event inventories · Definition of landslide triggers and related thresholds · Event vulnerability assessment and modelling	· Residual risk definition and mapping · Location of safe areas for relocation of elements at risk · Post-event motion assessment · Residual risk zonation

Table 2. Scientific and operational user needs for landslide hazards.

It is clear from this list that the information required to address these needs is constrained in terms of spatial and temporal scales of observation. The spatial scale for landslide phenomena ranges between regional and local, i.e. varies from studies of landslide mapping over very wide areas (up to a few thousands of square kilometres) to analysis of isolated phenomena. For this reason, the technologies supporting landslide studies should guarantee both large area coverage and access to detailed information over very small areas (e.g. a few square meters), as well as very accurate ground motion characterization. Temporal scales for landslide hazards are strongly controlled by the intensity of the observed phenomena and may range from monthly observations for extremely slow processes[4] to daily or even hourly observations for more rapid phenomena. Spatial and temporal scales also vary from phase to phase of the landslide management cycle, which deals with different needs in terms of frequency and resolution of information. More detailed information is required during response and recovery phases, in terms of both spatial and temporal sampling of the observed phenomena; up to centimetre resolutions might be required, with temporal resolutions as high as every few minutes during emergencies.

3.4 The European case

Landslides occur in many different geological and environmental settings across Europe[5]. Based on the GDLND (Figure 3), most European landslide processes occur in the Italian, Austrian and Swiss Alps, as well as in the Pyrenees with a medium to high degree of hazard. Medium to very high-risk areas are also present in Romania, the Balkans and Asian Turkey. Based on the GDLND, Europe represents ~7% of the global hazard areas with moderate to very high landslide hazard, and this percentage rises to more than 14% when one includes the areas exposed to landslides in Asian Turkey. Intense and long-lasting rainfalls represent the most frequent triggers of landslides in continental Europe. However, rapid snowmelt events and earthquakes are also responsible for many landslides, including a few large landslides. Human activities frequently contribute to many slope failures, especially in built-up

4 $V < 16$ mm/yr, and 16 mm/yr $\leq V < 1.6$ m/yr, respectively (according to the velocity classification by Cruden & Varnes (1996).

5 Large rock falls, rockslides, rock avalanches and debris flows dominate in the Alps and steep slopes in other mountain ranges, while slides and flows abound in flysch belts of Slovakia, Czech Republic, Poland, Italy, Spain, France and other countries. Slides of various types are frequent on cliffs and steep slopes along the coastline of Southern and Eastern England, as well as along the Bulgarian Northern Black Sea coastline. Shallow slides and mudflows are widespread in the peat slopes of Ireland, and slides and lateral spreads affect gentle slopes in quick clays in Sweden and Norway. Flows and slides also typically occur in clay-rich sediments and sedimentary sequences in Tertiary basins as well as on riverbanks.

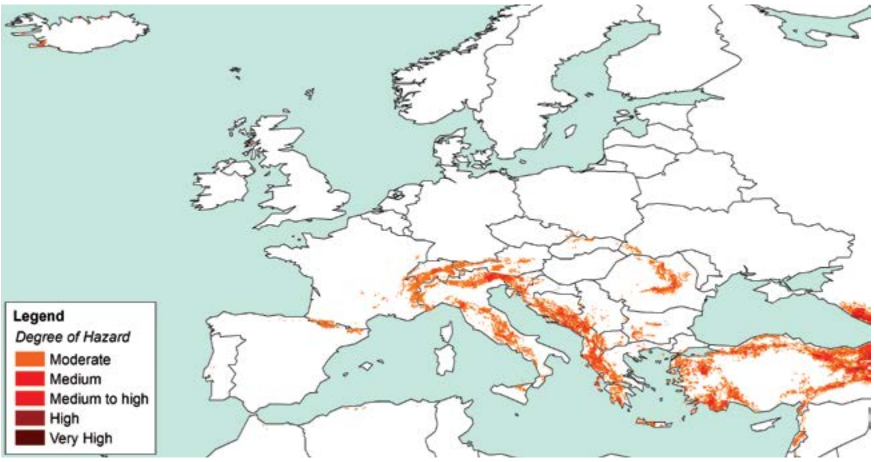

Figure 3. Distribution of areas with higher landslide hazard in Europe derived from the GDLND (CHRR, NGI and CIESIN, 2005).

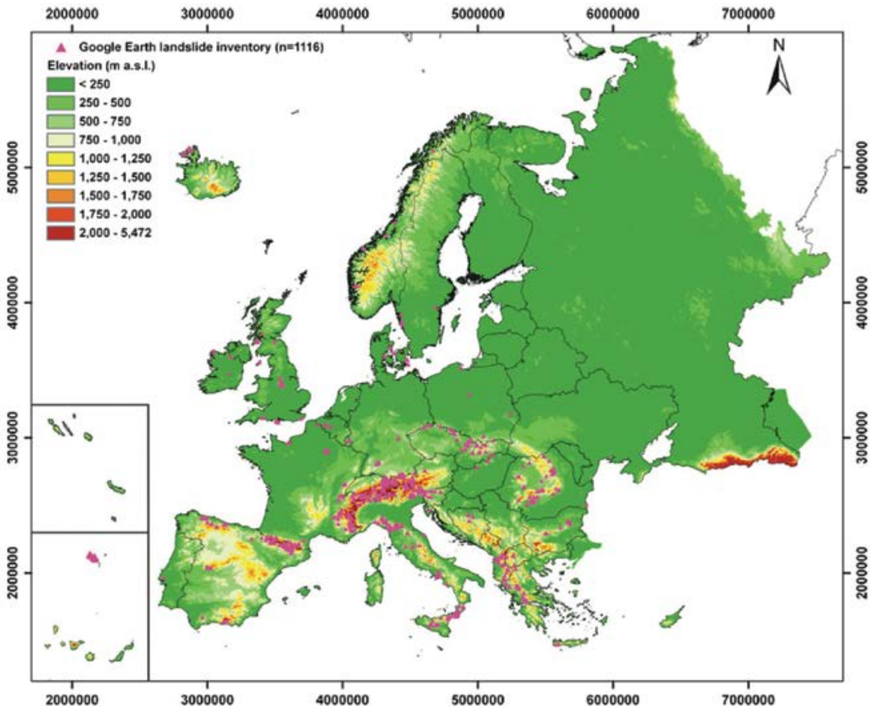

Figure 4. Landslide inventory at European scale produced in the framework of the SAFELand project (Van Den Eeckhaut et al. 2011).

areas. Over the last few decades, landslide risk has increased as a result of population growth and urban expansion in areas at risk; furthermore, climate change and variations in the precipitation trends in areas at risk will likely change the nature and frequency of landslide events, in some cases with detrimental effects. Geological, morphological and other geo-environmental settings and conditions are greatly variable in Europe, and landslide mapping is not carried out homogeneously in EU member states. As a result, there is a lack of harmonisation of mapping approaches and models, input data, susceptibility, hazard and risk representation levels and scales in Europe (Hervás, 2007). Currently, no comprehensive landslide database exists for Europe (EEA, 2010). Although many European countries have taken the initiative to create a national database, the combination of these databases into one continental database is difficult due to accessibility restrictions and high variability of level of information and resolutions (Van Den Eeckhaut et al., 2011). There is also a significant underestimation of European landslide events reported in world databases, which is probably due in part to the frequent occurrence of small and isolated landslide events in Europe (EEA 2010), as opposed to catastrophic events. For example, a comparison of the hazard map of Nadim et al. (2006) and landslide hazard maps of Kirschbaum et al. (2009) shows that both maps attribute high landslide risk

> **Terrafirma**
> Started in 2003, the project (www.terrafirma.eu.com) was funded under the GMES Service Element (GSE) programme of the European Space Agency in the framework of GMES. Terrafirma has concentrated on federating public users and delivering precise terrain deformation mapping and value adding services to support civil protection agencies and local authorities in charge of risk assessment and mitigation. Terrafirma is a pan-European ground motion information service focused on seismic risk, flood defence and coastal lowland subsidence, inactive mines and hydro-geological risks. As part of the hydro-geological risk theme, the project built on the foundations of EO-landslide methodologies set down by the previous SLAM project. Terrafirma has 16 services concerning mountainous areas affected by slope instability: 9 Landslide Inventory (LSI), 6 Landslide Monitoring (LSM) and 1 Landslide Modelling (LSMd) services delivered in Italy, Switzerland, Spain and Greece (e.g. Moretti et al., 2012). The products use advanced terrain deformation measurements based on satellite InSAR and PSI techniques.

or hazard to the major mountain ranges in the world. Apart from Italy and some Balkan states, no other European countries are located in the defined hotspot areas, even though many of them face extensive landslide problems (Van Den Eeckhaut et al., 2011).

The FP7 SAFELand project[6] (Figure 4) performed an analysis to identify landslide hazard and risk hotspots in Europe. This included a susceptibility assessment of slide and flow-type landslides at the European scale employing logistic regression modelling. A landslide dataset was also produced combining the extraction of landslide-induced geomorphologic features from Google Earth imagery and the locations of landslide events all over Europe reported in about 40 scientific publications. In total, the inventory includes more than 1300 point-wise landslide locations, which mainly correspond to major active landslides in the Alps, Pyrenees, Carpathians, and Apennines.

3.5 Current state of satellite EO services & applications

EO satellite technologies are very well-suited to supporting both operational and scientific users in the process of landslide identification, mapping, characterization and monitoring. The ability to rapidly image large areas at relatively low cost and at high resolution enables the monitoring of landslide-induced surface features and land motion. For many areas, long historical records of acquisitions are available. High-resolution multi-spectral and other optical sensors are used to assess fault rupture and damage assessment, and identify secondary hazards such as triggered landslides. EO geohazard optical imagery is often used to map and monitor regions at greatest risk and is most heavily used as a post response tool. Satellite radar is used on a case-by-case basis to further characterize the risks associated with a given landslide. More recently, satellite radar interferometry has been used to monitor areas on an on-going basis to identify areas at high risk and support mitigation activities. Access to EO data and the capacity to generate relevant information for decision makers is critical in order to implement better land use practices and to be prepared for crisis management (BRGM, 2007). EO resources available or soon to be available can address most of the spatial and temporal observational requirements of the landslide community.

EO is currently used both in the framework of near-real time and deferred time work, and includes support for the creation and updating of landslide inventory maps at a regional scale, and the characterization and long-term monitoring of single unstable slopes locally. In many cases, EO can now

6 http://www.safeland-fp7.eu

provide precise estimates of ground motion and indicators of landslide activity without requiring the installation of targets on the ground. Emerging research of the scientific community includes more advanced capacities such as support to landslide modelling and designing of early warning systems for near-real and real time applications.

In the European context, the landslide services and applications exploiting EO satellite technologies are found mainly in Italy, Switzerland, Greece, Spain, Slovakia, Hungary and France. The main EO capacities concerning landslides are strongly based on precursor projects such as Terrafirma (2003-2012) in the framework of ESA originated GMES Service Element programme[7] and EC projects such as FP6 PREVIEW (2005-2008), FP7 PanGeo (2011-2013), DORIS (2010-2013) and SAFELand (2009-2012)[8] and the SAFER (Services And Applications For Emergency Response) project (2009-2011) and its operational follow on GIO-EMS. Several national initiatives in Italy, Switzerland and Spain also contributed significantly to the development of the European EO capacities for landslide inventory, mapping and monitoring[9]. There is also a new EO-based service launched by CNES for the French Alps monitoring large landslides using optical imagery (e.g. SPOT-5, Pleiades) in the Southern Alps.

Main EO capacities used or in development

In the last 10 years, EO-based landslide applications covered more than 50 areas of interest with inventory, monitoring and modelling services based on InSAR, distributed mainly in Italy, Switzerland, Greece, Spain, Slovakia, Hungary. This represents roughly 35-40% of the European landslide hazard priorities shown by the GDLND in 2005. Preparing landslide maps is important to document the extent of landslide phenomena in a region, to investigate the distribution, types, pattern, recurrence and

7 http://www.esa.int/esaLP/SEMPG35KXMF_LPgmes_0.html

8 The applicability of a wide variety of remote sensing techniques according to the landslide characteristics, disaster management phases and spatial scales has recently been evaluated within the framework of the European Project SAFELand, and several deliverables have been issued (e.g. mainly on the presentation of the different sources of information, on the different techniques to process the data and obtain relevant parameters for landslide analyses, and on the proposal of guidelines for the selection of the most appropriate sources of data and processing techniques according to the landslide types, velocity and purpose of the study). The evaluation was carried out jointly by 12 collaborating European institutions. The results were compiled in the project deliverable D4.4 Guidelines for the selection of appropriate remote sensing technologies for monitoring different types of landslides.

9 Recent national initiatives funded by the Italian National Civil Protection Department were carried out to enhance the acceptance of EO-based applications and services for landslide risk in Italy (e.g., SAR.net project in 2005-2012). National projects such as MORFEO (MOnitoraggio del Rischio da Frana mediante dati EO, Monitoring landslide risk exploiting EO data; http://www.morfeoproject.it) funded by the Italian Space Agency (ASI) in 2008-2010, provided valuable examples on how applications based on EO and non-EO data can operatively support the DPC in the process of mapping, prevention and management of landslide risk during emergencies.
Since 2006, the natural hazard division of the Federal Office for the Environment (FOEN) in Switzerland exploits satellite based SAR-data for Monitoring and Early Warning System (MS/EWS) for landslides and other mass movements (e.g. rock glaciers, subsidence).
In Spain, the project DO-SMS 2009-2011, part of the Territorial Cooperation Program SUDOE between France and Spain (dosms.get.obs-mip.fr/cosiweb), aimed at developing tools for ground deformation monitoring and sustainable land management for natural hazards, and delivered three landslide mapping services in Spain and France.

statistics of slope failures, to determine landslide susceptibility, hazard, vulnerability and risk, and to study the evolution of landscapes dominated by mass-wasting processes. Conventional methods for the production of landslide maps rely chiefly on the visual interpretation of stereoscopic aerial photography, aided by field surveys, or in some cases by field surveys complemented by stereoscopic aerial photography. These methods are time consuming and resource intensive (e.g., Brabb, 1991; Galli et al., 2008). New and emerging techniques based on satellite, airborne, and terrestrial remote sensing technologies, facilitate the production of landslide maps, reducing the time and resources required for their compilation and systematic update (Guzzetti et al. 2012).

Several techniques and methods can be grouped in three main categories:

- analysis of surface morphology, exploiting very-high resolution digital elevation models (DEMs)[10];
- monoscopic and/or stereoscopic analysis of panchromatic multispectral and hyperspectral satellite imagery[11], with visual and semi-automated classification and interpretation methods; and
- interpretation of SAR images processed through InSAR and PSI techniques[12].

Satellite EO-based applications are already mature in some countries such as Italy, Switzerland and Spain, as demonstrated by many national and international initiatives carried out in the last years.

The main achievements of the above mentioned applications for the creation or updating of landslide maps at regional scale, and the long-term monitoring of unstable slopes at local scale, are summarized below:

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10 Jaboyedoff et al. (2010) and Guzzetti et al. (2012) reviewed the literature on applications of very-high resolution DEMs obtained by airborne LiDAR surveys for landslide investigations, and have shown that DEMs and derivative products (e.g., contour maps, shaded relief images, maps of slope, curvature, measures of surface roughness) are used primarily for the visual analysis of the topographic surface, and the semi-automatic recognition of morphometric landslide features (McKean and Roering, 2003; Glenn et al., 2006; Sato et al., 2007, Booth et al., 2009, Tarolli et al., 2010).

11 Techniques based on the interpretation of panchromatic, multispectral and hyperspectral images include: (i) visual (heuristic) interpretation of panchromatic, composite, false-colour, and pan sharpened ("fused") images (e.g., Marcelino et al., 2009; Fiorucci et al., 2011); and (ii) analysis of multispectral and hyperspectral images, including image classification methods and semi-automatic detection and mapping of landslides (e.g., Metternicht et al., 2005; Rosin and Hervás, 2005; Lee and Lee, 2006; Martha et al., 2010; Tsai et al., 2010; Mondini et al., 2011). Multispectral data of variable spatial and spectral resolution (e.g., Quickbird, IKONOS, SPOT-5, Geoeye, Resourcesat-1, Landsat) were extensively exploited for mapping, monitoring and forecasting landslides. Stereoscopic interpretation of pan-sharpened images (e.g., Nichol et al., 2006, Kouli et al., 2010) and automatic pixel- and object-oriented classification methods (e.g, Martha et al., 2010; Mondini et al., 2011; Hölbling et al., 2012) showed potential for landslide mapping. Change detection based on temporal variations of landscape spectral properties (pre- and post- landslide event) are particularly effective for updating landslide-affected areas (e.g., Fiorucci et al., 2011). Correlation of high-quality optical images showed good performances to quantify ground motions and monitoring landslide activity, and can ease the understanding of slope failure mechanisms (e.g., Delacourt et al., 2007; Leprince et a., 2008). Furthermore, imaging spectroscopy is essential for retrieving hydrological and geomorphological diagnostic features, such as soil properties, land use, rainfall fields, that are used as inputs in many landslide predictive models (e.g., van Westen et al., 2008).

12 InSAR and PSI recently demonstrated their suitability for the detection, monitoring and characterization of extremely to very slow moving landslides, and their complementarity with on-site measurements, at both regional and local scales (e.g., Czuchlewski et al., 2003; Singhroy and Molch, 2004; Strozzi et al, 2005; Farina et al. 2006; Colesanti & Wasowski, 2006; Lauknes et al., 2010; Bianchini et al., 2012; Cigna et al., 2012; and references therein).

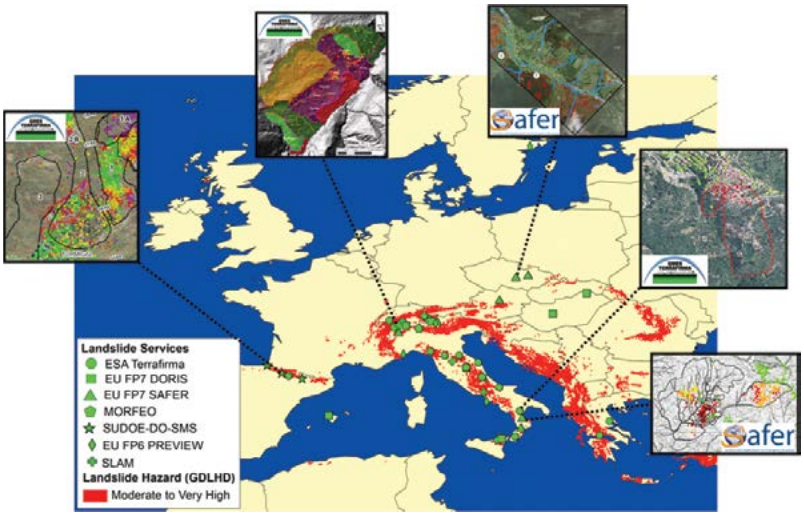

Figure 5. Satellite InSAR based landslide services and applications at European scale, overlapped onto the landslide hazard map of the GDLND (CHRR, NGI and CIESIN, 2005).

a) *Mapping and inventory:* EO-based landslide mapping and inventory applications and services provide information on the spatial distribution of mass movements and generally operate at regional scale. They integrate satellite-based ground deformation measurements into pre-existing landslide inventories produced with field surveys, conventional geomorphologic tools, stereoscopic photo-interpretation of multi-temporal aerial and/or satellite optical imagery, thematic, geological and topographic data. Satellite EO offers a cost-effective means to identify indicators of slope instability, in the form of terrain features and landforms identified through interpretation of optical imagery, as well as ground displacement estimates provided by InSAR and PSI technologies.

The final goal of these applications is the creation or the improvement of landslide inventory maps, through the delivery of qualitative (e.g. state of activity) and quantitative (e.g. intensity) information of each mapped phenomenon and the detection and mapping of those phenomena not previously identified through conventional means. Landslide services and applications like those of Terrafirma, SAFER, SLAM, PREVIEW and DORIS have shown how the exploitation of EO data can reply to most of the users' needs for landslide identification and mapping, through the rapid detection of unstable areas and the identification of their spatial extension and temporal evolution to support the emergency management process, especially in deferred time (e.g. Righini et al., 2011; Bianchini et al. 2012; Cigna et al., 2012).

b) *Monitoring and characterization:* EO-based landslide monitoring applications analyze the temporal evolution of landslide-induced ground motions by exploiting ground motion information provided by InSAR and PSI techniques. These data can support the geological and kinematic interpretation of the slope instability affecting the observed areas, especially in built-up and densely urbanized slopes, where landslide indicators are difficult to recognize due to the presence of the urban fabric. Local-scale, long-term monitoring of displacements induced by specific slope movements, using EO satellite data integrated and compared with the available conventional ground-based instruments networks (e.g. topographic levelling, inclinometers, extensometers, GPS), allows the analysis of the temporal variability of landslide motions and kinematics. Besides the use of PSI technologies, conventional InSAR allows analysis not only of motion velocities exceeding the limitation of the PSI approaches (i.e. few tens of cm/yr), but also deformation trends significantly

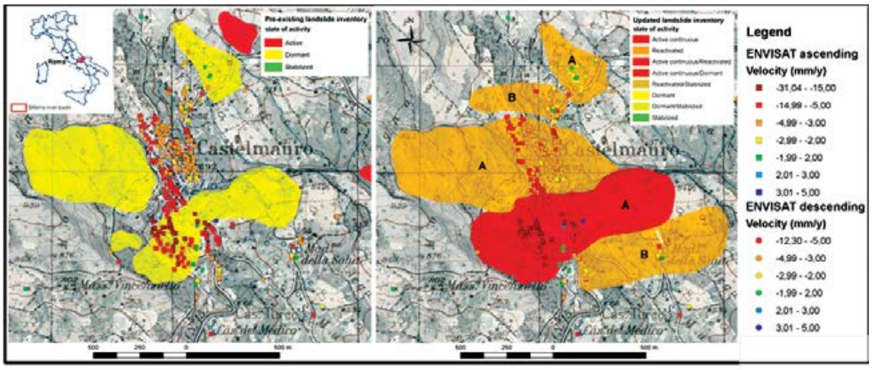

Figure 6. Mapping and inventory applications using EO satellite data: case of Biferno basin, Italy (Righini et al., 2011).

differing from the deformation model (e.g. linear) used during the multi-temporal PSI processing (e.g. non-linear and/or accelerated motion). A supplementary advantage of InSAR is the spatial coverage and the ability to detect the landslide limits with lower costs than with PSI. But InSAR analyses are very demanding and experience is needed to face 3D-problems, atmosphere deformations or phase unwrapping. Another innovation is the recent availability of wide-bandwidth, high-frequency, high resolution SAR data has resulted in better monitoring capabilities of space-borne remote sensing instruments. In particular, the new COSMO-SkyMed and TerraSAR-X sensors provide spatial resolutions one order of magnitude better than previously available satellite SAR sensors. Recent work focused on the exploitation of PSI techniques for detailed scale landslide analyses (Bovenga et al., 2012) and paid special attention to the impact of the improved resolution of new X-band radar imagery on the PSI results, in terms of quality and quantity of useful information. The evaluation demonstrated that with respect to high resolution Envisat PSI processing, fewer COSMO-SkyMed very high resolution images are sufficient to achieve comparable precision of the mean displacement velocity estimates. Between 3 to 11 times greater PSI densities were obtained with the higher resolution X-band data. This implies more information about ground surface displacements as well as improved landslide monitoring and slope instability investigation capabilities. Landslide services and applications like those of Terrafirma, SAFER, SLAM, PREVIEW, DORIS and MORFEO have shown that EO data can meet most user needs for landslide monitoring. It is capable of resolving the temporal variability of ground deformation and reconstructing the history of displacement of landslide-affected areas. It can recognize precursors to landslide failures or identify variability of motion behaviour due to triggering factors such as prolonged or intense rainfalls, thus supporting the risk management process during both near-real and deferred time.

In North America, USGS conducts research science on landslide hazards across the United States[13]. Their research program relies on in situ field instrumentation combined with space-borne and airborne optical imagery, ground-based and airborne LiDAR, with very limited use of satellite radar and airborne Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR). High-resolution optical satellite EO data are periodically analyzed on a case-by-case approach primarily to map landslides following a large storm or earthquake. The objective is to collect an inventory of landslides (snapshot in time) to understand the geomorphic response and hazard potential of large storms or earthquakes. This contributes to the development of predictive models for

13 http://landslides.usgs.gov

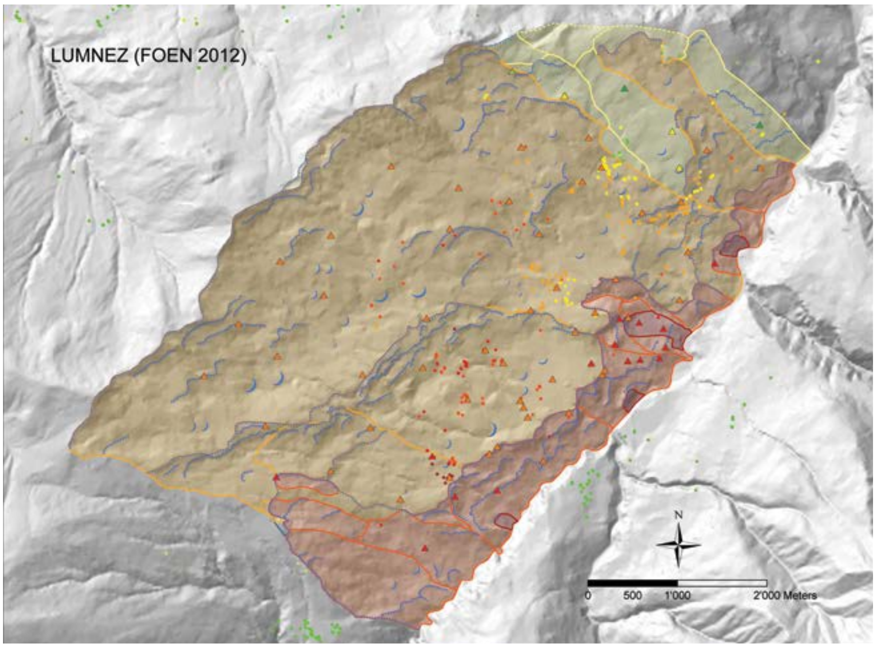

Figure 7. Example of monitoring application using EO satellite data: case of Lumnez landslide, Switzerland (modified after Raetzo et al. 2006). PSI based measurement using ERS 1995-1999 (points), Geodetic survey of the 20th century from Canton Graubünden (triangles) and geological interpretation with the activity of landslide zoning. Velocity measurements are according to Swiss guideline for landslides (Raetzo & Loup 2011) and are represented with polygons and triangles with the following color coding: green-yellow: 0-2 cm/year, orange: 2-10 cm/year, red: v>10 cm/year. The correlation between the satellite EO and the ground based monitoring is very high and validated, if 3D-corrections are done according to the mechanical model.

future events. USGS used space-borne and aerial imagery over Haiti following the 2010 earthquake to map the extent of landslides, thereby providing a geomorphic constraint on the distribution of ground shaking in a country with few near-field seismic stations. Optical satellite data has also be used in many other cases/countries to assess at least the affected areas and even more detailed characterization (e.g. Martha et al., 2010). The analysis of multi-temporal data may provide information about the horizontal displacement (e.g. Leprince et al., 2008) or changes of the landslide boundaries and sediment dynamics. The limited use of satellite EO data by USGS for routine monitoring of landslides is a function of the extent of the country, the spatial resolution of many of the data sources, heavily vegetated landslides, and finite resources to acquire and process the imagery at the level needed for a comprehensive monitoring program. Effective use of C-band satellite InSAR data for landslide detection and monitoring requires techniques such as PSI processing, but this in turn requires a significant data archive, currently lacking for most of the landslide prone regions in the United States, as well as significant resources for data processing and product generation.

Emerging research

Modelling

The main objective of landslide modelling by exploiting EO data is to develop and validate a methodology combining (i) space measurement of past displacement derived from InSAR and/or PSI analyses, (ii) conventional in situ investigations and (iii) geotechnical modelling, to characterize and predict the risk associated with slope instability under heavy rain, and to support the design of appropriate mitigation measures. These activities include development and testing of new data processing techniques (new PSI algorithms, data mining, etc.).

Early Warning Systems & Forecasting

For rainfall-induced landslides, early warning systems exploit the empirical observation that a minimum amount of precipitation is necessary to trigger landslides (Reichenbach et al., 1998, Guzzetti et al., 2007). Regional to national warning systems based on empirical rainfall thresholds and systematic rainfall

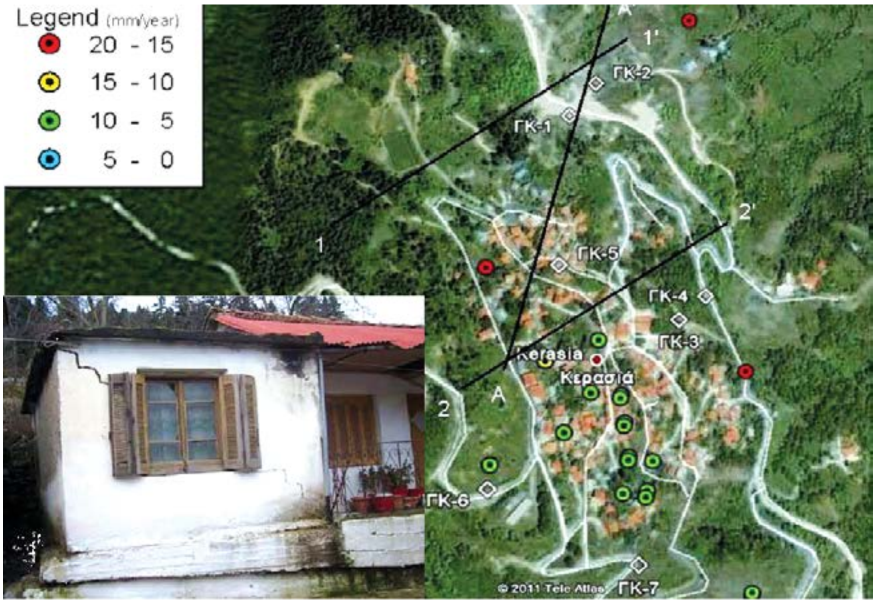

Figure 8. Modelling applications using EO satellite data: measured PSI displacements at Kerasia, Greece. (Moretti et al., 2012). White diamonds represent boring locations. Lower left, typical damage.

measurements or forecasts, are – or have been – operational regionally[14]. NASA has also developed a global system to forecast the possible occurrence of landslides (and floods) based on near real-time rainfall estimates obtained through a Multi-satellite Precipitation Analysis (TMPA) system (Hong et al., 2006). More recently, Wasowski et al. (2012) exploited high resolution multispectral satellite imagery to investigate surface-subsurface water linkages in a landslide-prone area. The appearance of the wet zones (fully saturated ground/soil) resulting from groundwater discharge or seepage was used as a forewarning signal of the increased susceptibility to landslides. The information about changing surface-water conditions retrieved from very high resolution multispectral satellite imagery timely acquired during rainy seasons can provide crucial input for temporal and spatial landslide hazard assessments. Very high resolution optical space-borne remote sensing may soon become a commonly used tool for monitoring landslide activity and for providing temporal series of spatial data necessary to improve understanding of causative and triggering processes leading to slope failures. In Italy, since October 2009, the Italian National Department of Civil Protection, uses a prototype national landslide warning system based on two main components (Brunetti et al., 2009): (i) a set of empirical thresholds for the possible occurrence of rainfall-induced landslides, and (ii) an ensemble of small scale, national (synoptic) landslide hazard and risk zonations. The warning system compares rainfall measurements (obtained from a national network of more than 1950 rain gauges) and quantitative rainfall forecasts (an output of Limited-Area Meteorological models) with empirical rainfall thresholds, to inform "where" and "when" landslides are expected in a given region. Hazard and risk zonations are used to establish if the expected slope failures occur in areas that are considered highly susceptible to landslides, or where landslide risk to the population is severe or significant (Brunetti et al., 2009).

Considering both the main EO capacity used or in development for landslide inventory and monitoring, and the emerging research in the field of landslide modelling and forecasting, the following EO data requirements can be stated:

— *space-borne SAR:*

HR SAR (i) for landslide inventory and landslide hazard purposes:

14 E.g. in Hong Kong, the San Francisco Bay region, Rio de Janeiro, Nagasaki, Jamaica, the Piedmont region and the Yangtze River (e.g., Keefer et al. 1987; Ahmad, 2003; Aleotti, 2004).

continuous observations with descending and ascending repeat coverage (at least 2 images per month in interferometric mode), in order to guarantee observations over mountainous and hilly terrain in priority areas defined in section 3.2. Narrow orbital tubes are required to get overall short spatial baselines and many pairs with very short spatial baselines. For Sentinel-1 all ascending and all descending orbits should be considered. Single (HH or VV) polarization would be sufficient.
VHR SAR: (i) for hazard inventory purposes: continuous observations with descending and ascending repeat coverage (at least 2 images per month in interferometric mode). The demonstration that this is also possible with VHR SAR is given by the COSMO-SkyMed constellation which achieves full interferometric coverage with 16-day repeat intervals in both ascending and descending orbits over Italy. (ii) for hazard monitoring purposes on hotspots (e.g. most critical landslides): continuous observations over one selected area in all descending and ascending repeat orbits (e.g. TerraSAR-X every 11 days) means that no data are then available for areas outside of this swath. A full spatial coverage with continuous observations descending and ascending repeat coverage (at least 2 images per month in interferometric mode) is required (e.g. using COSMO-SkyMed constellation of 4 satellites). If this is not possible, a secondary requirement is to pre-select for both ascending and descending geometry a set of modes which achieve full spatial coverage over the landslide areas and then to acquire as much interferometric data in these modes as possible. For VHR SAR, the viewing geometry should be considered, as some smaller landslides may only be viewable in one satellite pass.

— *space-borne Optical:*
HR Optical/VHR Optical: (i) for landslide inventory and landslide hazard purposes to provide background reference imagery: archive image (no more than 10-years old), panchromatic or true colour composite. (ii) for hazard inventory purposes (e.g. historical hazard mapping): VHR optical (no more than 1-year old), higher than 5m resolution, panchromatic or true colour composite, stereo pair (max 1 year apart) useful for delineation; (iii) for hazard monitoring purposes (including early warning and response): repeat observations for automatic image correlation with HR and VHR optical sensors (panchromatic or ideally multispectral, preferably with a resolution higher than 5m).

3.6 The way forward

The landslide community has developed a 5 to 10 year strategy building on the experience of the past decade. There are four fundamental questions that concern the use of satellite EO to support the landslide hazard risk management community:

— What objectives does this community need to achieve over the next 5 to 10 years?
— What factors can accelerate the realization of these objectives?
— Is the international community ready to collectively address the challenges associated with these objectives?
— What about other users not using satellite EO?

EO technologies already play a strong role in support of landslide hazard and risk applications, ranging from landslide mapping at the regional scale and monitoring of single slopes to modelling of landslide motion and correlation with triggering factors.
Over the next ten years, the landslide community aims to:

— Develop comprehensive EO-based inventories of known landslide hazard areas currently unmapped or insufficiently mapped to better understand the extent of the hazard. This corresponds to more than 40% of the GDLND hazard global extent over the next ten years, with a priority focus on Philippines and Japan and in Central and South America along the Pacific Coast, as well as in south-eastern Asia, with medium to very high degree of hazard. For instance, in Europe, this concerns mainly Austria, Bulgaria, Romania, Serbia, Bosnia, Albania and Turkey. This represents an additional 25-30% of the European areas of interest.
— Within priority areas above, monitor hotspots using regular satellite EO monitoring on a semestral to monthly basis, depending on the kinematic characteristics of the hotspot at hand, and by using both optical and radar imagery and derived products.
— Develop outreach programs, capacity building and demonstration projects with national authorities to increase use of EO and promote acceptance of EO as a standard, as is currently done in several European countries (e.g. Switzerland, Italy).

Figure 9. Falli Hölli landslide (1994) damage and destruction included 40 houses, slide distance 200 m, v: 6m/day (max). References Hugo Raetzo, PhD thesis (Raetzo 1997).

The USGS Landslide Hazards Program will increasingly be using EO for landslide research over the next 5 to 10 years, with a focus on fully characterizing the number of active landslides across the United States and assessing the risk they pose. Until there is sufficient SAR data archive for the United States to exploit more sophisticated PSI process approaches, routine monitoring of the nations landslides will be limited in scope. The ability to reliably and economically acquire SAR data from sources such as TerraSAR-X, TanDEM-X, Radarsat-2, and COSMO-SkyMed would greatly facilitate their use in assessing landslide hazards in the US. This includes rapid tasking, processing, and delivery during crisis response, and a reduction in the cost of the data. Ideally, geohazard EO data are needed to comprehensively assess the national landslide hazards and sufficient SAR imagery needs to be collected and analyzed for the top 5 to 10 percent of the landslides that pose the greatest risk.

Bearing these objectives in mind, the priorities and requirements to further improve EO-based applications supporting landslide management, and to increase acceptance by user communities, needs the engagement of all the actors of the community. This includes both operational and scientific actors as well as EO data providers. Space agencies should follow the example of ESA and CSA who collect data through background missions over priority areas, and offer improved spatial and temporal resolutions, wider area coverage, and sustainable costs and delivery times of EO products. Further advances on technology should include the reinforcement of the computing capacity to support large volumes of EO data and broaden the use of wide area processing strategies, which will be aided by a careful scientific validation of its performances.

Factors that can accelerate the realization of these objectives can be grouped in three categories: technology and services, science, users.

Technology and services

The landslide community has identified the following objectives to support the identification, mapping and monitoring of landslide processes:

- Continuity and consistency of acquisition of EO optical and radar data, to guarantee availability of image stacks and archives in the coming years, and allow the comparison of recent and past scenarios of landslide evolution and consequences. For SAR data, users require geometrical consistency (i.e. acquisition parameters of each radar stack must be kept identical for the whole set of images), to guarantee their suitability to be processed through conventional and multi-temporal interferometric approaches.
- Wide geographical coverage of EO imagery acquired during the background planning, to give the community the chances of activating EO-based studies of deformation processes in areas affected by landslide events not previously monitored with either EO data or on site instrumentation.
- Improved temporal resolutions (shorter revisit times) and regularity of acquisitions to enlarge the range of applicability of EO-derived motion services to landslides faster than a few tens of centimetres per year (e.g. current limitation of most InSAR and PSI-based landslide products, due to monthly acquisition frequencies of C-band data), and to guarantee proper and systematic temporal sampling of the observed phenomena. The Sentinel-1 mission is expected to largely increase the contribution of SAR based observation of landslides to support historical hazard mapping and operational monitoring. This is primarily due to its systematic observation capabilities with high resolution and large swath with a high temporal sampling (12 days, 6 with two platforms). Recent experiments with COSMO-SkyMed X-band data at weekly repeat cycles have shown the unmatched precision and level of details achievable with EO data acquired with improved

temporal resolutions, a crucial requirement for landslide monitoring and early-warning practices.

- Improved spatial resolutions of EO radar data, guaranteeing high resolution acquisitions for priority areas at highest landslide risk, to enhance the capability and scale of applicability of the derived motion services and include those evolving at local to single slope scales. Landslide services based on VHR radar data have allowed the estimation of ground motions with scales and level of detail up to 5 to 10 times higher than medium and high resolution data based products, with significantly improved capability of detecting and mapping landslide-induced deformation.
- Availability of dual-mode SAR acquisitions (i.e. ascending and descending) for hilly and mountainous areas, where the landslide products are strongly influenced by the visibility of the slopes and their orientations; dual-mode datasets allow to better constrain landslide motions (by combining the velocity estimated along the two geometries), and increase the number of slopes monitored within the observed areas (by increasing the chances of detecting slopes with different orientation and steepness).
- Sustainable costs of EO data and derived products, to enhance the affordability and ease of acquisition of EO imagery and their derivatives, and increase the efficiency-to-costs ratio of the EO-based landslide products. Whenever possible, open data and open source software development, and close collaboration between end users, data providers, geoscientists and computer scientists and companies in the private sector.
- Timeliness of the EO data access/distribution, to guarantee suitability of EO-based landslide products in the framework of the emergency response practices.

Most of these requirements and challenges will be fully addressed with the full implementation of the Sentinel system. Sentinel-1 will guarantee improved and more regular coverage compared to ERS and Envisat, and provide imagery for the GMES user community over Europe and the world, delivered within an hour of acquisition. As shown above however, landslide monitoring will be particularly dependent on the use of national missions such as COSMO-SkyMed and TerraSAR-X. The three Canadian satellites of RCM, to be launched beginning in 2016, will also address these needs by ensuring C-band SAR data continuity after Radarsat-2, improved operational use and enhanced revisit times (e.g. 4-day cycles), a wide range of spatial resolutions (from 100 m up to 3 m) and daily access to 95% of the world. As for optical imagery, the Sentinel-2 pair will also substantially contribute to respond to these needs, by systematically acquiring HR data globally and guaranteeing continuity of SPOT and Landsat data by providing optical acquisitions in the visible, near infrared and short infrared bands. The sector will continue to make advantageous use of VHR commercial missions such as Ikonos and WorldView, and the French Pleiades.

In addition to the above observational requirements, the priorities concerning EO data and technology to guarantee further advances and continuity of the EO-based landslide services in the next years include:

- Reinforce computing capacity and capability to fully support large data volumes such as those that will be available once the satellites of the Sentinel-1/2 and RCM will be fully operational.
- Develop efficient and reliable techniques for extraction of information from multi-temporal and multi-modal EO data.
- Assimilate multi-temporal and multi-modal EO data in dynamic hazard models.
- Make broader use of wide area processing strategies of satellite SAR imagery, as those employed in the framework of the nationwide PS processing of ERS-1/2 and Envisat data for the Extraordinary Plan of Environmental Remote

Sensing (EPRS-E) of the Italian Ministry of Environment and Territory of the Sea (METS), or the WAP strategy promoted by the Terrafirma project.
- Implement the Emergency Management Services in the framework of the GIO-EMS 2011-2013 plan and the GMES fully operational services starting from 2014, with main focus on emergency-response (rather than risk assessment); similar services have been provided during the GMES built-up phase in 2009-2011 by the FP7 SAFER project through the landslide mapping, monitoring and forecasting services, in the thematic and emergency support frameworks.
- Develop capacity and techniques for robust multi-interferometric re-processing of frequently updated SAR data stacks, for near real-time PSI applications.
- Develop effective low-cost/low-impact artificial reflectors by using new materials and models suitable also for smaller wavelengths, in order to easily increase measurement points in natural areas with scarce natural scatterers.

Science

Accounting for the remarkable improvements achieved in the last two decades with the progressive development of EO technologies and their integration into landslide-related research and applications, and considering also the upcoming advances that will be achieved with the thorough exploitation of new EO satellites and derived data, further efforts are still needed from the scientific community to make EO-based landslide services more consolidated. In particular, some of the scientific objectives and strategies that will be undertaken by the scientific community include:

- Development and further enhancement of the emerging techniques for EO-based landslide modelling and early warning purposes;
- Validation and assessment of the performances of wide area processing strategies (e.g. the Terrafirma WAP and the EPRE-E data) for landslide hazard and risk studies, considering real, near-real and deferred time applications; while these processing strategies present challenges in alpine environments, they are well-suited to built-up and urban areas; creation and public access to benchmark data sets for objective comparison of existing methods.
- Preparedness for the near-future exploitation of EO radar data from the ESA's Sentinel-1 constellation;
- Standardization of the methodologies employed for the implementation of EO-based landslide services, creating guidelines for the interpretation of EO data and their derivatives (e.g. PSI products) aimed at landslide mapping, monitoring and modelling. Better harmonization of European databases is required (INSPIRE); harmonization of methods for inventory mapping and hazard assessment in order to achieve results that are better comparable beyond national borders. A step forward to this objective is currently undertaken for instance by the EU FP7 project PanGeo, by creating a standardized procedure to be followed by the Geological Surveys for the interpretation of PSI products for the identification and mapping of geohazards affecting urban areas in Europe[15], and trying to make it compliant with the INSPIRE directive[16]; applicability of this procedure to landslide mapping will certainly need to be further improved to better address the specific needs and requirements of the landslide community of operational and scientific users.
- Improve the communication to the end-user by bridging the gap between science and operational application. Particularly at local and regional level the limited knowledge about the potentials and capacities of EO data may hinder further usage of satellite-based information. An improved

15 http://www.pangeoproject.eu
16 Directive 2007/2/EC - OJ L 108 of 25.4.2007

communication also includes the information about the constraints of the EO-based technologies. In order to convince the end-user to apply EO data based services we need to build trust that we only achieve by openly discuss also the limits of the EO data approaches.

Users and practitioners

Considering the already high level of maturity of EO-based technology and derived products for landslide hazards and risk, one of the main targets for the landslide community is to further act on the level of acceptance and understanding of these technologies in the end-user community. Although EO technologies are already accepted and widely employed by the operational landslide communities of some countries such as Italy and Switzerland, more effort is required to help EO-based landslide services become accepted by communities of users and practitioners from other countries. The following objectives were identified for the next decade:

— Improve the accessibility of EO-based landslide products, attract new end-users and enhance their understanding and knowledge on EO technologies and their potential in support of hazard and risk management; the PanGeo project is actively contributing to this purpose, by providing free and open-access geohazard information services for more than 50 towns of Europe, and encouraging the European geological surveys, decision-makers, regulators and civil protection agencies to systematically assess geohazards with the support of technologies based on EO radar data.
— Enhance the acceptance of EO-based products in the end-user community of Europe and worldwide, by demonstrating their compatibility with on site surveys, conventional and ground-based monitoring techniques.
— Improve the capacity of public authorities to upgrade the hazard mapping workflow, according to the availability and frequency of information provided by EO-based technologies.
— Stimulate further integration of EO-based products into everyday practices in the framework of landslide risk management, to support all phases of the disaster management cycle, from prevention, preparedness and emergency response, to post-emergency and recovery activities (relocation of elements at risk and reconstruction planning) and mitigation strategies; based on successful applications from the pre-operational GMES emergency support landslide services of SAFER activated in response to emergency situations in Europe (e.g. Rapid Landslide Mapping in L'Aquila, 2009), extend emergency support services to other countries.

Collapse of a slope at former lignite open pit Nachterstedt in Germany in July 2009. Due to that collapse 3 people died and several houses were destroyed. Credits: Fa. Ilv im Auftrag von LMBV mbH.

4. Perspectives Concerning Satellite EO and Geohazard Risk Management: inactive mine hazards

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4.1 Scope

This chapter highlights the European perspectives concerning how satellite EO can contribute to geohazard and disaster risk reduction in former mining areas. The aim is to consider the state of the applications and services starting from the situation in Europe and expanding to provide a global perspective. The chapter presents the outcome of analysis on how to further consolidate applications and services to achieve their expected benefits. A way forward is proposed considering activities and plans of this community for the next 5 to 10 years.

4.2 Abandoned Mining Hazard and Exposure

Since the beginning of civilization, people have used stone, ceramics and, later, metals found on or close to the Earth's surface. Mining is the extraction of valuable minerals or other geological materials from the earth, from an ore body, vein or seam, including the removal of soil[1]. Materials recovered by mining include base metals, precious metals, iron, uranium, coal, diamonds, limestone, oil shale, rock salt and potash. Today, active and abandoned mining areas are widely spread all over the world (Figure 1) and represent a possible subsidence hazard.

Every mining activity impacts the nearby environment, whether open pit mining or underground mining, small scale mining or large operations. Active mining operations are mostly well-monitored by mining authorities with, however, different standards of quality and quantity depending on the legal regulations within each country. Therefore, hazards caused by active mining are reported frequently all over the world. The 2010 mine disaster in Chile's San Jose mine is well-remembered. When a mine site is abandoned, the awareness of previous mining activities decreases quickly. Former mine shafts and underground cavities, re-filled open pits, tailings and dumping sites exist. Even when the former mine sites have been secured, depending on the knowledge and standards at the time of abandoning in the different countries, hidden legacies can represent a hazard. Typical hazards include: collapses migrating to the ground surface and sinkholes; slope instabilities and collapses (see main image); collapse of spoil heaps (see Figure 3); subsidence or uplift of the ground surface; pollution to air, soil, and water by toxic waste from mining; initiation of small earthquakes.

1 http://en.wikipedia.org/wiki/Mining

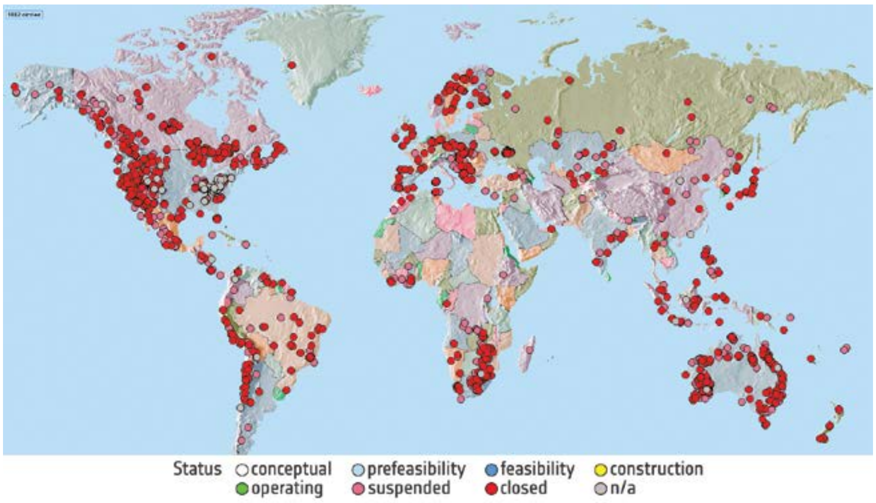

Figure 1. Inactive Mines of the world (Source: Raw Material Group 2012, www.rmg.se).

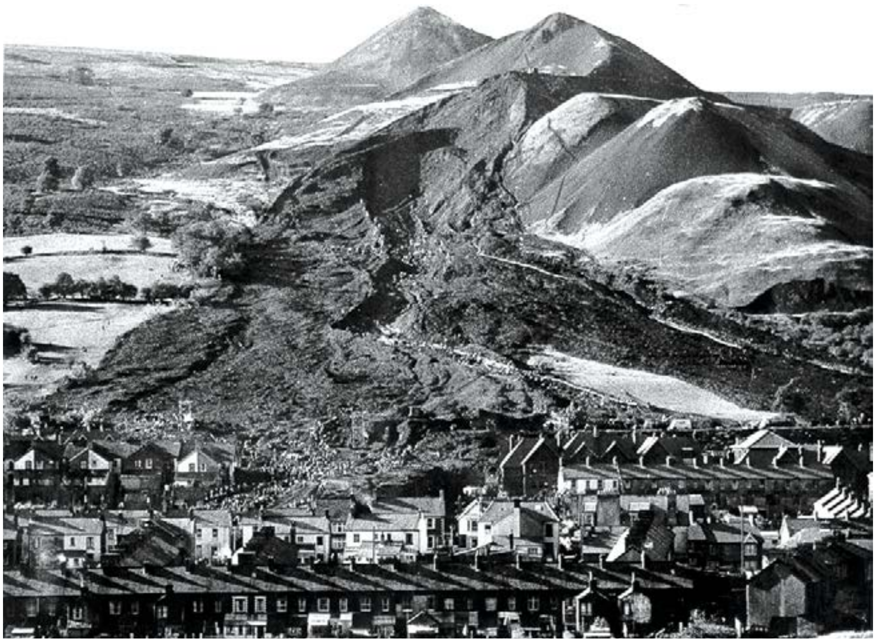

Figure 2. The aftermath of the Aberfan disaster in Wales (1966), the collapse of a coal mine spoil heap down a mountain side into a local village. The slide killed 144 people including 116 children from the local school. It was was caused by two days of continual heavy rain loosening the coal slag, which was situated on top of an underground spring.

4.3 Users and their information needs with regards to geohazard risks from abandoned mines

As geohazards caused by abandoned mining are man-made geohazards, in general an originator can be identified, namely the mining company who operated the particular mine. However, in most cases, this originator no longer exists or cannot be identified quickly after the disaster. Therefore, the responsibility for all abandoned mining in a country lies firstly with governments, typically a governmental mining authority. The detailed regulations and responsibilities differ from country to country; in some federal countries there are different regulations for different states or regions. However, in all cases, the responsible organisations have similar information needs. The common steps are to:

— identify the sites posing a possible risk;
— map and assess the hazard;
— identify the exposure of people and infrastructure;
— monitor the hazard with a frequency dependent on the magnitude of the hazard and the risk posed.

These information needs will be illustrated by the German example. As hazards from abandoned mining are a serious problem all over Germany, an interdisciplinary expert working group under the leadership of the German Geotechnical Society (Deutsche Gesellschaft für Geotechnik DGGT) and the German Mine Surveyors Association (Deutscher Markscheider-Verein, DMV) has been working on the theme of abandoned mining for more than 10 years. In particular this working group has developed technical guidelines for the following sub-themes:

— Geotechnical and mine surveying methods for investigation and evaluation of abandoned (underground) mines (published 2004[2]);
— Geotechnical and mine surveying methods for investigation and evaluation of abandoned open pits, dumping and landfill sites (published 2009[3]);
— Protection, ground support and permanent safekeeping of abandoned mines (published 2010[4]);
— Geotechnical and mine surveying methods for evaluation and reclamation of abandoned (underground) mines in urban areas (publication planned for 2012).

These guidelines represent the state-of-the art in dealing with abandoned mines in Germany and are accepted by all involved organisations, in particular mining authorities and mining companies, as well as consulting and service companies or expert bodies. These guidelines are also being considered in Austria and Poland. These guidelines contain detailed listings of relevant information and possible sources for this information. One of the most important needs is information about former and current surface movement. This information allows those responsible for territorial management to identify potential hazards through cross-referencing with known records or in situ investigation. In many cases where records have been lost, satellite EO measurement of ground subsidence may be the only warning that catastrophic collapse is imminent. In essence, satellite EO can be the fabled canary in the coal mine. Satellite EO also offers a means to constantly monitor safeguarded areas to track the evolution of surface movement.

4.4 The European case

Mining of different raw materials in Europe took place for millennia and became one of the most important industries in 18th century. Today, some European mines are still active, but several mining areas widely spread over Europe are abandoned and therefore are potential hazards. Unfortunately, no statistics on the number of affected areas are available. It is safe to say that the vast majority of existing deposits have been mined at some time in the past. Therefore, a geological map showing the deposits can be used as a rough proxy for areas at risk from inactive mines. The following European map with coal extraction areas (Figure 3) can be used as an example.

On a regional level more detailed information is often available. The following map, Figure 4, from the State Mining Authority of North Rhine-Westphalia (Germany) represents all communities which are affected by abandoned mines Within these areas, more than 20,000 former mine shafts are registered.

2 Geotechnical and mine surveying methods for investigation and evaluation of abandoned (underground) mines; published in proceedings of the 4th Altbergbaukolloquium, Leoben 2004.

3 Geotechnical and mine surveying methods for investigation and evaluation of abandoned open pits, dumping and landfill sites; published in proceedings of the 9th Altbergbaukolloquium, Leoben 2009.

4 Protection, ground support and permanent safekeeping of abandoned mines; published in proceedings of 10th Altbergbaukolloquium, Freiberg 2010.

Figure 3. Areas of mine deposit (Source ProMine Project: http://ptrarc.gtk.fi/ProMine/default.aspx). Brown points show coal deposits throughout Europe.

4.5 Current state of applications & services

As the knowledge about surface movements is one of the most important information needs in monitoring abandoned mining areas, the following examples from European practice will illustrate how satellite EO-based radar interferometry is able to deliver the required information about surface movements in abandoned mining areas. All three case studies presented have been executed within the ESA GMES Terrafirma project. Knowledge about the area affected by surface movements, the magnitude (from millimetres to metres per year) and the direction (subsidence or uplift) of the movements, as well as the velocity and possible velocity changes, permits appropriate, timely measures to be taken to minimize the impact of hazards. In March 2011, a European workshop focusing on the subject of post-mining was organized by the organisation DMT to bring together the EO community and the mining community. The meeting was successful in stimulating discussion and presenting the InSAR services available to the post-mining community. The workshop was open to all those interested in ground movement monitoring, in particular in relation to mining. There were 36 participants, mainly from the German and European mining industry, mining authorities and other governmental organizations (e.g. state ministries and geological surveys) as well as a few service providers and universities.

Overall, the observational requirements for Satellite EO concerning inactive mines are as follows:

(a) SAR data:
High Resolution SAR: (i) for hazard inventory purposes (e.g. historical hazard mapping): continuous observations with descending and ascending repeat coverage (maximum images per year, C and L-band in stripmap mode), the focus is to extend and guarantee observations over the priority areas defined in section 4.2; (ii) for hazard monitoring purposes: descending and ascending repeat coverage of hotspots (e.g. most critical mines) with more than 3 images per month, C or L-band (e.g. Sentinel-1 at least all cycles in descending mode and at least 50% cycles in ascending mode)
Very High Resolution SAR: (i) for hazard inventory purposes: specifically to survey small spatial extent abandoned mine motions and for any ongoing

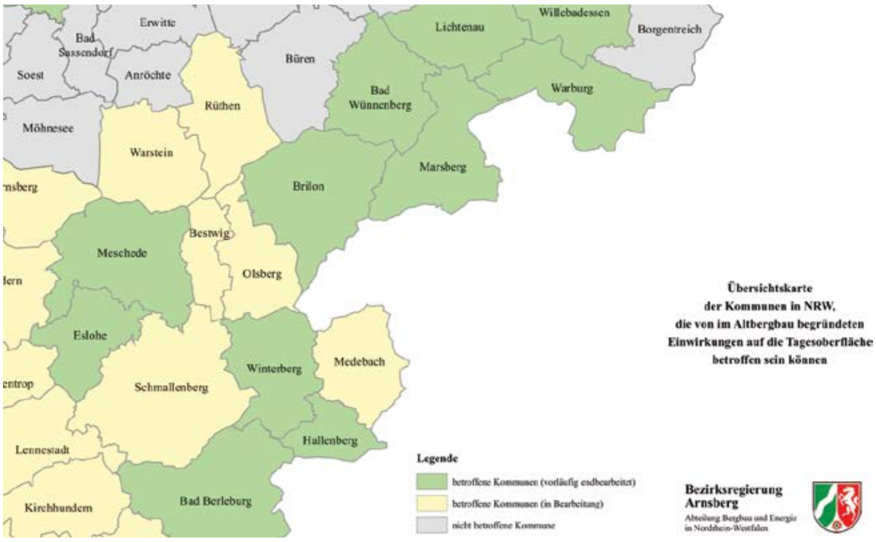

Figure 4. Map of German federal state North Rhine-Westphalia. All communities with affected by abandoned mines are highlighted in green or yellow.

motions: continuous observations with descending and ascending repeat coverage with a minimum of 20 images per year. (ii) for hazard monitoring purposes on hotspots (e.g. most critical mines): descending and ascending repeat coverage (e.g. TerraSAR-X every 11 days, COSMO-SkyMed every 8 days).

(b) HR Optical/VHR Optical: (i) to provide background reference imagery: archive image (no more than 1-year old), panchromatic or true colour composite.

The use of Satellite EO is illustrated with the following case studies:

Northumberland and Durham (UK) Case Study

The Terrafirma Abandoned Mines service for Northumberland and Durham has shown PSI to be a useful tool for the monitoring of minewater levels and their recovery. Northumberland and Durham, in the northeast of the UK, have a history of coal extraction extending over hundreds of years. The working of deeper and deeper coal seams, including those beneath the Permian bedrock cover, led to the need to pump mine water. Systematic pumping of mine water ended with the abandonment of underground mining. However, as part of a strategy to control and monitor mine water within the now abandoned coalfield,

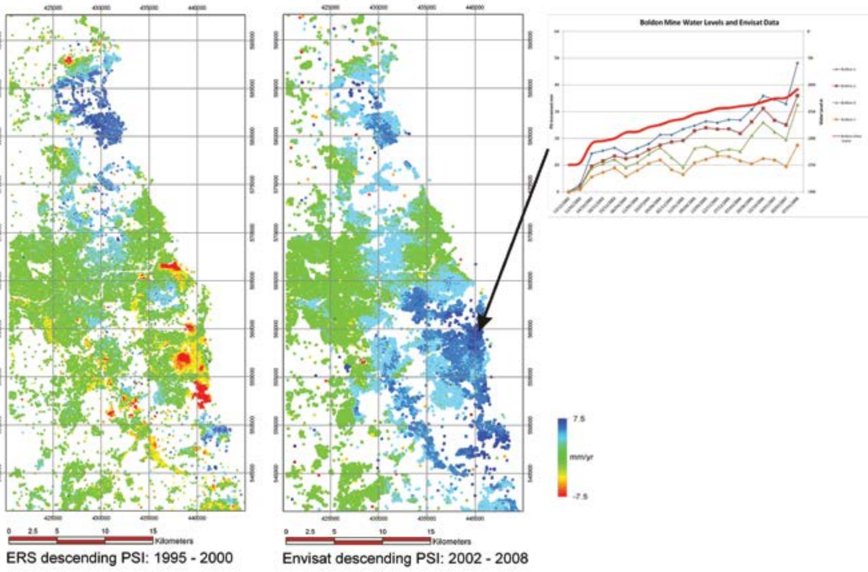

Figure 5. ERS and Envisat PSI for Northumberland and Durham. Inset graph shows the minewater recovery (thick red line) and PSI time series (thinner coloured lines) for the Boldon Mine water monitoring borehole.

the UK Coal Authority continued to pump minewater from a number of sites. Recent years have seen a progressive reduction in the number of pumping sites and groundwater levels within some parts of the coalfield have recovered.

Two PSI results, ERS 1995 to 2000 and Envisat 2002 to 2008, were produced for the area (Figure 6). In the earlier time period a complex pattern of ground motion is evident. There appears to be a complex relationship between areas of subsidence, undermining, changes in groundwater/ minewater level and the pattern of faulting. In the more recent time period there is a change to a regional pattern of uplift. The pattern of uplift follows the timing of recovery of minewater levels within the minewater recovery blocks (structurally defined areas within which the Coal Authority consider minewater levels to act in the same way); the greatest rates of uplift occur over blocks for which the minewater level has recovered most recently. Water level changes measured within monitoring boreholes show the same upward trend as the PSI ground motion histories (Figure 5).

This ability to identify areas of minewater level change offers potential savings to the Coal Authority by reducing the need for unnecessary monitoring boreholes, with boreholes being sited in areas where PSI data has shown that minewater levels are rising via its ground motion signature, rather than employing an expensive ad hoc monitoring network of boreholes.

Bedzin and Sosnowiec (Poland) Case Study

The project areas of Bedzin and Sosnowiec are located in the Upper Silesian Coal Basin, one of the major coal production regions in Europe. Ground movement hazards and related risks within this region are usually related to active and abandoned deep coal mining and causing severe damage to gas and water pipelines, electric cables, traffic infrastructure and buildings.

The collection of systematic information on the ground instabilities is very important and a main evaluation factor for responsible authorities, especially for land use planning purposes. In the Upper Silesian Coal Basin, ground motion monitoring is one of main tasks of the PGI which is responsible for Poland’s security in supply of mineral resources, groundwater management, monitoring of the geological environment and warning against natural hazards and risk.

To support PGI in its tasks, Terrafirma specialists conducted a PSI analysis for selected areas to provide large area, small-scale movement information with high accuracy. Several stacks of ERS and Envisat satellite data from 1992 to 2010 were therefore analysed in several processing campaigns and projects. In addition, the PSI results were further analyzed and enhanced with data related to mining, such as geological maps and mining maps. Through this integration, the evolution and cause of the mining induced movements was identified and this enabled the assessment of surface movements in response to abandoned mining works including ground subsidence, collapse or heaving due to mine water rise.

As an example, in the project area of Bedzin, the phenomenon of ground heave in abandoned mining areas was investigated by conducting extensive PSI analysis. The analysis included two different sets of Envisat SAR data covering an overall time period from 2002 to 2010 and an analysis and interpretation of auxiliary mining data. The PSI results delivered a large area overview with accurate motion information showing either stability or significant heaving motion in areas of inactive mining or subsidence in active mining areas. Incorporating the mining data, the ground heave can be attributed to hydrogeological conditions changing and groundwater level rising after the closing of the mine (see Figure 6). This heaving is particularly present in tectonic fault zones.

In summary, the results of the Upper Silesia case studies prove the necessity and applicability of Terrafirma PSI products for monitoring active

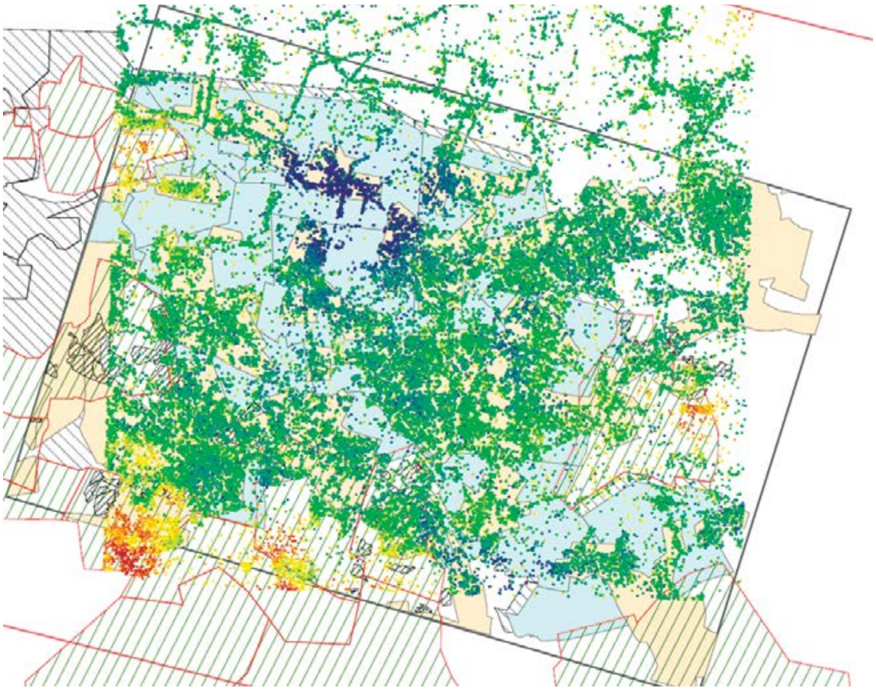

Figure 6. Bedzin PSI data set - large overview of the area of interest with average annual motion rate.

and abandoned mines and providing valuable information to protect the environment and ensure public safety in mining areas.

Liège (Belgium) Case Study

A strong mining subsidence of several meters was observed during the coal exploitation in the Liège basin associated with intensive groundwater pumping. After two centuries, the industrial coal extraction has ceased, along with the pumping. Since 1970, the recharge of the aquifers has led to several surface phenomena. In 2005, the Geological Survey of Belgium participated in the Terrafirma program. Using 102 SAR scenes, 28 000 PSI were identified in the region of interest with a density ranging from 100 to 480 PS/km². Analysis of the annual average velocity of the PSI highlighted different ground movements occurring in and around the city of Liège. Subsidence along the Meuse River was recorded, probably caused by building loads on the soft alluvial plain deposits near the river. On the other hand, strong positive annual average velocity values are observed in the Saint-Nicolas and Seraing districts. The rise of groundwater mining after several years of aquifer recharge leads to hydrostatic overpressure. This process resulted in several centimetres of elastic rebound (uplift) in these previously subsiding mining areas (see Figure 7).

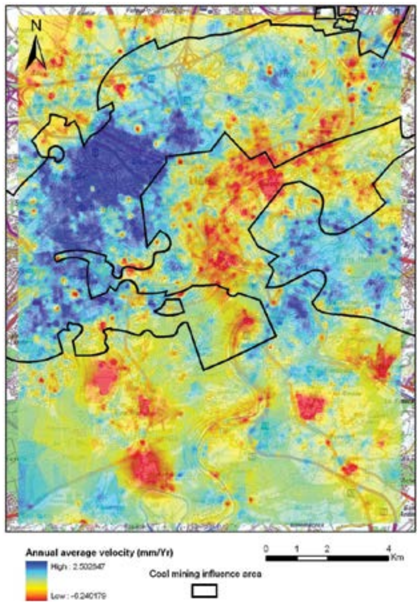

Figure 7. Kriging interpolation based on the annual average velocity and mine influence areas correlated with the uplifting (blue colours) regions.

4.6 The way forward

There are four fundamental questions that concern the use of Satellite EO to support the inactive mines sector:

— What needs to be delivered over the next 5 to 10 years?
— What factors can accelerate the realization of these objectives, looking at technology & services and looking at science?
— What organisations are involved?
— What about other users not using Satellite EO?

In 2011, the German organisation DMT organized an ad hoc working group under the patronage of the German Mine Surveyors Association (DMV) to work towards the acceptance of PSI-based monitoring of movement by the mining authority in Germany. The first meeting took place directly after the previously mentioned post-mining workshop and eleven participants from the German mining industry, mining authority and mining service industry agreed upon a work plan for the development of "Technical Guidelines for mining applications of radar interferometry". Follow-up meetings have resulted in an agreement about the general structure of the guidelines. Now the creation of a first draft is under progress. The final version of these guidelines is expected in 2012. They will define the technical state-of-the-art for mining applications using radar interferometry, articulating a clear statement of the requirements for the coming 5 to 10 years on at least a European basis. Although they will not become legal regulations, the German mining authorities will be able to accept monitoring concepts presented by mining companies on basis of these guidelines, as they already do with similar guidelines on GNSS and laser scanning. The German example is a prototype for how European countries might go forward to implement EO technologies as an important part of a monitoring concept for post-mining areas. Further work is required to develop standard procedures to systematically map former mining areas at risk and compare them with actual population densities and critical infrastructure.

In Europe, there are indications that renewed interest in mining may lead to new ventures. Despite the decline of many mining sectors in the last decades, renewed demand for raw materials is bringing a renaissance to European mining. In Germany, a German GMES user forum has been established, as required by the European Regulation No 911/2010 of the European Parliament and the Council on the European GMES[5]. In November 2011, a German National Actions Program[6] was published, which proposes several particular actions for the next four to five years. One of these actions is the development of a pilot service for monitoring abandoned mining areas using GMES data. This development is managed by the German Geological Survey BGR and the mining authorities of the Federal States, but the German mining industry may also become involved in this development. Furthermore, the State Government of North Rhine-Westphalia, the German Federal State with the most mining activities, has funded a new R&D project called GMES4Mining which investigates new developments in remote sensing technologies for mining purposes, in particular new hyperspectral sensors as well as high resolution radar data. The integration of remote sensing data with ground truth data is a key target of this project.

As far as the European perspective is concerned, it is understood that to meet the needs of risk management users concerned with the monitoring of abandoned mining areas, within the next five years, a regular service capability will be available in the framework of GMES data (primarily using Sentinel-1 data). In Germany it is expected that this capability will be exploited as an operational service. The German approach is intended to form a useful example of best practices for other European countries and worldwide.

There are many user organisations involved in exploiting the benefits of satellite EO for abandoned mines. This theme draws on expertise from within the minerals, mining, groundwater, urban geohazards and InSAR communities. This means that it cuts across data providers, value adders, mining technology companies and a selection of geological surveys and experts, representing the commercial, consultancy and research sectors. A cross section of activities undertaken include application of InSAR and other

5 REGULATION (EU) No 911/2010 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 September 2010 on the European Earth monitoring programme (GMES) and its initial operations (2011 to 2013); Official Journal of the European Union 20.10.2010.

6 Nationales GMES Massnahmenprogramm (Deutschland), 24./25.11.2011; Download from: http:// www.d-gmes.de/sites/default/files/dokumente/GMES_ Ma%C3%9 Fnahmenprogramm _dtp.pdf

EO technologies for mapping, measuring and monitoring affected sites across Europe, as well as some modelling activities that help establish the expected behaviour of abandoned mine lands. Other EO techniques that are important can include high resolution optical imagery, for mapping sites, and airborne hyperspectral data, to characterise the materials exposed at such sites. LiDAR and digital photogrammetry are used to measure detailed terrain models for the affected areas. In addition to EO, geological and mining knowledge and experience are critical to better understand the behaviour of these hazards and their manifestation in EO data.

Affected area in residential agglomeration in Queensland, Australia, in the aftermath of the severe flooding of December 2010 - January 2011.

5. Perspectives Concerning Satellite EO and Geohazard Risk Management: coastal lowland subsidence and flood defence.

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5.1 Introduction and Scope

This chapter presents perspectives on how satellite EO can contribute to the reduction of risks related to subsidence and flood defences in coastal lowlands, originally developed as a community paper presented at the Santorini Conference. The aim is to consider the state of the applications and services and to describe the consolidation efforts needed concerning these EO applications in order to achieve their expected benefits. Two main subjects are addressed in this chapter: subsidence problems in coastal lowlands prone to flooding, and monitoring the integrity of flood defence systems in coastal lowlands. Although these issues are also relevant for inland flood plains and associated defences, research and pilot activities discussed at the Santorini Conference are focused on coastal regions where these issues are predominant. At a later stage, the analysis could be extended to non-coastal flood plains and defences, where a large demand may exist for EO techniques and related services. This chapter outlines a 5 to 10-year vision for the coastal subsidence and flood defence community, based on the assessment of state of the art research and the application of EO for subsidence risk management.

5.2 Coastal flooding and subsidence

Figure 1[1], depicts global flood prone areas, including coastal lowlands and river basins away from the coast. At a global scale, it suggests that some 50% of the earth's surface is prone to flooding, of which 10% is located in coastal lowlands. Combining the observed flooding data in Figure 1 with geological data on extent and composition of coastal floodplains would provide a more fitting delineation of areas prone to flooding and subsidence.

1 This map was constructed using publicly available sources:

- Information from sea level rise maps, containing raster data for areas that will be flooded for a selected level of sea level rise – in this case 6 m rise, to account for extreme situations in case of storm surges. This measure is loosely connected to standards for storm surge defences around the North Sea. A list of major deltas in the world. Overlaying this information, it can be noted that most of the deltas coincide with coastal lowland areas;
- World Vector Shoreline, United States Defence Mapping Agency, 1989. Figures were calculated by L. Pruett and J. Cimino, unpublished data, Global Maritime Boundaries Database (GMBD), Veridian - MRJ Technology Solutions, Fairfax, Virginia, January, 2000.

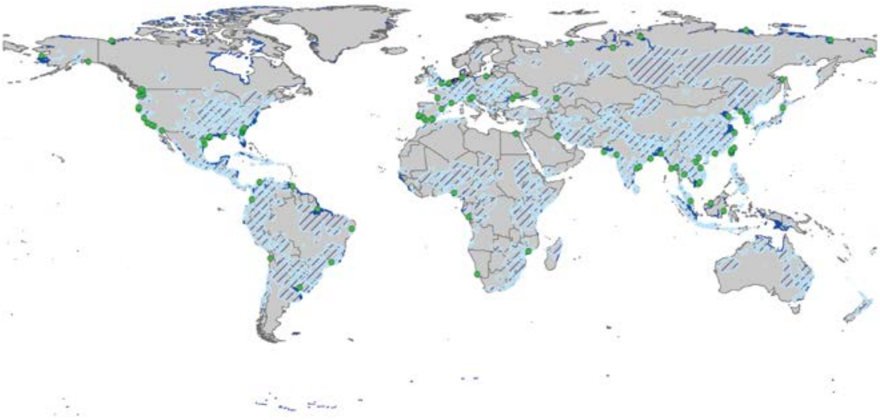

Figure 1. Geographic priorities for flood risk (hatched areas), with a subset in coastal lowland areas (solid blue areas) and deltas (green points). The total length of coastline in the world is 1.6 million km.

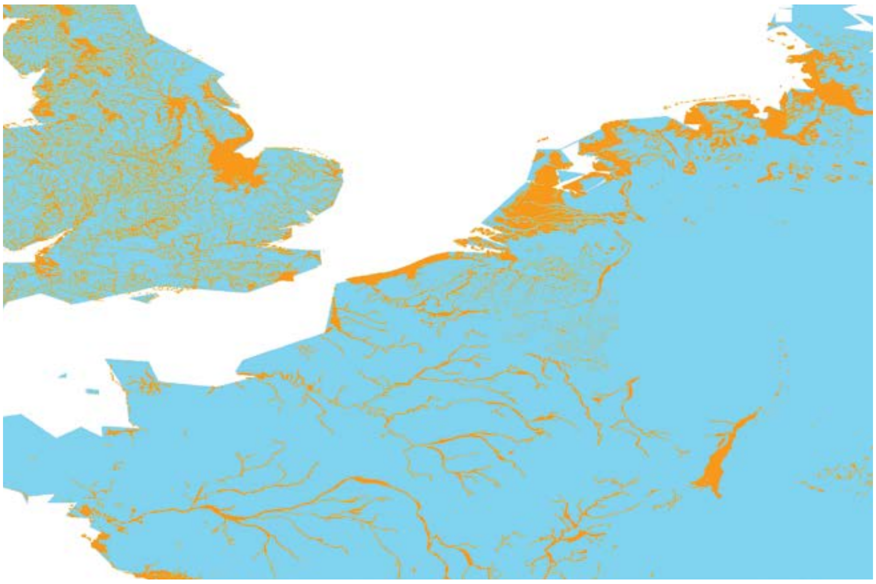

Figure 2. Example of coastal and inland areas with Holocene sediments, including clay and peat (white areas), in the central part of Europe. These areas, in most cases in deltas and in river basins, are prone to subsidence. (Source: http://www.onegeology-europe.org/).

An example is shown in Figure 2 for Central Europe. This chapter focuses on the coastal lowland areas delineated by the 6m + mean sea level contour (solid blue in Figure 1), a measure which is loosely connected to standards for storm surge defences around the North Sea. However, it is difficult to extrapolate these conditions and standards for other flood prone coastal areas worldwide (in most areas standards are much lower than +6m). This delineation may usefully serve as a proxy for coastal lowland areas exposed to storm surges and expected sea level rise due to climate change.

Issues of subsidence are generally associated with protection of critical infrastructures and damage to built-up areas. However, when rapid rates of subsidence are seen in coastal areas, the problem is augmented by the increased risk of flooding, compounding damage and extending the impact to large populations. According to the Worldwatch Institute[2], 24 of the world's 33 major river deltas are sinking due to flood-control efforts and other human-caused changes to the river systems. The combination of sinking deltas and rising seas will increase the damage caused by hurricanes and other flooding events in the future, according to Syvitski et al. (2009). The study estimates that the area vulnerable to flooding could increase by 50% worldwide. An estimated 500 million people live in river deltas, hence the focus of this chapter on coastal lowlands, especially deltas. While sea level rise is a factor, it is usually estimated in centimetres, while subsidence in some coastal areas can be measured in tens of centimetres and, in some cases, metres over decades.

2 www.worldwatch.org/node/6267

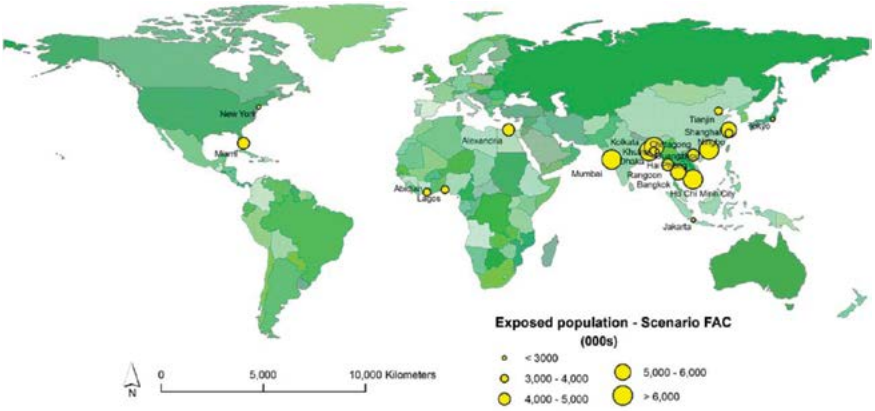

Figure 3. Top 20 cities for coastal flood risk by exposed population in 2070 (Source: Nicholls et al (2007), OECD, Paris).

Understanding the relative impact of subsidence is critical to properly estimate coastal flood risk.

A study[3] by the Organisation for Economic Cooperation and Development (OECD), attempts to quantify the impact of climate change and subsidence on populations and infrastructure. "By the 2070s, total population exposed could grow more than threefold to around 150 million people due to the combined effects of climate change (sea-level rise and increased storminess), subsidence, population growth and urbanisation. The total asset exposure could grow even more dramatically, reaching US $35 000 billion by the 2070s; more than ten times current levels and rising to roughly 9% of projected annual GDP in this period." It is clear from the study that subsidence will be a major factor for determining risk exposure in coastal mega-cities, especially in Asia, as evidenced in Figure 3, above.

A more recent report by the World Bank[4], in collaboration with the Asian Development Bank (ADB) and the Japan International Cooperation Agency (JICA), examines the impact of climate change on cities such as Bangkok and Ho Chi Minh City, under a range of different scenarios through to 2050. The report shows that as coastal megacities, the cities face increased risk from sea-level rise and extreme weather events.

Subsidence is a key contributing factor and needs to be better evaluated, especially in areas with large exposed populations. Asian megacities such as Bangkok and Ho Chi Minh City are centres of national and regional economic growth contributing substantially to the GDP of the respective countries. Ho Chi Minh City is developing an innovative integrated flood risk management strategy to protect the city in the face of significant and hard-to-predict future trends in sea level, subsidence, climate, land-use, and demographics, with the support of the World Bank. Thailand is implementing water management schemes to prevent a repeat of the 2011 flood disaster. The water management plans involve reforestation, the construction of dams, dikes and reservoirs and city planning. One of the project plans to plant trees and build dikes along upstream tributaries of the Chao Phraya River that flows from the north through Bangkok. Another involves the construction of reservoirs in the river basins where floods develop. Other projects include the building of floodways and irrigation systems, the cleaning-up of canals and waterways and establishing a data system for water management. Improvement of dikes, sluice gates and canals is also foreseen. These plans require informed decision making based on data input such as that provided by satellite EO.

Figure 3, above, from the OECD report, shows the countries with the greatest exposed populations to coastal flooding in 2070, with specific reference to subsidence and sea-level rise. While sea-level rise can be derived from global

3 Nicholls et al (2007), *Ranking of the World's Cities Most Exposed to Coastal Flooding Today and in the Future*, OECD, Paris.

4 *Climate Risks and Adaptation in Asian Coastal Megacities*, World Bank, 2010.

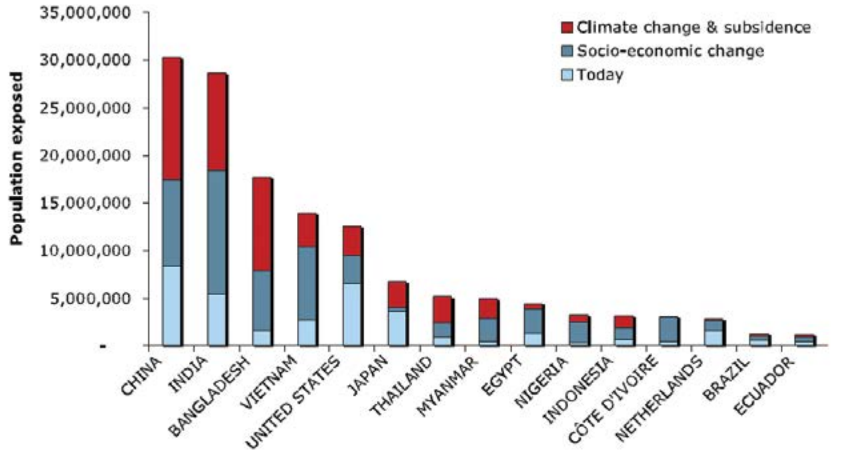

Figure 4. Top 15 countries by population exposed today and in the 2070s, showing the influence of future climate change vs. socioeconomic change (Source: Nicholls et al (2007), OECD, Paris).

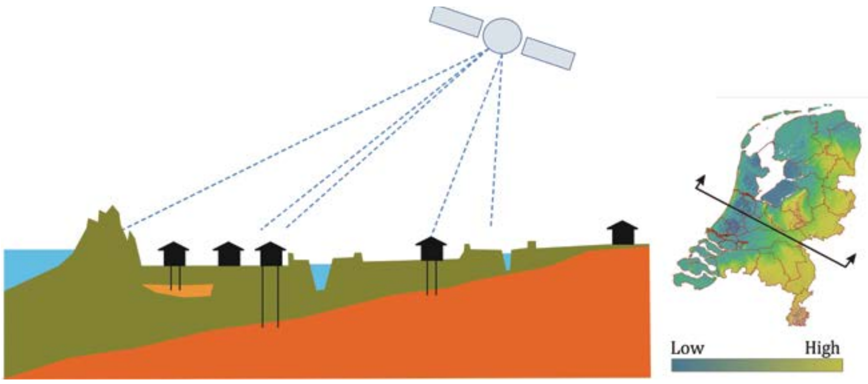

Figure 5. Illustration of coastal lowland terrain deformation monitoring in the case of the Netherlands; schematic cross section of the region from west (left) to east (right). Satellite EO-based PSI can provide continuous deformation measurements in the satellite line of sight direction between the satellite and terrain features. The yellow colors in the map represents the higher grounds (situated above sea level); the rest of the country (blue colors) lies below sea level. (Geological Survey of the Netherlands, 2012).

climate change models, accurate statistics on current rates of subsidence in rapidly developing megacities of Asia are not available and may dramatically worsen the impact of flooding in these areas. “The [...] assessment provides a much more comprehensive analysis than earlier studies, focussing on the 136 port cities around the world that have more than one million inhabitants. Most of these largest port cities are found in Asia (38%), and many of them (27%) are located in deltaic settings, again mainly in Asia. Cities in deltaic locations tend to have higher coastal flood risk as a result of their tendency to be at lower elevations and experience significant (natural and anthropogenic) subsidence.”[5] Understanding the rates of subsidence and monitoring them in conjunction with mitigation policies is critical to effective disaster risk reduction.

Subsidence is a typical geohazard for coastal lowland areas and river basins. Subsidence, when combined with sea level rise and extreme weather events (windstorms, heavy rainfall and related river discharges), aggravates flood risk increasing the hazard by deteriorating the flood defence and increasing the exposure in lowering the height of subsiding areas. Therefore, subsidence and flood risk are closely related. Subsidence is caused by peat oxidation, ripening of young sediments, compaction of compressible sediments or anthropogenic sources (water or gas extraction). Lowland areas are often densely populated with varied land use including industry, agriculture and infrastructure. The shallow subsurface in these areas frequently contains compressible soils which are vulnerable to subsidence. Almost half of the Netherlands is situated below sea level (see Figure 5) and thus highly vulnerable to floods. The shallow subsurface consists of Holocene deposits as can thick as 10 to 15 metres, sometimes containing up to 6 metres of compressible clay and peat. Furthermore, these deposits have a substantial spatial variability due to

5 Nicholls et al (2007), OECD, Paris

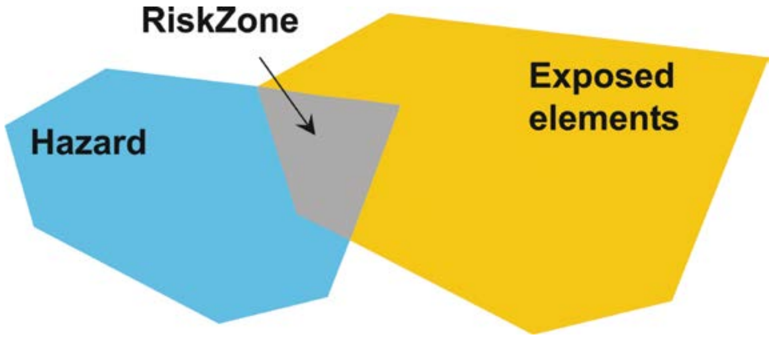

Figure 6. An INSPIRE natural risk zone results from the coincidence over the same area of a natural hazard and exposed elements that are vulnerable to this hazard.

sedimentation and erosion processes, introducing a spatial component in the vulnerability to subsidence. For stability reasons, infrastructure and buildings in these areas are now constructed on piles or on sand beds installed to replace the compressible sediments. In addition to natural processes of ripening, compaction and peat oxidation, human factors also influence the stability of the foundation layer.

The extraction of natural resources like groundwater, salt, oil or gas in deeper layers (ranging from tens of metres up to thousands of metres) may cause subsidence at the surface. On the other hand, a rise in the surface level may result from the storage of CO_2, for instance, or groundwater recharge after extraction has stopped. Additionally, geological processes along faults may cause terrain movement. These factors lead to regional rather than local terrain movement.

In addition to recurring floods in areas of subsidence that require monitoring, storm surges present extraordinary situations where damage can become catastrophic. During surges, strong winds drive seawater against the shore, often causing significant loss of life and damage to property. The combined effect of sea level rise and subsidence will increase exposure to extreme flooding in low-lying countries and harbour cities. For instance, in the UK more than one million properties are at risk from sea and tidal flooding. The storm surge event that struck the East Coast of England and the southwest coast of the Netherlands in January 1953 was the worst natural disaster in northern Europe over the past two centuries. The Thames Barrier in the UK[6] and the Delta Project in The Netherlands[7] were developed as a direct consequence of this storm surge.

Risk is the combination of the consequences of an event (hazard) and the associated likelihood/probability of its occurrence[8]. The consequences are calculated from the vulnerability of the exposed elements to the hazard. Following this definition, flood risk will be determined by the (1) probability of a flooding event happening and (2) the vulnerability of the exposed area in terms of expected damage (loss of life and/or economic damage), or simply stated, the coincidence of a natural hazard area and exposed elements that are vulnerable to this hazard (cf. Figure 6[9]).

Both elements are affected by terrain movement (see Figure 7). The probability of a flood event increases for a subsiding flood defence structure, by an increase in the probability of overtopping. Additionally, with a subsiding hinterland the difference in height between the extreme water level and the exposed terrain increases, destabilising the flood defence structures. Secondly, the impact of a flood will be larger for subsided terrain

6 http://www.rms.com/Publications/1953_Floods_Retrospective.pdf
7 Deltacommissie 1961 Report Delta Committee Parts 1–6. The Hague, Staatsdrukkerij en Uitgeverijbedrijf.
8 ISO 31010
9 D2.8.III.12 INSPIRE Data Specification on Natural Risk Zones – Draft Guidelines V2.0, INSPIRE Thematic Working Group Natural Risk Zones, 2011.

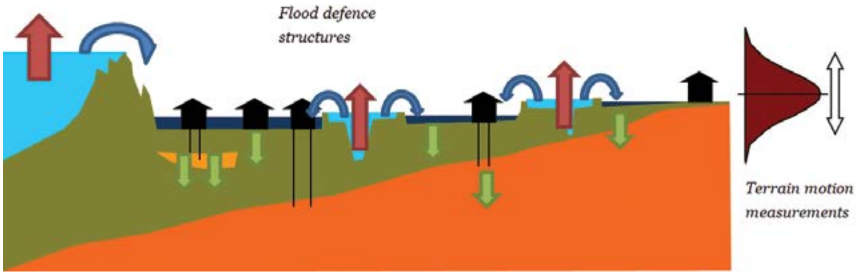

Figure 7. Rising sea levels and extreme river discharges (red arrows) in combination with terrain movement (subsidence, green arrows) influence the probability of a flood hazard (dark blue arrows) and the vulnerability of the exposed area. Linking relative deformation data from PSI measurements to absolute positions of ground features and the sea level is a critical issue (Geological Survey of the Netherlands, 2012).

by an increase in inundated area both in depth and in extent. This means that terrain movement is a relevant parameter for all flood prone areas, whether protected by flood defence structures or not.

5.3 Users and their information needs

Although subsidence is a serious geohazard, the problem is often understated and receives insufficient attention. The costs associated with subsidence are enormous, not only due to actual damage (e.g. to buildings or infrastructure), but also indirectly, given increased flood risk and the related threat to human life. The relative obscurity of subsidence as a hazard is due to the multi-sectoral character of its impact. There is not one specific organisation that is responsible for subsidence, rather, subsidence is a small part of the responsibilities of many stakeholders. Technical, socio-economical and governance aspects are important in tackling subsidence and its effects.

In contrast to subsidence, issues related to floods, flood risks and flood defences are usually public affairs. The level of governance depends on the institutional structure within countries and the mandate of stakeholders. The issues at hand determine the scale, timeframe, level of detail, reliability and accuracy of the information needed. Flood related issues are governed on various levels:

— On a local level by cities and municipalities.
— On a regional level by provinces, regions, water boards and hydrographical confederations.
— On a national level by national governments.
— On an international level by e.g. European directives.[10]

In order to deal with the long term effects of climate change and flooding, the EU prepared the EU Flood Directive. Its aim is to reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity. It states the need for a monitoring strategy to assess risk of flooding along coastlines and water courses. For the river basins and coastal areas at risk of flooding, flood risk maps and flood risk management plans focused on prevention, protection and preparedness need to be made. Moreover, access to this information should be freely accessible to the public. The Floods Directive opens the door to transnational/cross border emergency planning in Europe. On a global scale, however, floods are governed completely differently. In some parts of the world, floods are accepted as a fact of life (e.g. Bangladesh). However, the risks to life and property have been reduced by better flood forecasting (warning) and measures taken during the response phase. User needs should reflect the culture and governance, predicted risks and available means, in order to ensure that reasonable and realistic plans and budgets are developed for action. In two European projects, the information needs of public stakeholders that have a responsibility in flood mitigation were evaluated. The ESA funded project Terrafirma focuses on the use of PSI for flood plain and flood

10 EU Floods Directive, Directive 2007/60/EC.

defence applications. In the FP7 project SubCoast, research is concentrated on subsidence in European coastal lowlands. The user needs summarised below are distilled from the user needs documents of these projects.[11]

Governmental organisations responsible for spatial planning and safety in flood prone areas need to be aware of the combined effects of subsidence and sea level rise in their region. They will only be able to take the necessary 'no-regret' actions and measurements if they are provided with adequate information on the subsidence process. Whereas tectonic subsidence is a relatively slow process, human induced subsidence can be rather quick, e.g. up to 40 cm per year in Jakarta. In other areas human induced subsidence is on a longer timescale, but still of the same order of magnitude as the expected sea level rise. So especially when planning large scale and long term investments like infrastructure, industrial sites, and urban development, these effects have to be taken into account. PSI data combined with additional data such as levelling, geological data and GPS can provide this information.

The different needs for information can be mapped as (1) driving forces, (2) vulnerability and impacts, and (3) risk assessment and measures. Driving forces are processes that cannot be changed by the stakeholder itself, such as socio-economic aspects (demography, macroeconomics), climate change (sea level rise, extreme weather events) and subsidence (man-made and natural). The vulnerability of a land use function to the impacts of the driving forces depends on the level of resistance and resilience of the function for the changing effect. Risk assessment is a crucial step in the preparation of adaptation measures. It is a combination of the vulnerability (effects) of a land use function in relation to the pressures (chance that the effect will occur).

A driving force in flood vulnerability is for example subsidence of soft compressible soils. This results in an information need on the magnitude of historical and predicted future soil subsidence in order to perform a risk assessment and decide on measures concerning the flood defence system or adjustment of ground water management.

The information needs can also be differentiated by relevant spatial planning layers and time frames. The occupation layer has a typical speed of change of 1 to 50 years. The infrastructure or network layer changes on timescales of 10 to 100

Table 1. Summary of user information needs for floods with potential PSI contribution.

Themes	User information needs
Occupation layer (Time scale = years: 1-50 yr)	
Flood vulnerability	Economic activities (including value)
Planning in Urban areas	Population density
Buildings & civil engineering works	Local trends in subsidence, in relation to groundwater level fluctuations
Planning in Rural areas	Forecasting of subsidence based on models
Agricultural land use	High resolution maps of subsidence rates (urban and rural areas, roads and levees)
Natural/recreational use	Groundwater extraction and use policy
	Information on spatial variability of ground movement, with uniform coverage
	Estimate of waterlogging
Network layer (Time scale = decades: 10-100 yr)	
Planning in Urban areas	Subsidence rate of roads and levees
Infrastructure development	Subsoil stability
Flood defence system	Model to link soil subsidence - groundwater level fluctuations
	Predictions of flood extents
Base layer (Time scale = centuries: >100 yr)	
Water management	Model to link soil subsidence - groundwater level fluctuations
Flood hazard (coastal, fluvial and pluvial)	Erosion rate and sediment balance
Mining (water, coal, oil/gas, salt)	Historical, current and predicted subsidence rate and total amount
	Predictions of flood extents

Figure 8: Coastal lowland areas (solid blue) and deltas (green points) in Europe (extract of figure 1).[12]

years, while the subsurface or ground layer changes over even longer timescales of more than 100 years.

The information needs for the different layers are summarised in table 1.

In general, there is a need for reliable spatially distributed historical data on terrain motion covering large areas to better understand the processes involved. In addition to historic subsidence maps, several users have expressed the need for a regular update of these subsidence maps every one or two years.

End users also need higher temporal and spatial resolution than that offered in the past by ERS and Envisat. New missions like Sentinel-1 will offer temporal revisit adapted to operational services. Users also need uniform spatial coverage of subsidence information. This is a problem in areas with vegetation such as grass covered levees and agricultural fields in rural areas. Users rely on comprehensive quality reports containing metadata, quality checks, processing steps and identification of sources of reflection. These data also extend to other types of deformation, apart from linear. The linear deformation assumption is not valid for areas of recent reconstruction works for which exponential consolidation behaviour is expected.

Concerning flood mapping, users' needs have been characterized in various studies and projects. Satellite based observations of the extent of plain flooding is used in operations and, as an example, represents one of the core components of the GMES Emergency Management Services. While this chapter is concerned with flooding in coastal areas, its focus is on the impact of subsidence on flooding and does not directly address broader flood monitoring requirements. In essence, plain flood mapping information needs primarily comprise flood extent observations with high temporal sampling – to estimate the maximum of the flood extent – at different observation scales according to different service types and geographic areas (e.g. 1-100m for plain flood extent). Generally users require fresh and repeat information based on a rapid service that requires a 24/7 capacity.

5.4 The European case

Europe's major river deltas and coastal lowlands are depicted in Figure 8. Flood prone areas with high economic value are often protected by flood defence structures.[13] Global information on these flood defences is not readily

12 The main deltas are found in the Netherlands (Rhine/Meuse/Scheldt estuary), Northern Germany (Elbe estuary), Eastern Denmark, Northern Germany/Poland, Eastern Great Britain (Thames), Western France (Garonne), South East France (river Rhone), North-East of Italy (Po), Eastern Romania (Danube) and Northern Russia (3 deltas).

13 http://www.eea.europa.eu/data-and-maps/data/geomorphology-geology-erosion-trends-and-coastal-defence-works

Levee Monitoring along the IJsselmeer (Netherlands)

For two stretches of flood defence structures along Lake IJsselmeer in the centre of the Netherlands, the PSI data from Envisat (2003-2010) and TerraSAR-X (May 2010-August 2011) were used to monitor levees. The Netherlands is covered with Holocene deposits which can be 15 m thick. The soft, compressible sediments make this polder landscape, with its numerous flood levees, prone to compaction.

In total, 43 frames (ascending) and 148 frames (descending) of ASAR Envisat data from 2003 to 2010 were processed (see Figure 10). PSI data were combined with information from digital terrain models, high resolution LiDAR, aerial photos, 3D geological model of the Netherlands, dyke safety analyses, elevation data for top of the Pleistocene surface, geological maps and cover material. Overall, the levees are stable. However, there are some stretches of levee with relative subsidence that could be linked to recent reconstruction works. PSI motion patterns could also often be explained by the underlying geology, e.g. by relatively thick layers of peat and clay deposits.

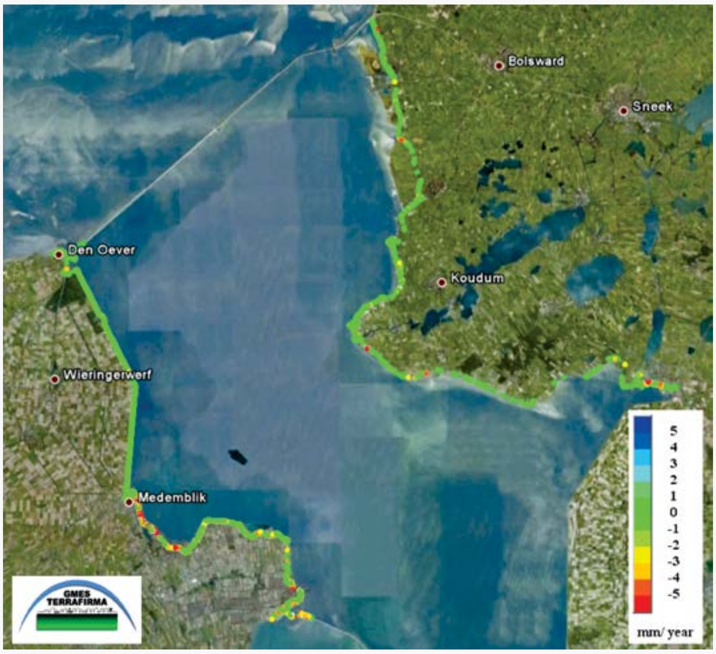

Figure 9. PSI result for levees around the lake IJsselmeer, the Netherlands. Envisat 2003-2010, descending and ascending tracks (Terrafirma 2012, www.terrafirma.eu.com, background image: © 2012 Google, Data SIO, NOAA, U.S. Army, NGA, GEBCO, image © Aerodata International Surveys).

available. On the European scale, however, the European Environmental Agency (EEA) has a database on flood defence structures. The database contains information on artificial flood defences, coastal embankments for construction works (e.g. earthworks) and harbours. However, this database is not complete. Other inventories can be established using data from initiatives like OneGeologyEurope, GEO, GEOSS, the European Geological Data Infrastructure (EGDI)[14] and others.

14 In September 2011, the Geological Surveys of European countries announced a European Geological Data Infrastructure. This system would disseminate all relevant geological information to be applied, inter alia, in understanding and forecasting geo hazards. This system could be used as the information source for terrain movement in Europe, or perhaps as a portal for freely accessible PSI data. This requires that metadata be developed for existing PSI datasets, with information on accuracy, quality and comments related to processing. Planned missions such as Sentinel-1 and RCM are well adapted to support geohazard and flood risk applications. They offer high resolution and improved temporal sampling enabling operational applications. In the case of Sentinel-1, free and open access to high resolution observations in IWS mode once every 12 days (or 6 days with both Sentinel 1A and 1B) will be guaranteed over the priority areas of the mission. Looking at flooding, these priority areas should be derived from Figure 9.

5.5 Current state of applications and services

Historical subsidence maps are typically based on a single analysis of a SAR datastack, e.g. using ERS or Envisat acquisitions, spanning a timeframe related to the operation time of the satellite – typically a decade. Today, collecting a datastack may be done over as little as 9 to 12 months. Over the last 20 years, PSI based on satellite SAR data emerged as a technique to accurately measure terrain movement such as subsidence. Successful use of PSI requires reflections originating from 'hard' and 'rough' surfaces, such as buildings and infrastructure (roads, railways, paved dykes). Therefore, flood defence structures that can be monitored by PSI are engineering works (such as bridges and storm surge barriers) and levees and dams with hard cover (such as rubble mounds and concrete). Flood defences which have grass cover cannot be easily monitored with PSI. In other application fields where the monitoring of critical infrastructure is needed irrespective of its suitability to PSI, corner reflectors can be installed in situ. Corner reflectors are metallic often trihedral reflectors which provide a reliable return signal to the sensor, allowing monitoring via satellite EO of vegetated or otherwise adverse ground cover. PSI data has an added value in spotting unknown movement phenomena and quantifying known movement phenomena. Understanding terrain movement by analysing PSI in flood prone areas has added value because it provides science and policy makers with firm evidence on subsidence rates. The dimensions of the subsidence can be used as an input in models to better understand the process of subsidence and models to identify possible 'no-regret' measures through the analysis of potential impacts. 'No-regret' measures reduce risk without any negative impact in the future. For this reason, they are easier to implement. Currently, PSI data is used to calibrate movement calculations based on geological, geotechnical and geo-hydrological models. For new construction sites, PSI data can be useful to assess the geotechnical characteristics of the ground and detect past instabilities. These are critical inputs for the identification and location of specific ground related risks of the site. To provide updated information concerning terrain deformation – typically needed on a yearly or biennial basis – users can rely on the satellite derived measurements in their maintenance task, e.g. to localise potentially unstable situations, to prioritise reinforcement works or to optimise the design.

During construction works, PSI data can deliver information for the reduction of risks. Both during and after construction, PSI can be incorporated into monitoring plans which are a requirement of European construction design standards.

Based on feedback from user organisations with an operational mandate to monitor risks, such as in the framework of Terrafirma and SubCoast, the most relevant strengths of PSI are:

1. The historical observations – typically over 15+ years – to estimate ground movement and characterise main subsidence areas.
2. The combination of wide-area coverage and sensitivity to small deformations.
3. The ability to analyse terrain movement over time.

Main EO capacities used or in development

The EO satellite applications for flood hazard are mainly concentrated on multispectral images or on SAR. In this section, the current state of applications for PSI is illustrated using two European projects (Terrafirma and SubCoast) where several service deliveries and pilot studies illustrate the contribution of precise terrain deformation and the potential of combining measurements with ground truth data such as GPS.

	Flood plain PSI standard/wide area product (FSW)	Flood plain subsidence mapping product (FSM)	Flood defence monitoring service (FDM)	Flood advanced subsidence modelling product (FAM)	Flood risk maps (FRM)
Pilot	North Germany floodplain Scheldt estuary (The Netherlands)	South-Denmark floodplain	Willemshaven (Germany) IJsselmeer (The Netherlands)	Scheldt estuary (The Netherlands)	Rhine/Meuse delta (The Netherlands) Baltic sea (Denmark, Poland, Lithuania) Po delta (Italy)
Project	Terrafirma, SubCoast	Terrafirma	Terrafirma	Terrafirma	SubCoast
Scale	Local / Regional	Regional	Along dyke	Regional	Regional
Geological	Maps	Maps	Maps	Models	Models
Geotechnical	-	Subsidence vulnerability	Subsidence vulnerability	Models	Models
Added value	Combination of relevant maps	Subsidence quantification	Monitoring	Identification of mechanism and forecast	Identification of flood risk
Product [map]	Subsidence rate contours or delineated subsiding areas	Classes with vulnerability to subsidence	Localized phenomena along flood protection systems	Identification of subsidence mechanisms	Identification of flood risk
Subsidence forecast	Subsidence rate contours or delineated subsiding areas	Classes with vulnerability to subsidence	Localized phenomena along flood protection systems	Identification of subsidence mechanisms Subsidence forecast	Maps showing e.g. flood risk forecast, relative sea level rise, ecological risk, water defence integrity
Typical end user	Local / regional government	Regional /national government	Water board / national government	Regional / national government	Regional / national government
Scalable to EU/ world	++	+	+ (where applicable)	+	+

Table 2. Currently available EO service products[15] of Terrafirma & Subcoast.

15 The following services are provided by Terrafirma & Subcoast:

- The flood plain PSI wide area product (FSW) provides information on subsidence of large coastal areas which are or will be prone to flooding.
- The flood plain subsidence mapping product (FSM) provides information on a smaller area than the FSW product and there is integration with ground-truth data (levelling and GPS) and geological data.
- The flood defence monitoring product (FDM) provides information on the condition of flood defence systems using PSI derived information to pinpoint and monitor localized phenomena along flood protection systems. The monitoring service is characterized by continuous updates of the time series and interpretation after an initial (historical) PSI processing.
- The flood advanced subsidence modelling product (FAM) builds upon the mapping and monitoring services for flood prone areas. PSI, as one of the available sources of geodetic information, can be used in combination with geo-mechanical modelling to assess and quantify the mechanisms contributing to subsidence or failure of flood defence structures.
- The flood risk maps (FRM) use information from the wide area product, advanced modelling of regional effects areas and hydrologically linked subsidence to produce maps of e.g. land movement in relation to sea-level rise, flood risk forecast, water defence system integrity, and maps of ecological risk forecast and groundwater risk forecast (salinity, extraction vs. compaction).

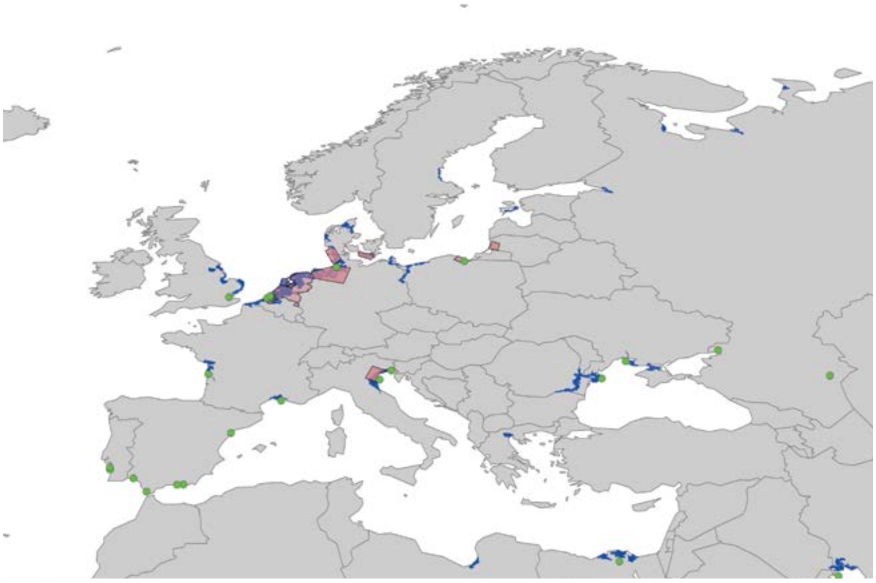

Figure 10. Europe, coastal lowlands (dark blue) and available PSI datasets concerning the coastal lowland subsidence and flood defence products of Terrafirma or SubCoast in orange and red (data derived from Terrafirma, www.terrafirma.eu.com and SubCoast, www.subcoast.eu).

In Europe, the geographical distribution of all service deliveries from these projects is represented in Figure 10. The currently available flood related EO services in Europe and their applicability are summarised in Table 2. Ground truth is provided by GPS or levelling. Flood risk evaluation related to subsidence is part of the SubCoast project.

As seen from Table 2, the different services offer varying levels of detail ranging from simple overviews to comprehensive monitoring and advanced modelling. The precise terrain deformation service using the PSI is still considered a complex solution that requires expert involvement to create added value for flood related issues. Specialised companies or universities are capable of converting the raw satellite data into PSI maps. For the end users, the observed deformation in PSI maps needs to be translated into information that is useful for their task. For this, the PSI maps are combined with other data (e.g. geology, construction, hydrology, population density and economic value). The combined data can be presented as flood risk maps and used as input for models for flood response and prevention or preparedness.

In the United States, the US Geological Survey treat land subsidence as a single issue – regardless of whether the motion is coastal or not. The pumping of subsurface reservoirs (groundwater, hydrocarbon, coal bed methane, carbon sequestration, aquifer storage and recovery systems), as well as natural process (sediment compaction, extreme rainfall events, drought) can all result in seasonal (elastic) and permanent (inelastic) elevation changes to the land surface, as well as, horizontal motion that may result in damaging ground fissures. Monitoring, regulating, and mitigating land subsidence resides within each state and local governments and in some cases dictated by the judicial system. The US Geological Survey Water Resources Mission Area conducts a wide-range of research on aquifer system compaction nationwide through the integration of field instrumentation, geodetic measurements, remote sensing, and comprehensive 3D numerical modeling. Field measurements are used to correlate water level changes in each aquifer with time-series data from extensometers that measure sub-millimeter changes in elevation between the depths of a borehole and the land surface. Campaign geodetic measurements (leveling and GPS) directly measure changes to the land surface at preexisting benchmarks; while relative and absolute gravity field based measurements are used to measure changes in the water surface at depth, especially in unconfined aquifers where subsidence is less of an issue. Continuous GPS sites provide very detailed time-series information (typically daily measurements) that can be used to track subtle vertical and horizontal changes as aquifer production and recharge change to meet water demands. Satellite remote sensing for aquifer

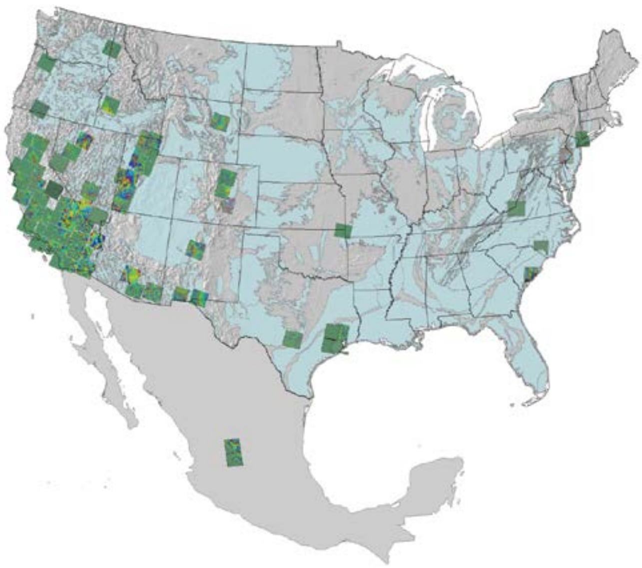

Figure 11. US Geological Survey InSAR (ERS-1, ERS-2, Envisat, and ALOS) land subsidence analysis (green/colored rectangles: InSAR scenes) superimposed on aquifer map of the United States (pale blue) and shaded relief map (gray scale). Image: Gerald Bawden, USGS.

systems compaction typically falls into two categories: InSAR and gravity (NASA's Grace mission). While Grace provides a dynamic synoptic overview of water changes at depth, the scale is too coarse to be of value to water agencies and municipalities. InSAR imagery provides excellent spatial measurements of how aquifers respond to stress. Furthermore, InSAR imagery can identify subsurface groundwater barriers, such as faults, that may not be previously recognized especially in sedimentary basins. Detailed predictive numerical models of aquifer systems are then developed and calibrated by integrating all of the available data sources.

Systematically monitoring land subsidence in the United States is daunting but necessary for both coastal and inland aquifers. Approximately 50% of the landmass has viable aquifers, whereas InSAR analysis has only begun to focus in areas with significant historic subsidence, such as the California Central Valley, Los Angeles, San Jose, and the greater Houston region in Texas. The low numbers of radar scenes in the ERS1/2, Envisat, and ALOS archives for the Eastern United States combined with high humidity and dense vegetation pose significant challenges in resolving aquifer system compaction, especially in the rural agriculture communities where groundwater is heavily exploited.

The precise percentage of aquifers, hydrocarbon fields, coalbed methane, and carbon sequestration fields that are routinely monitored with InSAR imagery represent a small fraction of the total area of the United States that has managed subsurface reservoirs (see Figure 11).

Internationally, ESA and the World Bank have partnered for the purpose of mainstreaming the use of EO in the World Bank's lending operations, across all of the Sustainable Development Network's sectors. This is achieved through the EOWorld initiative.[16] The aim is to establish a stable connection between the specific information needs of Bank projects and new developments in EO and services. In order to demonstrate the utility of EO techniques to the World Bank Group activities, ESA and the World Bank agreed to conduct a set of pilot projects in several domains; Water Resources and Coastal Zone Management, as well as Climate Changing Adaptation are topics that have been investigated.[17] An analysis of land subsidence in Jakarta served as a demonstration project.

16 www.worldbank.org/earthobservation

17 http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1278006228953/EOworld_Progress_Report.pdf

Subsidence related to ground water pumping (Jakarta, Indonesia)

Jakarta, with a population of about 9 million people and an area of about 660 km2, is located in the delta of thirteen rivers. Subsidence due to groundwater extraction, increased development, natural consolidation of soil and tectonics in Jakarta has been known since the early 1900s [Abidin et al, 2010]. The World Bank EOWorld project selected analysis of land subsidence in Jakarta as a demonstration project. Several PSI datasets were analysed (ALOS PALSAR 2007 to 2011 and VHR COSMO-SkyMed October 2010 to April 2011). The PSI results are shown in Figure 13. The sub-districts of Penjaringan, Cengkarang, the South Center of Jakarta and the suburban district of Cikarang are affected by strong subsidence rates. Figure 13 shows the largest subsidence in the Pantai Mutiara housing complex (in Jakarta Bay). The better temporal distribution of measurements achieved with the high revisit rate of the COSMO-SkyMed mission (in this case every 16 days) allows for a better assessment of changes in the trends of the subsidence (acceleration and slowdown). The PSI results in Figure 12 are in agreement with the total historical subsidence over the last decades (1974-2010, cf. Figure 13) derived from classical InSAR and in-situ measurements. The latter used PSI, leveling campaigns, measurements with GPS tide gauges, extensometers and groundwater level measurements. The current average land subsidence rate is 7.5-10 cm/year along the coastline. In some regions, however, total subsidence was more than 4 m. Using an integrated approach, the interaction between groundwater management, land subsidence and flood risks were investigated. If the current groundwater extraction regime continues, it is estimated that another 2.6 m of subsidence will occur between 2010 and 2030. However, by controlling groundwater extraction, subsidence can be greatly reduced. Based on measurements, modeling and simulation, it is possible to identify the most appropriate adaptive measures. PSI can also be used to monitor the effects of the adaptive measures.

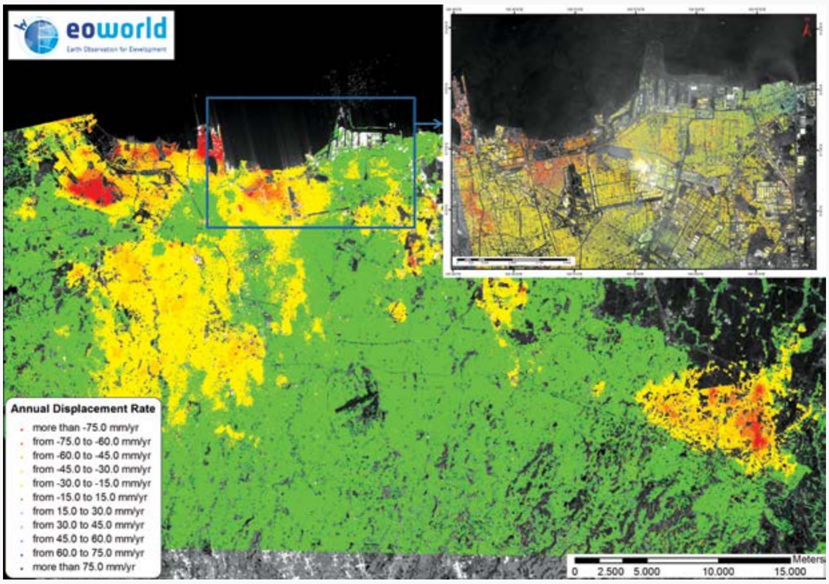

Figure 12. Terrain deformation map of Jakarta generated in the framework of the EOWorld project and derived from the analysis of ALOS PALSAR data (2007-2011). The zoom shows the deformation in Jakarta Bay and harbor derived from the PSI analysis of VHR COSMO-SkyMed data (Oct. 2010 – Apr. 2011). Color scale between -75 (red) and 75 (blue) mm/year. Source: EOWorld project/Altamira Information, Credits: ESA, World Bank.

The main satellite EO contribution requires InSAR, with the following observational requirements:

— High Resolution SAR:
  — for hazard inventory purposes (e.g. historical hazard mapping). This consists of continuous observations of descending and ascending repeat coverage (maximum available images per year, C and L-band in stripmap

mode). The focus is to extend and guarantee observations of the priority areas defined in section 2.
  — for hazard monitoring purposes: descending and ascending repeat coverage of hotspots (e.g. most critical water defence structures) with more than 3 images per month in C or L-band.
— Very High Resolution SAR:
  — for hazard inventory purposes: specifically to survey flood defence structures for any ongoing motions continuous observations descending and ascending repeat coverage with minimum 20 images per year on grass free flood defence structures.
  — for hazard monitoring purposes on hotspots (e.g. most critical water defence structures): descending and ascending repeat coverage (e.g. TerraSAR-X every 11 days, COSMO-SkyMed every 8 days).

Additionally, High Resolution Optical and Very High Resolution Optical imagery can provide background reference imagery. For this, the archive image should not be older than 1-year old and may consist of panchromatic or true colour composite images.

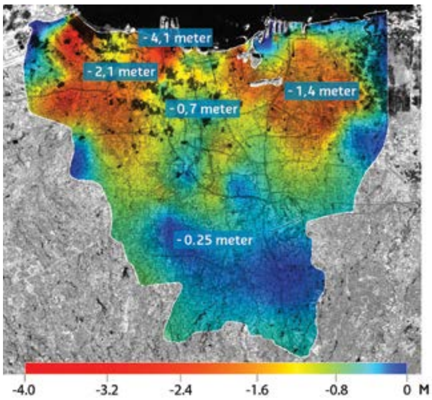

Figure 13. Land subsidence in Jakarta during the period 1974-2010, based on PSI (ERS-2 1996-1998, Envisat 2007-2009 and ALOS PALSAR 2007-2010), levelling, GPS, extensometers and groundwater level measurements. Source: Deltares 2011.

Emerging research

Services concerning coastal lowland subsidence and flood defence are primarily based on terrain deformation mapping (using archive data over 10 years or more) and monitoring (using repeat observations and analyses on a monthly basis).

R&D concerning various aspects of PSI based precise terrain deformation techniques includes the use of very high resolution images (where available, e.g. for water defence structures, such as sluices, dams, etc); detection of semi-persistent scatterers; the retrieval of non-linear deformation; identification of scatterers; identification of multiple reflections in one resolution cell; and distributed scattering. New topics for investigation to improve the EO technologies for coastal lowland subsidence and flood defence include increased use of corner reflectors or other techniques to augment the capabilities of PSI to monitor a greater range of flood defence structure types (esp. grass covered dykes); combining subsidence mapping with flood mapping when subsidence is related to plain flood; and combining subsidence mapping with storm surge applications when subsidence is related to storm surge in coastal zones.

5.6 The way forward

The community has identified three objectives over the next 5 to 10 years:
— Develop historical terrain deformation maps over known areas of subsidence and flood defence structures where stability needs to be assessed. This is of particular concern for urban resilience linked to flooding and storm surges in coastal areas. Even when subsidence is slight, the cumulative effect over decades may dramatically increase exposure of populations to flooding. This involves mapping all coastal flood risk areas of the world prone to subsidence over the next 5 years, and updating these maps regularly (e.g. every five years).
— Establish on-going monitoring of critical areas 1) where subsidence greatly increases exposure to coastal flooding; 2) where stability of flood defence structures is critical to population safety. The need is evident for example in Asian megacities. On-going monitoring of critical areas also allows one to measure the impact of mitigation policies on a local scale.

- Within 10 years, enable the combined use of terrain deformation and flooding information to support risk management authorities in coastal lowlands. This requires direct real-time access to terrain deformation and flooding data and information products.

Some specific countries have more detailed objectives. In the US for example, the goal for the next five years is to continue detailed InSAR analysis and modeling of land subsidence in the western United States, expanding into new areas of suspected land subsidence. USGS will begin processing and analyzing more cities along the southern and eastern coasts of the US as processing techniques become more adept at removing atmospheric signal from the data. It is worth noting that this part of the United States is the region most affected by coastal lowland subsidence. A realistic goal would be to increase the current analysis by about 20 percent over the next 5 years. Improved access to SAR data from sources such as TerraSAR-X, TanDEM-X, Radarsat-2, and COSMO-SkyMed would greatly facilitate this vision.

To realise the above mentioned mapping and monitoring objectives, progress is required in key areas:

- Data: systematic acquisition of SAR images in coastal areas
  - Wide-swath SAR satellites like Sentinel-1 or RCM must be tasked to acquire regular data over coastal areas. As the boundary between land application and maritime applications, these areas are often the subject of data request conflicts. Regular acquisitions over the entire coastal area are required to perform global mapping of areas prone to subsidence.
  - High resolution and frequent acquisition on the subsiding area to perform regular monitoring of the evolution of the subsidence.
- R&D: dedicated InSAR processing with non linear technique to increase density of measurement points
  - Non urban coastal areas are complex zones for InSAR processing. Deltas, flooded regions and soft soils are not good candidates for the application of classical InSAR techniques. Fast growth of cities is also an issue for preserving measurement points over the year. In addition, water consumption and recharge with or without flood, may generate complex motion patterns that are not easily processed by standard Persistent Scatterer measurements tools. Dedicated efforts to generate high quality, dense and non linear motion map over very large areas may be required to perform global mapping of all the coastal areas.
- R&D: monitoring of flood defence systems
  - Additional HR and frequent monitoring of flood defence systems is another kind of PSI processing that requires specific tools and satellite data. Integration of InSAR result with local measurement and expertise are needed to provide an operational service for the monitoring of flood defence system
- R&D: absolute subsidence versus sea level
  - The combination of subsidence with sea level rise significantly accelerates the extension of flood prone areas. In places where the subsidence is slight, sea level rise has to be taken into account to evaluate with precision the extension of flood prone area and the increase occurrence of flood hazard. The absolute calibration of InSAR based subsidence map, as much as the absolute measurement of sea level rise, in a common reference is a complex topic. This may require the use of innovative technology or processing to merge data.
- Services and infrastructure : dissemination
  - Mapping of coastal lowland will generate large volumes of data. These data may include the temporal evolution of each point. Dissemination of these data may require the creation of specific service infrastructure, including access to data, possible control for access and additional data.

One of the challenges in achieving a consensus within the international community to address these objectives is the absence of a clearly structured community around this specific issue at international level. There is however progress evidenced by recent interest from the World Bank and other major stakeholders. As a general comment, the international flood monitoring community is diverse and disconnected, as a result of specific local, regional or national perspectives and the diverse origins of its members. This is even more the case for communities related to the specific issue of subsidence, which are much less developed. Different actors use different methods for various applications, ranging from rapid mapping to hazard mapping and exposure mapping. For coastal subsidence, in-situ methodologies are widely used when the problem is well-established, but are not an effective tool to determine new areas of concern, as they do not offer the reach and scope of EO. In some cases where subsidence is GPS monitored, there is a potential to use PSI due to the large coverage offered and higher density of points. In these cases, satellite EO may be a complement or replacement to existing in-situ methods.

Operational services require an up-to-date database of reference products for high vulnerability 'hotspots' globally. For flooding, this could be a combination of flood prone areas with land use and population density maps. The rapid flood mapping service is a downstream service to be activated on demand, and therefore the milestone planning for PSI could have as one of its aims the identification of the areas where and when such a service must be operational. The combination of hazard measurements (rapid flood mapping) with vulnerability and exposure data will help to refine the forecasts, and improve the overall portfolio of the downstream services.

Factors that can accelerate the realization of these objectives can be grouped in three categories: technology and services, science, users.

Technology and services

The impact of flooding depends on the inundation level (metres of water above the surface level) and the land use. GMES downstream emergency response services are labelled as 'preparedness', 'response' and 'recovery'. The services will be delivered upon activation requests coming from authorised users within 24 hours if needed. The pre-disaster situation products provide information on the exposure of the area, i.e. information on land use (most likely population density and or economic activity), but also data on hazards such as the current mean (sea-) water level, and storm surges or extreme river discharges that are foreseen. Products also consider what changes in these two parameters are expected in the near future due to climate change and what current surface level must be calculate to determine the expected inundation depth, as well as the changes in this surface level for the future. It is with regard to the latter where PSI shows added value, by enabling accurate estimation of subsidence and its relative impact.

Science

Improvements

Challenge the underlying assumption of linear deformation in PSI processing in order to improve the use of PSI to understand natural processes causing terrain movement. This would also enable differentiation between deep and shallow natural processes.

An increase in PS point density in vegetated areas would be welcomed, particularly for flood defence monitoring. The main focus of flood risk assessment is of course on highly populated urban areas.

Finally, the automation of PSI map construction is necessary to facilitate regular updates of deformation data, for instance after each series of satellite passes. Detecting a change in already measured terrain movement is considered useful.

Operations

Future services are expected to a large extent be based on data acquired by the Sentinel-1 mission, with its open data policy. Planning data acquisition is therefore important. The mission has two main modes of operation: Interferometric Wide Swath (IW) mode (land applications, ship detection, oil spill detection) and Extra Wide Swath (EW) mode (sea-ice detection, oil spill detection). For PSI applications IW data is required. Especially for coastal lowland areas the transition between land and water, and thereby for some applications the transition between IW and EW mode, poses a potential problem for data acquisition. The transition time between the modes is 2.4 seconds, which corresponds to about 20 km. When the transition is made over land, a critical strip of the coastal lowland and especially the water defence structures are missed. Hence, a proper evaluation between the requirements of the land and sea applications is required to address this potential conflict of requirements for Sentinel-1. This is especially relevant between the coastal lowland and the sea-ice community, for instance in the Baltic Sea area and other arctic regions. For oil spill detection the situation is less clear, since both acquisition modes can be applied. A consistent polarization should be applied and it is recognised that the HH polarisation meets the requirement of the geohazard land motion community and the hydrology community.

Both ascending and descending pass images are required, to maximise the ability to detect consistent scattering objects and to create the possibility to separate vertical and horizontal deformation components. Furthermore, the combination of ascending and descending measurements improve the reliability of the result (two measurements are better than one).

Users and practitioners

Within the user community, there is a need for increased dialogue between the different segments, especially between those concerned by science, technology and engineering and the civil protection authorities. In parallel, training activities focussed on transferring knowledge to local and regional users would increase the reach and effectiveness of current activities.

The user community is in fact made up of different categories of users – those focussed on monitoring activities with periodic updates, and those focussed on catastrophic response. This needs to be better recognised in the outreach activities to user communities. There are also varying levels of geohazard awareness within the user community, and large regional differences in the institutional configuration for mitigation and response activities.

Many activities today generate PSI maps which are viewed as raw data by user communities. The relevant information needs to be extracted and new user-oriented product needs to be generated. In fact, the step from PSI map to useful product for end users is significant and it is not always clear on the supply side what information users need. Additional research projects such as Terrafirma and SubCoast are still needed to obtain detailed information and focussed feedback from end users.

TerraSAR-X PSI-derived terrain deformation map of Barcelona Port. Colour coding indicates subsidence rate measured over Jan-Nov 2009, where green indicates stable areas and red 15 cm/year. Processing carried out by Altamira Information. TerraSAR-X data: copyright Astrium Geo Information Services. Background image: Microsoft Bing Maps.

6. Industrial Perspectives on the Satellite-Based Geohazards Services Sector

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6.1 Scope and Context

EO is an important element for improved knowledge of hazards and risks and a basis for more efficient decision making and better mitigation and preparedness for disasters. Satellite EO can support scientists and operational users for a range of applications. To cite two examples of phases of the risk management cycle this is the case for prevention / preparedness, as well as for the immediate response phase in areas affected by natural disasters. In both areas information requirements are maturing with the objective to better link EO-based response with EO-based risk mapping. This chapter provides an overview of the state and capabilities of the EO sector and presents perspectives on how the satellite EO value-added industry can contribute to improved geohazard risk management with primary focus on EO-based risk assessment. It is the result of extensive discussions held during the Santorini Conference in May 2012. While many of the participants in those discussions were European, the scope of the analysis was global.

6.2 Overview of Industry Capability and Capacity

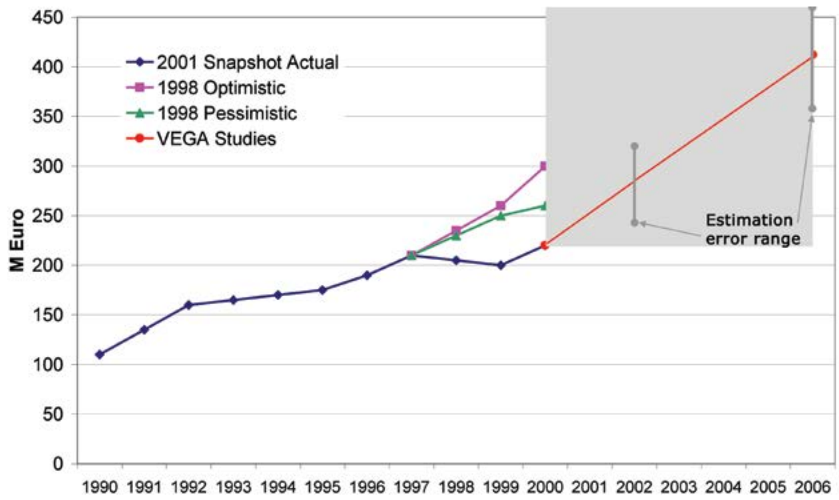
In 2004, in the framework of ESA's Earth Observation Market Development (EOMD) programme element of the Envelope programme (EOEP), VEGA and Booz Allen Hamilton produced a report on the state and health of the EO sector[1]. It was based on the results of a detailed fact-finding exercise begun in 2003, involving Value-Adding Companies (VACs) throughout the ESA member countries. The assessment was performed again for 2006, and is currently being updated for 2012.

These assessments represent the most detailed picture of the Value-Adding sector with information on the financial status within the industry, the products and services on offer, the market sectors and customer types (private, public) being addressed. This information is aimed to give a comprehensive picture of how the EO VACs operate (development, production, marketing, sales, strategy) and the challenges they face. The financial research was primarily targeted at quantifying revenue sources (sales and development), profitability, expenses and costs within the industry.

From the most recent survey, the industry appears to be dynamic, with accelerated growth. The overall employment by the EO VAC industry in Europe and Canada has risen in recent years to an estimated 2,900 employees in 2004, and 3000 employees 2008; these generated average EO-specific revenue per employee of 107,000 Euros at that time. This is in the lower range of technical

1 ESA document ref. EOMD.REP.018

Figure 1. Total Revenues (estimated) of European and Canadian EO service providers (previous studies + surveys conducted for 2003 & 2006. Source VEGA/ BAH).



labour-intensive industries (engineering services and IT were typically in the 100k to 150k range), and below the typical returns in capital intensive industries (fixed telecoms and pharmaceuticals could generate in excess of 200k per employee).

The estimated total annual revenue for EO value adding activities across the complete industry was 285 million Euros in 2002. These revenues excluded primary sales of basic EO imagery (estimated at 25-30 million Euros per year). Looking at the assessment performed for 2006, the estimated total revenues amounted to 412 million Euros (services and data) and included 306 million Euros for services only. Overall, the revenues were growing at 8% compound annual growth rate at that time. First estimates for 2011 indicate that revenues have continued to grow to 800-1.000 million Euros annually (including EO data and software sales).

Overall, this is a services industry with consistent, solid and respectable growth, but note that there have been no ‘killer-apps’ that dramatically increase revenues.

The EO Service Industry in Europe and Canada is an extremely diverse sector. The industry shows the characteristics of mainly small, fragmented, expert consultancies offering niche services. In 2003, governments and other public bodies were the dominant customers with 78% of products marketed towards this sector. The bulk of sales were within Europe, but there was evidence of a wider geographical spread of customers, showing that some VACs have successfully accessed export markets outside Europe (e.g. offshore oil slick monitoring using ERS data).

A large portfolio of EO products and services, which are themselves diverse in terms of what they deliver and how they are produced, supports each of a wide range of land and ocean thematic areas. There are recent developments in atmospheric applications but at the time of the first study no commercial services existed on the market. Figure 2 illustrates the breakdown of total revenues for 2006 (services + data) from two different perspectives; the supply breakdown (i.e. against the products/services on offer) and the demand breakdown (ie against the market sectors which are generating these revenues). In addition, to give an indication of the level of competition, the total number of companies operating in these sectors has been displayed.

From the supply perspective, land use monitoring, Cartographic & topographic mapping, marine and coastal surveillance and agriculture are the primary EO products / services that generate revenue. From the demand perspective, defence and law enforcement is the highest value sector but with regional planning, and science and technology all being active and no single market sector dominating revenues.

Services pertinent to the geo-hazard risk management sector include crisis/ damage mapping, risk/vulnerability mapping and land motion mapping

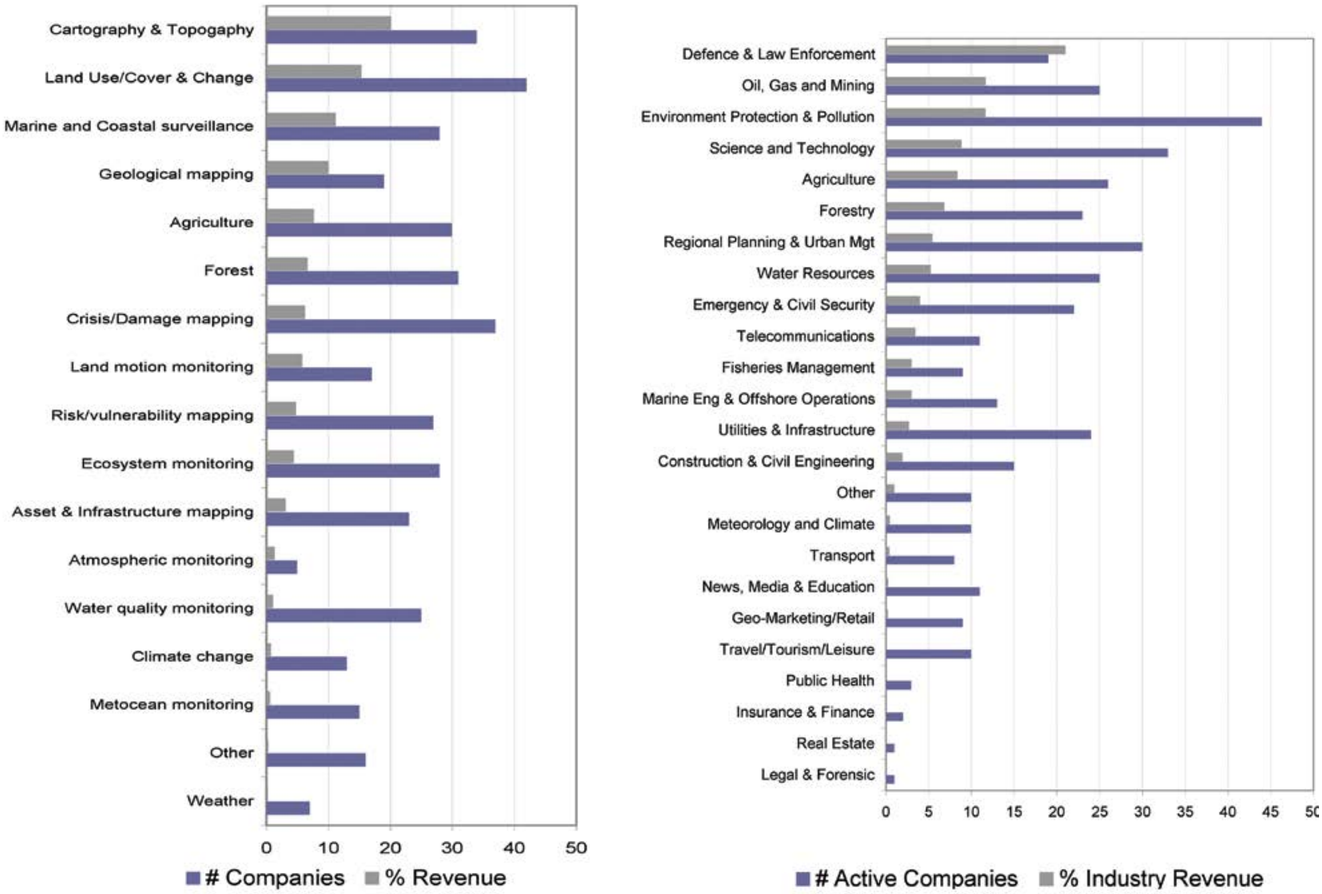


Figure 2. Breakdown of total revenue (services + data) against products/services (left) and market sectors (right) for the services of European and Canadian providers in the survey conducted for 2006.

alongside a wealth of more generic services from the categories cartography/topography/DEM, asset & infrastructure mapping, and land use/land cover monitoring (e.g. urban land use maps), including agricultural monitoring (e.g. crop inventory services, to estimate damage in rural areas after disasters).

In the last 5 years since this data was compiled, a couple of developments have taken place that are worth noting. The first is in the area of land motion mapping (via SAR Interferometry) which has further developed into a mature services sector with a range of specialist providers and a growing level of commercial revenue from several sectors (e.g. mining, oil and gas, civil engineering, utility operators, transport etc). Given the relevance of this unique information service to risk assessment, further information on this sector is provided in Section "The InSAR Value-Added Sector". The second development is that a few specialist EO service providers are being integrated into the businesses and operations of bigger, more diverse geo-information service companies (both in the land and marine domains). This is an indication of the continuing maturity associated with EO services and it will be interesting to see if this trend is maintained in the future.

Overview of Satellite Capabilities

The coming decade will bring an impressive satellite capability that in Europe alone represents a major increase of available resources. This capability covers a broad range of sensor types including medium and high resolution optical data; medium and high resolution microwave radar data (C, L and X band, as well as possible S-band); interferometric SAR data products; infrared and thermal data and meteorological data sets and models.[2] These new missions

2 From CEOS EO Handbook 2012.

Figure 3. Main planned missions and geohazard applications discussed in Santorini. Source ESA.

Seismic	Volcanoes	Landslides	Mining	Coastal Lowlands
ERS-1 & -2 ENVISAT ASAR Sentinel-1 ALOS Radarsat-1 & -2 TerraSAR-X COSMO-SkyMed SAOCOM Ikonos WorldView GeoEye-1	JERS ERS-1 & -2 ENVISAT ASAR ALOS TerraSAR-X COSMO-SkyMed Landsat ASTER	JERS ERS-1 & -2 ENVISAT ASAR Sentinel-1 ALOS Radarsat-1 & -2 TerraSAR-X COSMO-SkyMed Resourcesat-1 SPOT Ikonos Quickbird GeoEye-1	ERS-1 & -2 ENVISAT ASAR Sentinel-1 TerraSAR-X COSMO-SkyMed	ENVISAT ASAR Sentinel-1 Radarsat-1 & -2 MODIS DMC SPOT RapidEye

will be able to support the emerging services to support geohazard risk management developed over the last ten years.

Typically the main modes of operations of an EO mission are i) on-demand acquisitions; this is the case of many VHRO missions generally able to orient the acquisition and providing data with a limited field of view; ii) on-demand acquisitions with a Background Mission complementing ordered acquisition with acquisitions to build strategic datasets; for instance, risk management applications are part of the aims of the strategic datasets of CSA and ESA concerning Radarsat and ERS SAR & Envisat ASAR; iii) systematic observations pre-defined upfront as the main operational planning of the EO mission; this is the concept adopted for Sentinel missions.

The Sentinels offer a depth and breadth of coverage not previously possible with most sensors on a single platform. For applications requiring optical data, Sentinel-2 A and B will provide complete global coverage of land surface at 10m resolution every 6 days offering systematic acquisition or predefined acquisition alongside systematic processing to a predefined product type (per Area Of Interest). Together, the Sentinels and national EO missions will provide extensive coverage, offering wide-field imagery with high temporal revisit and various resolution options. Of key importance is the prospect of long-term (decadal) continuity of data that the Sentinels will bring, which is a pre-requisite for the provision and uptake of operational, sustainable EO-based information services.

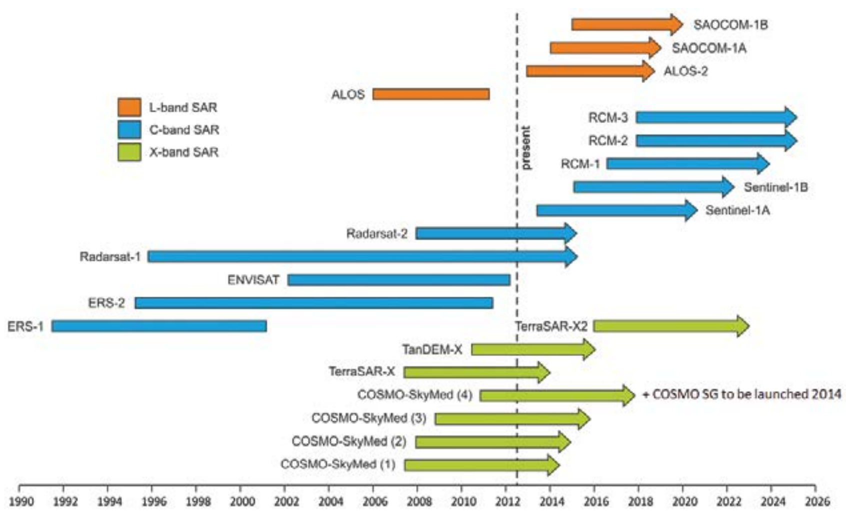
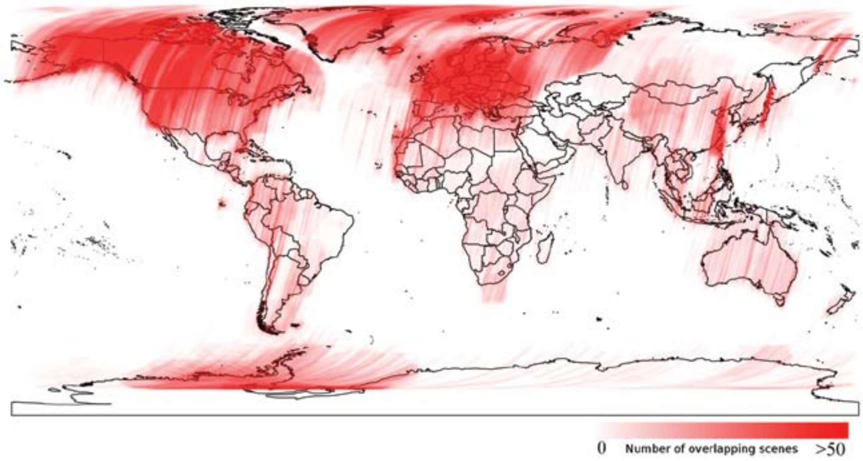
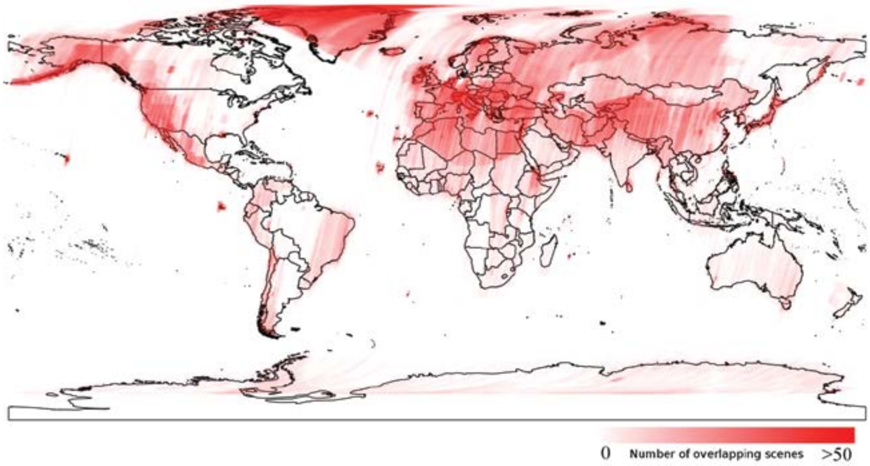


Figure 4. Current and planned SAR missions. S-band NovaSAR planned in 2014. Source: ESA.

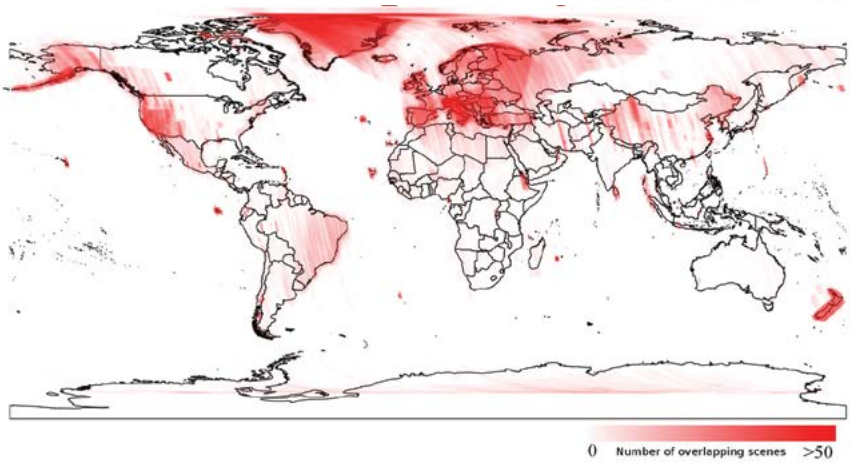
Figure 5. Illustration of the density of data ex archive of main SAR missions.



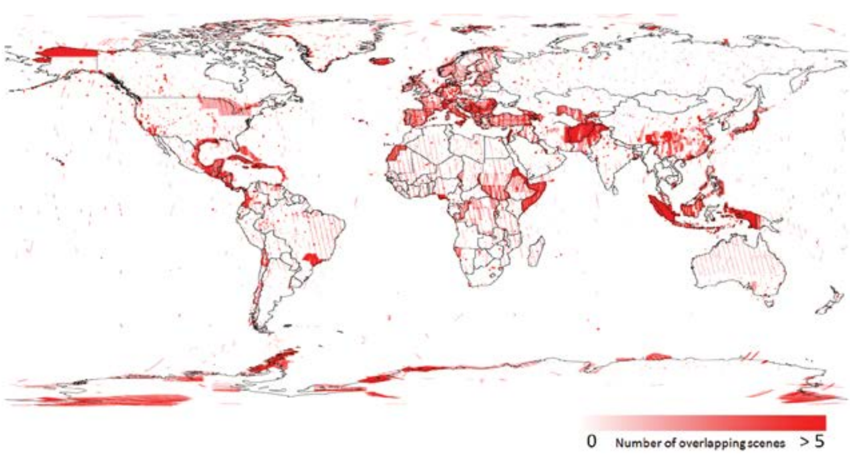
a) ERS-1 & -2 SAR Descending VV



b) ENVISAT ASAR_IM Descending IS2 VV

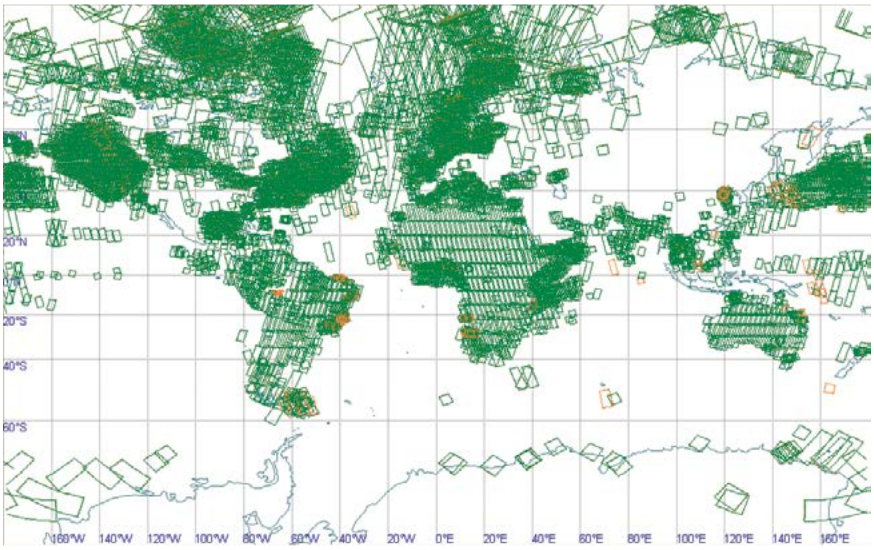


c) ENVISAT ASAR_IM Ascending IS2 VV

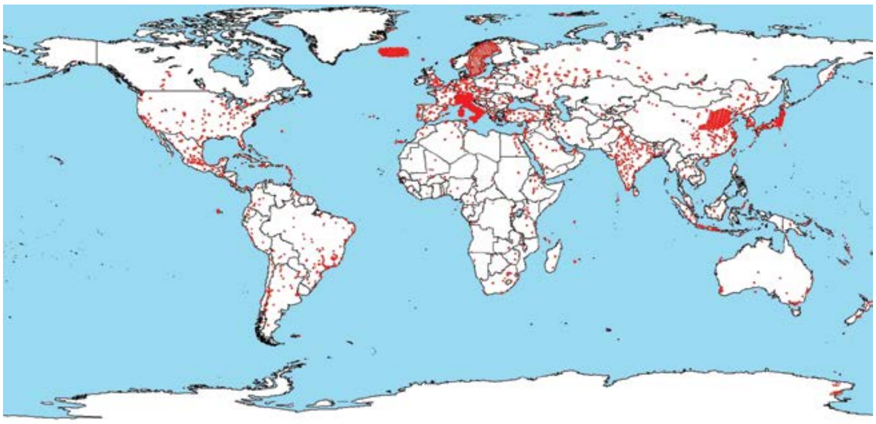


d) TerraSAR-X SAR Stripmap

e) RADARSAT-2 ScanSAR narrow



f) COSMO-SkyMed StripMap HI acquisition mode



The sum of the satellite assets from current and planned SAR missions represents a strong observation capacity, in terms of spatial and temporal resolution and coverage. As an example of the enormous potential of new systems, Sentinel-1 will acquire imagery over an area 200 times the size of Greece in Interferometric Wide Swath mode at high spatial resolution every day, while national missions such as COSMO-Skymed, Radarsat-1/-2/RCM and TerraSAR-X provide complementary coverage with a more limited field of view but at high and very high resolution with high revisit, for instance once every 4 days using COSMO-Skymed. The illustration above represents the current and planned SAR missions pertinent to interferometric applications.

Looking at the heritage of SAR missions, the extent and timespan of the archive already represent a significant and valuable asset. The figures below illustrate the density of archive of the missions operated by ESA, DLR, CSA & MDA and ASI & e-geos.

Data ex-archive are key to enabling terrain deformation analysis in support of geohazard risk assessment; time series over years and even decades are key resources allowing characterisation of ground stability and derivation of hazard risk inventories.

Further to this, data continuity must be ensured alongside the ability to guarantee repeat observations of wide areas over time, as and when needed by users. For interferometric applications, the increased revisit of newly available and planned EO missions carries an added advantage. The time needed to acquire a stack of images for interferometric analysis is greatly reduced. The Sentinel 'stack' of data can be acquired in 17% the time required for similar

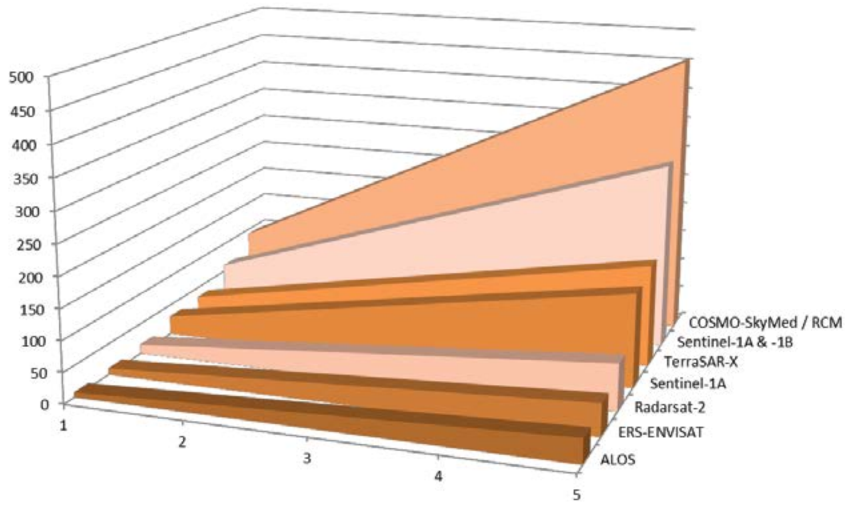


Figure 6. Theoretical volume (number of scenes) acquired over time (years) for a given point of interest based on the temporal sampling of current and planned SAR missions.

ERS analysis, enabling a host of new applications without the pre-existence of well-populated archives.

With planned SAR missions, the supply of data is going to increase greatly and data availability will not be an issue. The challenge to the EO sector and practitioners and users of EO is how to prevent a potential data bottleneck, ensuring new applications are both developed and are ready for operations. Indeed, many of the long-standing complaints of the user community will be answered by the full implementation of the Sentinel system.

If one considers the theoretical volume of data acquired by Sentinel-1 (~465-700 scenes per day i.e. 23-35 million km^2), compared to the volume of production of a project such as, for instance, Terrafirma (~750 scenes/yr equivalent to 43 million km^2), the excess data capacity reaches a factor of approximately 200 to 300 times current levels of exploitation; this is assuming a 17 to 26% duty cycle for the satellite, a parameter that will progressively evolve in the course of the mission. Of course, Terrafirma is only one project, albeit a large one. Other applications, particularly maritime surveillance applications, are expected to be very large data consumers. Based on the assessment of the geographic priorities for terrain deformation inventories to support geohazard risk assessment in Europe, if one considers that the total requirement concerning EO data to meet is three times the volume of data ordered by Terrafirma, the EO capacity exceeds current use by 66 to 100 times. If one arbitrarily considers global needs to be 9 times the Terrafirma level, capacity is still 20-30 times greater. The potential overall need for such data is still greater than available supply, but currently planned systems have been designed for new communities of users which must be prepared to use data as these systems come on line in the near future.

Overall, long-term continuity of acquisitions is assured with observations in a systematic fashion at high revisit and with free and open access to data. Significant effort has been invested to move satellite EO from an R&D technology to operational geo-information services. Looking at value adding, EO services for geohazards are developed and validated, technical specifications, accuracies, limitations, constraints and costs have all been documented. The conditions are ripe for mature exploitation of satellite EO for geohazards, particularly InSAR data.

The InSAR Value-Added Sector

Of specific interest to the geohazard community is the development of services providing precise terrain motion mapping. They are based on terrain motion measurements and can be used to detect and monitor movements in relation

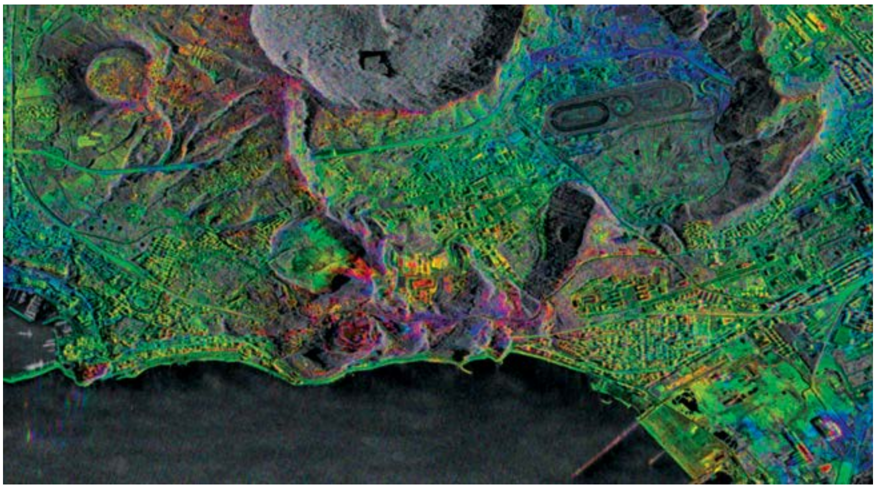


Figure 7. Monitoring the uplift of the Campi Flegrei caldera (Italy) using time series of TerraSAR-X data using High Resolution Spotlight acquisitions over 15.12.2009 – 22.03.2011. Credits: DLR, INGV - Sezione di Napoli "Osservatorio Vesuviano".

InSAR and PSI

L.C. Graham for Goodyear Aerospace Corporation first demonstrated the concept of radar interferometry in 1974 and the first publication concerning space-borne interferometry was published by NASA's Jet Propulsion Laboratory in 1986. At the same the Italian university POLIMI started investigating InSAR alongside with CNES. CNES described the displacement field of the Landers earthquake mapped by D-InSAR which was published in the international weekly journal of science Nature in 1993. POLIMI developed methods which led to a US-registered patent by ESA on 26 July 1994, followed by the registration of the PS Technique patent in 1999. Today there are InSAR specialist providers in many countries including for instance:

Tele-Rilevamento Europa (Italy) - www.treuropa.com
e-Geos (Italy) - www.eurimage.com
Globesar (Norway) - www.globesar.com
Altamira Information (Spain) - www.altamira-information.com
Gamma Remote Sensing (Switzerland) - www.gamma-rs.ch
Fugro NPA Ltd (United Kingdom) - www.fugro-npa.com
Hansje Brinker (The Netherlands) - www.hansjebrinker.com
Astrium Geo-Information Services (Germany) - www.astrium-geo.com
MacDonald, Dettwiler & Associates Ltd. (Canada) - www.gs.mdacorporation.com

to land subsidence, building stability, landslides and seismicity. Space-based monitoring, as opposed to airborne and ground-based surveys, is possible day or night independent of weather conditions; this means that synoptic, 2D views of displacements can be periodically obtained at very low costs and over large areas. In addition, techniques based on space-borne radar imaging instruments provide the capability to map past and on-going displacements in absence of ground networks, making possible the identification and monitoring of previously unknown terrain-movements. Monitoring of terrain motion can be achieved with EO satellite data via the technology that employs a SAR instrument that scans the ground in successive passes and determines the difference in distance between the satellite and stable natural reflectors (i.e. buildings, engineering structures, rocks etc.). It is possible to measure the difference in position of the reflectors by combining two radar images that have been acquired over the observation period. With this method - Differential radar interferometry, or D InSAR - differences of distance as small as a fraction of the radar wavelength can be measured, providing millimetric accuracy in the case of current space borne SARs. The technique has been applied using SAR data from different EO missions including ERS-1 (1991-2000), ERS-2 (1995-2011), JERS (1992-98), Radarsat-1 (1995-), Envisat (2002-), ALOS (2005-2011), Radarsat-2 (2004-) and is applicable to newly available Very High Resolution SAR missions such as TerraSAR-X (2007-) and COSMO-SkyMed (2007-).

Services available today comprise both generic terrain motion products without interpretation of the cause of motion phenomena) and thematic services for which specific interpreted products have been developed. The archive of satellite imagery used as a source for these measurements are all-weather radar data from a range of civilian EO missions; today the availability of the world's largest and most dense EO archives, spanning over almost two decades in the case of the ERS mission, makes SAR data an invaluable and unique input for the creation of historical deformation maps.

Generic terrain motion products are either measurements of historical motion – motion mapping – or continuous measurements based on dedicated acquisition campaigns – motion monitoring. Historical terrain motion products are based on multi-year time series of data ex-archive generally using High Resolution C-band SAR data. Monitoring terrain motion services are based on updated or continuous observations using either High Resolution C-band SAR or Very High Resolution (up to 3-5 metres) C or X-band data.

The most robust method to extract motion measurements from SAR data is the PSI technique that combines geometrically identical time series of radar data; it is InSAR processing with very high accuracy and reliability when applied under certain conditions. The PSI technique typically provides displacement rates in the form of tabular data with location and average annual motion rate (mm/year) of PSI points and a database of time-series providing location and displacement data. Generic terrain motion products based on the PSI technique have the following specifications: i) products based on High Resolution SAR: high line-of-sight motion accuracy - better than a few mm/yr; high spatial resolution (better than 3 m dependent on terrain features); high absolute location accuracy (better than 2 m). Very dense world-wide archive (20+years) and low cost data; ii) products based on Very High Resolution SAR: high line-of-sight motion accuracy - better than a few mm/yr; high spatial resolution (better than 20m); high absolute location accuracy (better than 20m). They are primarily dedicated to monitoring rather than historical analysis, with archives of limited spatial and temporal extent.

Another form of the generic terrain motion product lies with the Corner Reflector InSAR technique that uses artificial point targets i.e. man-made reflectors anchored to or near the structure to be monitored such as a dam, tunnel, flood defence system, etc.; such reflectors and natural reflectors with stable radar response over time (with regard to the radar intensity and phase information) allow interferometric applications over areas that normally suffer from coherence loss and measurement artefacts. Furthermore a Wide-area PSI product is being developed which could input into any of the previous themes; this is another form of the generic terrain motion product based on more automated processing than current supply chains provide to allow coverage of large areas with reduced expert labour during the product manufacture stage.

Thematic services derived from PSI-based terrain motion products are either mapping/monitoring products (observations of the motion and its causes) or modelling products (forecasting of motion phenomena observed) which vary as to the degree of integration with external data.

They are available for a number of application themes:

— Hydro-geology theme (groundwater management, landslides and inactive/abandoned mines); geo-information services for hydro-geological hazards affecting urban areas, mountainous areas and infrastructures. This is multi-hazard focusing on urban and mountainous areas, concerning the ground motion directly or indirectly connected with the hydro-geological systems.

In particular, the expected causes of ground motion should be mainly linked to groundwater over-pumping and recovery from pumping, mining, above ground and underground construction and slope instability. Landslide services comprise landslide inventory product, terrain deformation maps over large areas e.g. entire watershed basins, integrated into a pre-existing landslide inventory created using conventional geo-morphological tools, and the landslide monitoring product, terrain deformation maps across specific landslide events as identified within an inventory product and based on historical and up to date/continuous satellite observations.

— Tectonic theme (mapping of crustal deformation and soil vulnerability); services that present information on seismic hazards and that are oriented by the needs of the end user. The services are customized to allow product integration into geo-information systems. There are two services: the crustal block boundaries service, based on the analysis of terrain motion measurements to investigate surface movements and to discriminate different crustal blocks. It has the aim to help investigate major and local faults, to support analysis of the earthquake cycle and to assess vertical deformation

Validation of PSI based measurements for geohazard risk assessment:

To achieve user acceptance Terrafirma conducted a careful evaluation of accuracy and performance; ERS and Envisat data were used over a rural and an urban test site in the Netherlands: Alkmaar - displaying spatially correlated deformation due to gas extraction; and Amsterdam - with autonomous and spatially uncorrelated ground motion over the 9.5 km long N-S metro line route, under construction at the time of the validation project.

- Inter-comparison results: the estimated standard deviations for each supply chain are 0.40 – 0.53mm/yr for velocities and 1.1 – 4.0mm for time series and 2.14 – 4.71m for geocoding.
- Product validation against ground truth: for Alkmaar, direct velocity validation against the levelling shows RMS error ranges from 1.0 – 1.5 mm/yr for ERS, and 1.3 – 1.8mm/yr for Envisat. Direct time series validation shows RMS error rages from 6.2 – 8.7mm for ERS, and 3.6 – 4.8mm for Envisat; for Amsterdam, the absolute standard deviation of the double difference in velocity ranges from 1.0 to 1.2mm/yr. The average RMS errors of single deformation measurements in the time series range from 4.2 to 5.5mm.

sources in urban areas. And the vulnerability map service, based on very dense spatial data and detailed measurements of surface displacements, used as input to be added to in-situ measurements to compute vulnerability maps. It has the aim to contribute to the investigation of possible causes of surface movements as well, providing the discrimination between primary tectonic displacements and seismically induced movements.

— Coastal lowland subsidence and flood defence theme (height-change mapping and flood defence structure monitoring). The services comprise the basic wide area service, that is the combination of terrain deformation measurements over extended regions prone to flood risk using multiple scenes; the flood plain subsidence mapping service, which is the integration of the basic PSI Wide Area Service with ground truth data, notably levelling data and GPS, and geological data and information in order to develop a service which enables users to interpret subsidence maps within their geodetic reference system of use and to assess mechanisms of subsidence risk; the flood defence monitoring service, a focused application of terrain motion monitoring and evaluation of coastal defences and flood protection systems.

	Service Providers	ESA Member States																			EU	EU org	Int org	Ex EU
		AT	BE	CA	CH	CZ	DE	DK	EL	ES	FI	FR	IE	IT	LU	NL	NO	PT	SE	UK				
CH	Gamma				●	●			●												●			
DE	DLR		●				●																	
EL	HUA								●															
ES	Altamira	●					●	●		●	●	●			●						●			
IT	TRE								●					●		●		●			●			●
NL	Hansje Brinker															●								
UK	FNPA		●					●					●						●	●	●			●

Figure 8. Illustration of the service providers (rows) and the country of their respective users (columns) in the framework of the GSE project Terrafirma. Users are engaged via Service Level Agreements.

ESA originated a range of precursor projects looking at risk assessment to better characterize hazards and risks; these include large scale activities to deliver services to nationally mandated organizations over European territories; for instance this is the case with the Terrafirma and Risk EOS actions of the GSE programme. Today Terrafirma has been able to engage with 50+ Geological Surveys and geoscience centres from Europe and has provided them with PSI-based thematic products via Service Level Agreements; this has helped demonstrate the cost benefit of providing risk assessment based on satellite EO data. The R&D for these services is completed and the services are mature, precise and documented. The Terrafirma project has transferred its services into other EC-funded projects focused on DRM to support the GMES initiative; agreements have been made with the FP7 PanGeo project, where 27 of the total 52 PSI services incorporated have been provided from Terrafirma for direct use with multi-hazard analyses in urban areas. During 2009, ESA initiated a large scale project designed to validate the PSI processing and results of four operational service providers TRE (Italy), Altamira Information (Spain), Gamma Remote Sensing (Switzerland), Fugro-NPA (UK) followed in 2010 by Hansje Brinker (Netherlands). This was conducted in the framework of Terrafirma. It consisted of two main parts to validate both precision and accuracy: a process validation, involving the comparison of disparate PSI processing chains, and a product validation, in which the geo-coded output products were checked for accuracy against ground truth. For the first time, the project placed an accuracy and precision on PSI measurements over typical test sites for geo-hazard risk applications. Its comparison has resulted in tightened quality control in the processing chains, first qualification of service providers, a path for additional providers to qualify, and quality assurance to users.

Figure 8, above (from the Terrafirma project) shows how some of the leading providers of geohazard deformation services are now capable of operating beyond national borders and have established a diverse international client base in various geographic markets , several of which are outside their original region or continent.

Concerning risk management services of GMES, clients generally are public organisations alongside private organisations working in the framework of publicly financed activities. Many of the service providers illustrated above have commercial clients in other countries worldwide.

Rapid Mapping and Asset Mapping

In addition to the hazard mapping services described above, the Satellite EO value-adding sector have developed significant expertise in rapid mapping, asset mapping and new techniques that show promise for future applications.

In the area of emergency response, user requirements typically translate into a requirement for 1:25 000 to 1:100 000 scale reference (background)

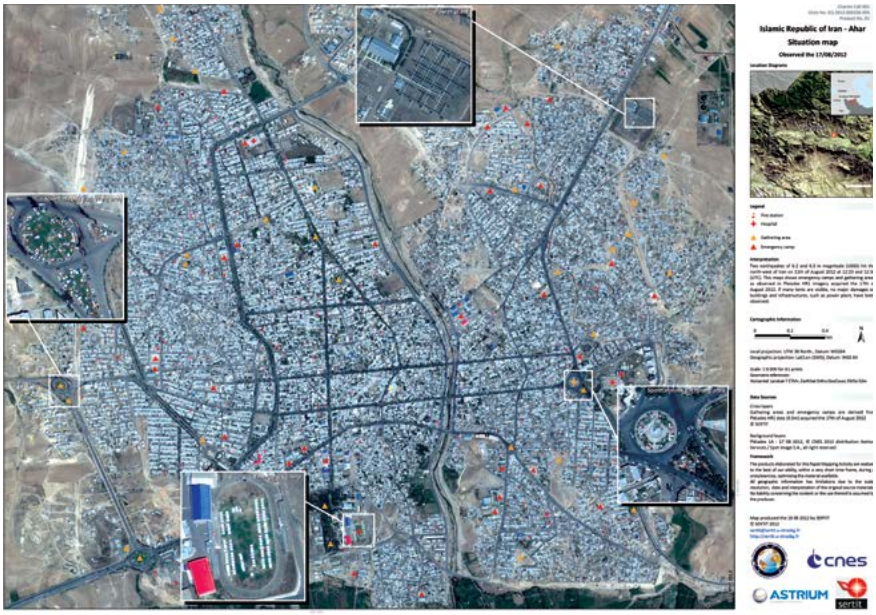


Figure 9. International Charter rapid mapping product in Iran, August 2012. Source: International Charter Space & Major Disasters and GMES SAFER project (EC).

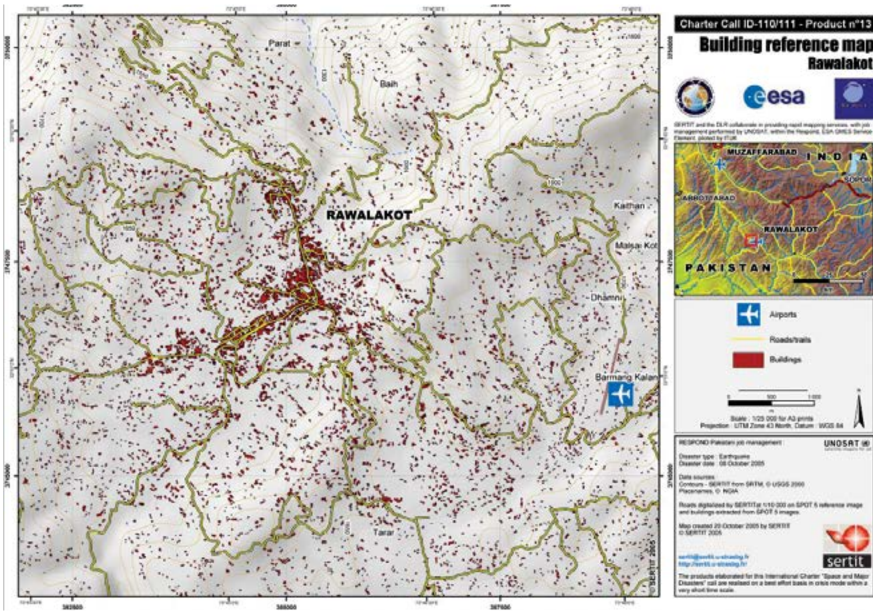


Figure 10. Extract from an asset mapping product by SERTIT in Pakistan, following the 8 October 2005 Asian earthquake, using SRTM DEM for contours and SPOT-5 data for road networks and built-up areas. Source: International Charter Space & Major Disasters and GMES Respond (ESA).

mapping within 6 hours following an request for EO-based emergency response and 1:10 000 to 1:50 000 scale damage mapping available within 24hr and updated on a daily basis. Organisations such as DLR ZKI, UNITAR/UNOSAT, SERTIT, Astrium Geo-Information Services, Fugro NPA, MapAction and e-geos are examples of providers with a capacity to provide crisis mapping and damage assessment services. Maps are generated to show situational awareness in the hours and days following natural disasters, whether for earthquake damage, volcanic eruption or landslides, etc., such as the International Charter Space and Major Disasters product generated above.[3]

Another area of expertise for the satellite EO industry is asset mapping. Asset and exposure mapping refers to the integration of socio-economic statistics into EO-derived geo-information products on land use and cover.[4] The resulting assets map serves as a basis to characterise the asset at risk and

3 http://www.disasterscharter.org/image/journal/article.jpg?img_id=125720&t=1345452997843

4 Definition from SAFER. See http://www.emergencyresponse.eu/gmes/docs_wsw/RUB_138/SAFER-D30500-4.pdf

assess the direct impact and consequences of natural and man-made disasters and hazards on populations and assets. Relevant exposure data can be derived from very high-resolution optical imagery. For both rapid mapping and asset mapping, commercial satellites such as WorldView and Ikonos are ideally suited, as well as the new French system Pleiades.

This topic is not the subject of this paper, but publications concerning satellite EO for exposure or asset mapping are available such as for instance the report Using high resolution satellite data for the identification of urban natural disaster risk (Uwe Deichmann, Daniele Ehrlich & al.) prepared in association with EC/JRC and published by the Global Facility for Disaster Reduction and Recovery (GFDRR).[5]

Innovative new EO services in development

There are also new services being developed today, currently at the research stage, which will likely lead to new services tomorrow. These potential services are based on techniques and methodologies under development in universities and academia. They include, for example, infrared data to track thermal anomalies in volcanoes, or visible and UV data to track volcanic ash in near real-time. Some of the main measurements leading to new service development include:

— *High-temperature thermal anomalies on ground,* dealt with at all spatial and temporal resolutions at high spatial and low-to-moderate temporal resolution;
— *High-temperature thermal anomalies on ground,* dealt with at all spatial and temporal resolutions at very-high to high temporal and moderate-to-low spatial resolution;
— *Volcanic aerosols* (in particular, volcanic ash and sulphur dioxide).

The objective progress, and the State-of-Art of EO techniques to monitor volcanic aerosols, were described in detail in the proceedings of the ESA-EUMETSAT workshop on the 2010 eruption of the Eyjafjallajökull volcano in south Iceland, held in Frascati, Italy, 26-27 May 2010.[6]

Innovative Information Technologies supporting new EO applications

Certain computing and processing innovations will change the way that data are exploited by enabling vastly accelerated applications. One such example is the WAP technique for wide area processing. To support the development of InSAR based risk assessment and to augment the base of seismology experts using terrain deformation data using space-borne SAR, a need was identified to increase the processing capacity and reduce the computational cost of current processing chains. WAP is a new processing chain that may become a standard for the upcoming Sentinel-1 mission. This technique allows for the continuous mapping of wide areas with PSI providing accurate motion measurements over extended areas – typically

5 DEICHMANN, U., EHRLICH, D., SMALL, C. and ZEUG, G.,2011. Using high resolution satellite data for the identification of urban natural disaster risk. European Commission - Joint Research Centre, GFDRR, World Bank. gfdrr.org/gfdrr/ sites/gfdrr.org/files/publication/using_high_resolution_data.pdf.

6 ZEHNER, C., Monitoring volcanic ash from space -ESA-EUMETSAT workshop on the 14 April to 23 May 2010 eruption at the Eyjafjoll volcano, South Iceland; ESA-ESRIN, 26-27 May 2010. ESA STM-280 Jan. 2012

10 times larger than the conventional processing chains used in SAFER and Terrafirma. A technical note to investigate the implications of using the TOPS mode of wide swath Sentinel-1 radar data with WAP interferometric processing has been prepared by DLR. The applicability of WAP to exploit Sentinel-1 data may allow aligning the provision of terrain motion maps to the huge throughput of the sensor. From the viewpoint of tectonic analysis, the WAP approach is consistent with the investigation of local deformations and regional movements originating from active tectonics.

New IT technologies such as cloud computing can change the way EO Ground Segments operate as they are able to adapt to upcoming increasing data volumes, to integrate capacities in a multi-mission setting, to support new sophisticated products (decision-aid) and to deliver on-demand services, through one-stop-shops. The increase of capabilities can stimulate the development of new scientific applications. In particular concerning data as a service, new technologies can help provide innovations such as the creation of data marketplaces. The can also leverage Linked Open Data (LOD) initiatives and support data quality traceability from the start; concerning processors (software) as a service, new IT technologies can help sell usage rights at low cost units (pay-as-you-go), provide entry-level online presence and support usage monitoring from the start.

ESA put forward a Super Sites Exploitation Platform or possibly a Science and Services Exploitation Platform (SSEP), depending on how the concept evolves. It focuses on infrastructure and would combine large-scale Cloud computing assets, all relevant space and in-situ data and input from the global science community. The SSEP is an activity proposed by ESA, CNES, DLR and Italian CNR within the Helix Nebula, the European “Science Cloud” initiative. The SSEP stakeholders are partners of the GSNL initiative: space agencies providing EO satellite data, government organizations and research institutions responsible for the ground-based monitoring of earthquake and volcanic areas (in-situ data), the global solid-Earth scientific community, providers of EO data processing software and value-adding services and industry participating in the “Science Cloud” initiative (and any other industry) interested in exploring business opportunities related to EO data exploitation.

For owners and suppliers of EO data, this initiative will enlarge EO data exploitation (space agencies) or increase EO data sales (commercial distributors), in particular for archived data. For IT companies (computational facilities), the SSEP brings new business and contributes to science development. End users may see the greatest benefits through increased data access at no cost or low cost, increased processing capabilities free or at low cost, access to processing software free or at low cost and the existence of a forum for discussion and sharing, leading to more geohazards science and improved risk management practices. Software providers also see benefits through low investment costs, increased sales and increased visibility for their products.

6.3 Views and Perspectives of Industry

The industrial role in the delivery of satellite geohazards services raises a number of questions, including:

- What has EO delivered to date, and what will it deliver tomorrow?
- What is the vision for EO service provision over the next 5 years?
- How will space assets be fully exploited?
- What new actions need to be taken and what will they produce?
- What is the scope and role for new partners and new players?
- How can sustainability of service provision be achieved?

The role of EO in risk management has evolved significantly over the last ten years. Today, mature services exist including:

- in relation to emergency response: rapid crisis mapping & damage assessment; situation mapping;
- in relation to prevention, preparedness, recovery and reconstruction: detailed damage mapping, hazard mapping/monitoring services to support risk assessment; and
- in relation to all phases of DRM: reference mapping, digital elevation and digital terrain models, land use/land cover mapping, asset mapping/modelling.

These services are available globally but exist at various levels of maturity ranging from research through pre-operations to operations. The main areas covered by geohazards services are seismic hazards, volcanoes, landslides, inactive mines, coastal subsidence and urban geohazards. Precise and accurate land motion information is a key input to understanding these risks. Services in these areas can be useful to, and are already used in, a wide range of different industries including mining, oil and gas, civil engineering, utilities, transport, insurance, nuclear, CO_2 capture and storage and others. They support emerging businesses and grow existing ones. In these areas, Europe is a leader in commercial service provision based on InSAR technology. Other services rely on optical satellites with ultra-violet, visible and infra-red measurements.

The services that exist today are not all at the same level of development. Some tailor to science users, such as the establishment of the GSNL. Others cater to service development and production, such as those targeting public sector users. ESA has financed the development and validated these services, now transferred to EC GMES for production and delivery. The service community has also benefited from 10 years of operations of the International Charter, with 30 to 50 activations per year. In Europe, some 50 Geological Surveys are engaged via Service Level Agreements to exploit terrain motion services to support their risk assessment mandate. Although not all these services will be sustainable, a path in that direction has already been identified. For example, in Italy, the government has purchased InSAR data for the complete territory; in Switzerland, the authorities have formally accepted EO as a method in the regulations for landslide risks.

The primary building blocks for establishing terrain motion based services are: guaranteed data stacks, high temporal sampling, high or very high spatial resolution, dual viewing geometry (ascending/descending) and easy/stable data access. As compared to 10 years ago, the industry has made astonishing progress. There are more data, more “case histories”, more processing chains, more algorithms, more (small) companies. Eventually, this will also bring many more users. The market development stage has not yet been completed. Companies in this sector, however, remain small and private investment is still limited, at least compared to other high-technology sectors.

After many overviews and projects, feedback from users and market assessments, it is possible to make a few statements about what EO applications require to provide sustainable services within a few years. A first key point is the need to move from a perspective of data continuity over the “next 2-3 years” to one covering the next 5 to 10 years. This will be accomplished with the full implementation of the Sentinel system. From a data redundancy standpoint, it is necessary to move from single sensors to constellations. That said, there must be data consistency, i.e. no change in acquisition mode (similar to meteorological satellites). For data reliability, we need efficient and effective space and ground segments (e.g. few missing acquisitions, few conflicts, a short delay from image acquisition to image delivery). Finally, for efficient conflict resolution, well-planned background missions are necessary, which are of course by nature difficult to task. It should be noted that as requirements are drawn up for users, science and business often express different needs.

The future geohazards services will likely be drawn along the same lines as today, with two types of services:

- Precise terrain motion mapping projects (e.g. generation of data for a landslide inventory project at regional scale) that require C or L-band SAR data, medium spatial resolution (10x10 m), monthly repeat cycles of the satellite. Data can be updated every 1-2 years.
- Precise terrain motion monitoring projects (e.g. monitoring of a sliding area threatening a village) that require X or C-band SAR data, high spatial resolution (<3x3 m), weekly repeat cycle of the satellite. Data should be updated as soon as new images become available.

Monitoring projects strongly benefit from the high spatial resolution and the shorter revisiting times of the new X-band sensors, namely, COSMO-Skymed and TerraSAR-X. Inventory projects strongly benefit from the rich, consistent archives of ERS-1/2, Envisat, Radarsat and PALSAR sensors.

During the last decade, processing chains have been improved and algorithms have been made more and more effective. ESA data and ESA projects have supported new algorithm development and opened new markets related to InSAR and SAR applications in general. Typically, SMEs have been the icebreakers and large companies have followed. Algorithms can always be improved, but - nowadays – algorithms and technological limitations do not block market development or the creation of sustainable SAR-based services. However, low quality results can jeopardize the success of the SAR community and hinder market development. One clear lesson learned is that SAR data need to be interpreted and integrated with other data sources to become a "solution to a problem". End users also need time to appreciate the potential of EO data (in particular InSAR) and to trust new data sets. Eventually, users become the best promoters of the technology. Education of end users should be considered one of the top priorities of any future roadmap to foster new EO applications.

6.4 Feedback from users of industrial services

Feedback from the users of industrial services provides an assessment of the relative success achieved to date and the need for further progress. At the Santorini Conference, two user groups were well represented: the insurance sector and the international development sector. Both of these user groups can be considered to be new to the use of EO, and to be at early stages in their EO use. Both sectors show strong long-term promise for uptake of EO data and information products.

Insurance Sector

When the insurance sector uses Earth Observation information, it is always in relation to risk. The process includes risk identification, assessment, quantification and ultimately transfer. During and after a major event, insurers need to identify affected policy holders or claimants, mitigate against further losses (e.g. flood sandbags), mobilise and plan loss adjuster activities and estimate losses, sometimes claiming reinsurance. The key areas where satellite EO products have been successfully applied to insurance applications are:

- Exposure mapping and classification;
- Post event monitoring and damage assessment;
- Environmental monitoring and risk parameterisation;
- Hazard model calibration and validation.

For exposure data, one of the areas where the most information is required, data already comes from a wide variety of sources, often not as complete or as detailed as the industry desires. EO data could fill critical gaps here, by enhancing the incomplete or poor quality exposure information which already exists. Specifically, EO may provide more accurate location (lat/long) and details about building characteristics (e.g. type, age, construction, occupancy or height). Currently available EO can be challenged in providing some of these details, but there is clearly a role even with existing sensors. For some applications, sensors may not be designed to provide the level of detail required. For example, very high resolution and high horizontal and vertical accuracy are needed especially for flood insurance.

EO applications are also increasingly mature in relation to Post Disaster Needs Assessment. Using the Willis Research Network, the usability of remote sensing techniques for damage assessment following an earthquake was investigated. Traditionally, damage surveys have been carried out by sending a team of specialists into the field. The improvement of the spatial resolution of commercial satellites capable of acquiring images at a sub-metre resolution is opening up the possibility for using these techniques instead of, or in support of, ground teams. The application of these new techniques would assist in speeding up the process of damage assessment post event monitoring. Interpretation of course remains a challenge. A very high resolution optical satellite image can clearly indicate total destruction of the structure to anyone in the world who views the image. Examples of more challenging tasks, requiring expertise or high-quality images, are identifying partially-collapsed structures or interpreting SAR imagery.

There are however significant barriers to the adoption of EO by the sector. One of the key barriers to address is cost, especially cumulative costs given the coverage extent needed. The cost of licensing sufficient data for an entire country or region at a high resolution is often prohibitive. Cost/benefit is always a consideration. It may be possible to pool purchasing, or perhaps work on a transactional pricing model. Availability is another issue. Consistent national data sets are not always available for every territory covered by a global insurance programme. Another barrier to overcome is convincing senior decision makers of the value of the purchase prior to purchase. To assist in this respect, low cost or free data for pilot studies would be invaluable. There are also licence terms and conditions to overcome, especially for onward distribution of derived products or data sharing between partners, but this can probably be dealt with on a negotiated basis with providers. In fact, the main barrier is the lack of knowledge with regard to what data is available and where to access it. From a user perspective, the EO sector presents a potentially overwhelming choice of suppliers. It is difficult to know who to approach and what is being offered.

Things have been changing quickly. There is a growing utility of satellite data for risk management. There is now a long enough record of satellite data to work with (i.e. over 20 years). The resolution is reaching a level that allows identification of sub-metre details. Applications such as Google Earth have delivered image-based data to desktops across the industry, making their use commonplace. With the release of the TanDEM-X DEM, high resolution satellite EO-based DEMs will become widely available in the industry. This enables new applications. In the future, the insurance sector foresees several applications of interest, including some specifically mentioned at the Santorini Conference: satellite rainfall estimation for index based agricultural insurance schemes (replacing rain gauge measurements); post event damage assessment to reduce loss assessments costs (image analysis replacing 'on the ground' surveyors); communication and visualisation via geo browsers and geospatial technologies; identification of more detailed characteristics of insured properties (e.g. building footprints, roof types, building heights, tree heights and tree distance to properties); mapping non modelled risks (e.g. global flood risk); real time event monitoring; terrorism and conflagration risk assessment in densely populated areas; and identification of fraudulent claims.

For the insurance sector, EO-based applications, products and services remain a pilot effort, aimed at determining to what extent the tools and data available today can meet the needs of the community. It is clear however that critical data currently obtained (or in some cases not obtained) from other sources could be supplied through EO services. Clear steps are necessary to move the insurance sector from a trial user to a full-fledged end user of EO data on an operational basis. One of the hesitations of the sector seems to be the guaranteed availability of data in the hours and days following events. Key issues identified to improve uptake were:

— Simplification of sources of supply for processed data/information;
— Speed of access to the information;
— Entry cost;
— Appropriate license terms;
— International Development Sector.

International Development Sector

For the international development sector, represented at the Santorini Conference by the World Bank Global Facility for Disaster Reduction and Recovery (GFDRR), EO is being used on a trial basis in several areas. At the World Bank, a dozen projects have been undertaken in close collaboration with ESA. It is unclear to what extent these trial projects will be successful, but it is already clear that there is significant interest within the international development community to continue to explore new applications of data for risk reduction. The key potential areas for EO application are for hazards, exposure vulnerability and post-disaster needs assessment. At GFDRR, EO is principally being examined for its potential application in Post Disaster Needs Assessment.

Post-disaster needs assessment validation is currently undertaken using remotely sensed data. The remotely sensed data are used to independently validate the government-led ground survey data. Validation is undertaken to confirm the order of magnitude for the government led damage estimate. Remote sensing validation is generally done by in-country space agencies or mapping agencies, with support from GFDRR. It has a trilateral agreement called CoSA (Collaborative Spatial Assessment) between the Joint Research Centre (JRC), UNOSAT and GFDRR for remote sensing validation. To date, CoSA has been activated for the Haiti earthquake (2010), the Pakistan flood (2010), the Chile earthquake (2010), and the Lesotho flood (2011). Key sectors that remote sensing validation is used for include housing, agriculture, transportation, irrigation and environment. In the future, Post Disaster Needs Assessment may use tools such as InSAR to determine the relationship between surface deformation and damage distribution, to perform rapid (1 day) damage assessments, to track surface displacement, ground faults and validate surface slip models or to make ground shaking predictions.

There is a 2-year long collaboration between ESA and the World Bank that focuses on mainstreaming EO applications to support the international development community in a range of global risk management activities. This is part of an overall ESA initiative concerning multi-lateral development banks such as the European Investment Bank, the African Development Bank, the European Bank for Reconstruction and Development, and others. This initiative aims to demonstrate the potential of EO services to support the operations within international financial institutions concerned by development.

Satellite EO is also increasingly included in risk mitigation and climate change adaptation programs in a broad range of situations such as for instance coastal lowland subsidence and flood defence. To further raise awareness and demonstrate the capabilities of the EO sector to provide innovative services, ESA has set up five urban risk assessment pilot studies implemented in collaboration with the World Bank. They include urban mapping and thematic mapping to support risk assessment for hazards such as flooding, terrain subsidence and landslides in the agglomerations of Tunis, Alexandria, Jakarta, Yogyakarta, Rio de Janeiro, Ho Chi Minh City, and Guyana's capital city Georgetown.

The international development community recognises that EO, combined with other data sources, can be a powerful tool, with important opportunities to support risk management. While some EO data helps derive hazard information, the main attention within the development community has focused on the ability of EO to provide exposure information relating to assets and vulnerability. There are entire EO-based applications that, for the development community, remain uncovered or under utilised. Flood extent monitoring was specifically mentioned as a mature area where applications are not regularly used. Upcoming missions should open new areas for investigation, given the large amount of available data and open data policies of Sentinel-1 and 2 in particular. The issues of cost, continuity and sustainability must be carefully considered when considering applications in developing countries. These remain hurdles, but once addressed, EO may be a much needed catalyst in work on improving data preparedness. Improved data preparedness will result in accelerated risk assessment, which will assist in targeting in-country capacity development.

6.5 Future Vision for Industrial Services

There is already in orbit, and planned in the next few years, a substantial space capability including C, X and L-band SARs, optical very high resolution satellites and high resolution satellites. This collective capability offers high revisit and wide area synoptic coverage that has not been previously available. There is some concern today that these unprecedented resources will not be fully exploited without coordinated and consolidated planning. This includes harmonising national EO mission operations to ensure that the combined space capability is maximised for risk a management (e.g. background mission planning), developing user capacity, and supporting value-adding industry in capitalising on the opportunities that will emerge.

Today, services already exist that serve operational users and have successfully demonstrated the cost-benefit of providing risk assessment based on satellite EO data. The R&D for these services is completed and the services are mature, with accuracies, performances, limitations and costs all documented. Communicating the benefits of these services within the working environment of operational users remains a challenge. As science applications continue to progress, established services such as precision terrain motion, asset and exposure mapping and rapid damage mapping are soon to be followed by emerging services requested by geohazard risk management users such as thermal anomaly detection, or atmospheric constituents monitoring. However, EO alone is rarely the complete information solution required by users. There is a continuing need for EO information to be further integrated with other data sources and models into a non-satellite centric vision of service delivery, and this will require the involvement of new players. This approach may require the value-added industry to form new partnerships with larger geo-information providers incorporating the EO offering and bringing it to end users (a trend that is already taking place in the sector).

Today, EO Service providers must specifically identify the authorities that manage the thematic issues in their user communities, and convince them on a case-by-case basis of the merits of adopting a satellite EO-based approach. This

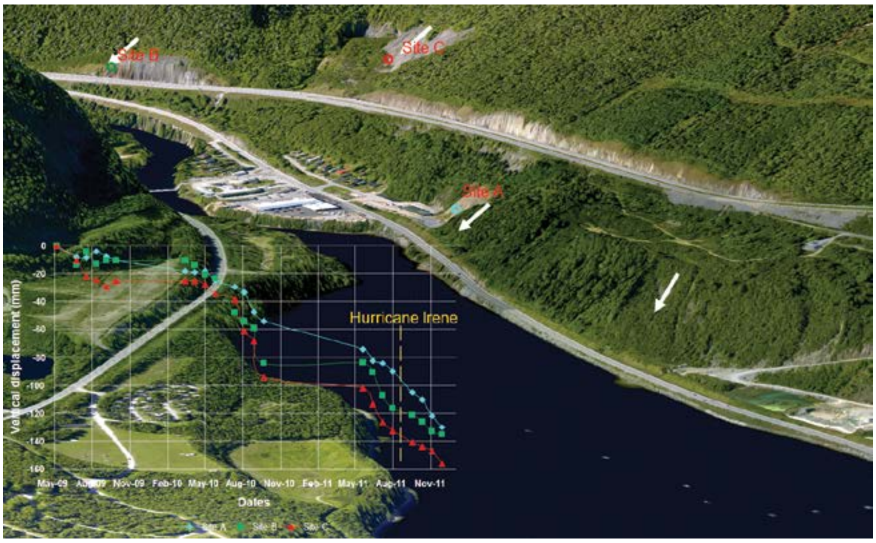
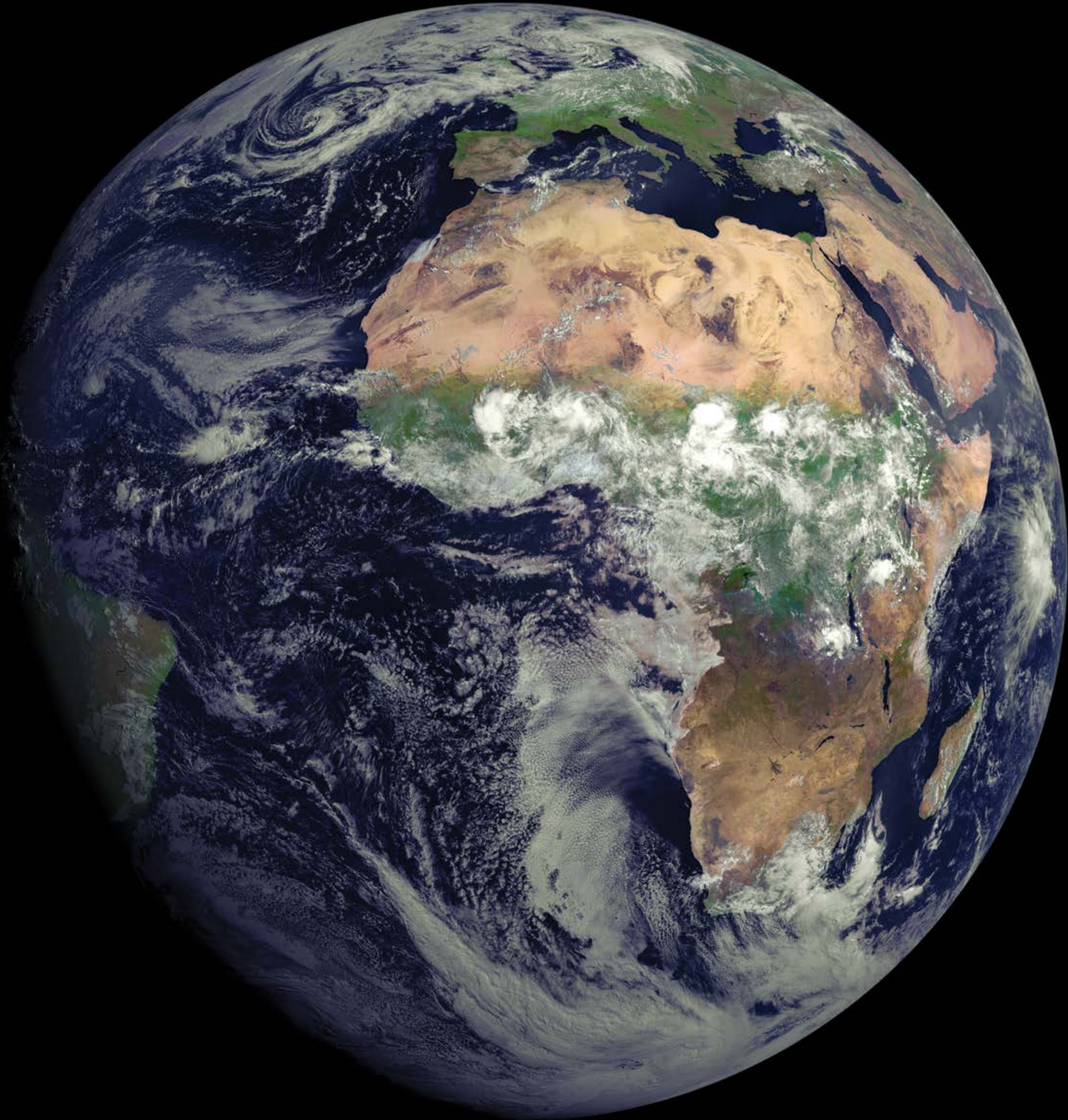


Figure 11. Landslide monitoring in the area of highway routes, Corner Brook, Newfoundland, Canada following the impact of Hurricane Irene. INSAR measurements using RADARSAT-2. Credits: Singhroy and Li (CCRS 2011), EO data: MacDONALD, DETTWILER AND ASSOCIATES LTD. (2012), Canadian Space Agency, 2012 / Agence spatiale canadienne, 2012.

was the case in Italy for geohazards, with the result that the entire country is regularly mapped using various sensors. Most of the large national government users of EO information services are currently working in the context of pilots that aim to validate a much broader application of the resources. However, developing this potential is a significant level of effort and risk for the EO service industry to undertake by itself. Further investment may be required for new user communities and to support emerging partnerships. Ensuring these technology developments take place and encouraging business to pursue a collaborative approach with national authorities are critical steps to ensuring success over the coming years.

Beyond these existing user communities, there are new communities with evident, long-term needs and requirements from large industrial users such as the insurance sector, or international organisations such as those active in the development sector. Global development actors (such as the multi-national development banks) could and should play a critical role as catalysts to bring these technologies to the developing world by working within user communities to develop capacity and raise awareness. Dedicated support to the EO service industry is required to establish sustainable take-up of information services within these emerging user communities.

Sustainable services can be created if VACs have a reliable and robust space segment, an effective and efficient ground segment, and easily accessible EO data at reasonable cost. This should be the main role of space agencies. VACs are like engines. They need fuel (i.e. satellite data) to work. VACs, on the other hand, should provide end users with high quality products, integrated when necessary with other data sources. Furthermore, users have to have the capacity to understand and use the EO information services that are produced. VACs and space agencies should continue investing in building this capacity with future clients and users. VACs, research institutes and space agencies can make others aware that some EO products and services are no longer R&D exercises but are standard, fully validated services available now from different providers within a competitive service industry. In the end, the largest hurdle in progressing operational take-up of EO information services in remains the lack of awareness of what exists, what has been accomplished and what can still be done.



MSG-3 first image of Earth, acquired on 7 August 2012 by
its Spinning Enhanced Visible and Infrared Imager (SEVIRI).
Credits: Eumetsat

7. Global perspectives concerning satellite EO and geohazard risk management: GEO and other international aspects.

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7.1 Overview

Over the past decade, considerable international attention has been paid to the issue of geohazards and the application of satellite EO to addressing the management of geohazard risk. This chapter aims to provide an overview of the initiatives that have gone forward in relation to each of the themes considered at the Santorini Conference: seismic hazards, volcanoes, landslides, inactive mine hazards and coastal subsidence and flood defence. The work of the past decade received a strong impetus from the 3rd International Geohazards workshop of GEO, held in November 2007 in Frascati, Italy, which recommended "to stimulate an international effort to monitor and study selected reference sites by establishing open access to relevant datasets according to GEO principles to foster the collaboration between all various partners and end-users". That led to the creation of the GSNL, described below, which remain the premier contribution of satellite EO to geohazard research. The publication of this volume on the Santorini Conference also marks a milestone in the international effort to apply satellite EO to geohazards, by defining clear objectives for each of the geohazard communities listed above, and charting out a vision for the implementation of strategies to achieve these objectives.

Several CEOS space agencies have been or are involved in projects and initiatives related to DRM either as CEOS or outside the CEOS framework (e.g. International Charter or Sentinel Asia).

From 1997 to 2002, the CEOS Disaster Management Support Group (DMSG), an ad hoc working group, was active holding numerous meetings and workshops and issuing reports. The goal of the DMSG was to support natural and technological disaster management on a worldwide basis by fostering improved utilization of existing and planned EO satellite data. The DMSG focused on developing and refining recommendations for the application of satellite data to selected hazard areas. At the last CEOS Plenary Meeting in Lucca, Italy, CEOS principals discussed the need to examine activities of member Agencies across the disaster cycle and ensure a balanced effort across the cycle and amongst the agencies. ESA proposed that an ad hoc team be formed to look at a more effective CEOS contribution to Disaster Risk Management, by assessing gaps, overlaps and consideration of the balance of effort. This could be achieved by a focussed discussion of those agencies that are investing resources in the current disaster-related activities – reporting to a future CEOS meeting on the recommended way forward. The CEOS DRM ad hoc team was subsequently formed early in 2012, and met in Frascati in February and in Tokyo in April, as well as several times by teleconference. The Team currently includes representatives from the following agencies: ASI, CSA, CNES, DLR, ESA, EUMETSAT, JAXA, NASA, NOAA and USGS, as well as from the CEOS CEO and Systems Engineering Office. The Team was mandated to report back to the Plenary in October 2012.

The IGOS Geohazards theme was a combined initiative of UNESCO and two other IGOS members, CEOS and the International Council for Science

(ICSU). The IGOS Geohazards theme intended to respond to the scientific and operational information needs for the prediction and monitoring of geophysical hazards, namely earthquakes, tsunamis, volcanoes and ground instabilities. The IGOS Geohazards Theme Report, published by ESA in 2004, set out a long-term (10-years plus) strategy for the better observation and monitoring of geohazards. One of the main strands was to build a stronger global geohazard community and this has been taken forward for volcanoes for example by increased cooperation over that decade amongst the small volcano observatory community. The IGOS Partnership was an excellent forum for designing strategy but it lacked political stakeholders and so implementation was on a best-endeavours basis amongst the partners. This is one of the reasons behind the formal establishment in 2005 of GEO, an intergovernmental organisation with the objective of building GEOSS. Once GEO was established, with almost 100 Member States, and the IGOS Partners had joined it as Participating Organisations, the IGOS Themes were then integrated into its 10 year Work Plan during 2009. GEO became responsible for implementing IGOS through its Disasters Societal Benefit Area. This has a series of Tasks or Sub-Tasks focused on different elements of the disaster management cycle.

In 2007, ESA sponsored an International Geohazards Week that led to the Frascati Declaration. One of the most significant outcomes was a recommendation to establish a number of geohazard Supersites, now the GSNL. These 'super sites' include permanent sites, event sites and natural laboratories. Collectively, they provide a capacity for scientific investigation to provide access to space-borne and in-situ geophysical data of selected sites prone to volcanic, earthquake, or other geohazards. In the European context, Icelandic and Italian volcano supersites were financed by the EC's Framework Programme in 2012, as well as a supersite over the NAFZ to study seismic processes in Turkey.

The Supersites' stakeholders are Agencies responsible for ground based monitoring, whereas data suppliers and users are virtually connected by an e-infrastructure which gives open access to relevant data sets (archive and fresh). The data are provided in the spirit of GEO ensuring that easy access to earth science data will promote their use and advance scientific research, ultimately leading to reduced loss of life from natural hazards.

7.2 Seismic Hazards

Considerable effort has been put into global seismic hazards over the past 50 years, ranging from strategies for mitigation and observation to sharing experiences from different continents. Following the International Strategy and then Decade for Disaster Reduction in the 1990s and early 2000s, the strategic aspect was picked up first by CEOS and then brought into sharper focus when they joined with UN agencies and science programmes under ICSU. This was dedicated to setting IGOS, and the Geohazards Theme had earthquakes as one of four main pillars. The IGOS Geohazards Theme Report set out a long-term (10-years plus) strategy for better observation and monitoring of earthquakes. One of the main strands was to build a stronger global geohazard community and this has been taken forward for earthquakes by increased cooperation with and amongst the existing global seismic community, principally through the Global Seismic Network, GSN. The Global Earthquake Model (GEM) Foundation is another international collaborative venture. It is a public-private partnership that drives a collaborative effort aimed at developing and deploying tools and resources for earthquake risk assessment worldwide. Hundreds of organisations and individual experts, professionals and practitioners are working together on uniform global databases, methodologies, tools and open-source software. The GEM currently uses satellite data for exposure information, and might consider using EO as a tool to map hazards as well.

Within GEO, the community building process has continued through establishment of the GHCP. This community of practice has set out a Roadmap for the Disasters SBA based on the four recognised stages of the disaster response cycle; preparedness, early warning, response and recovery. This roadmap helped to shape the new GEO Work Plan for 2012-15 and the Disasters Task in that plan is now taking forward its implementation. This provides a potential framework for defining new activities on seismic hazards in the global context. There are also activities related to GMES that could fit within this framework. GMES funds several projects, in particular the GMES Emergency Management Service, which is currently entering the Initial Operations phase, and might benefit from closer ties to the GEO Work Plan.

The Community was recently brought together again by the GHCP, with assistance from the European Science Foundation and the COST Office, for a High-Level Conference on Extreme Geohazards. There was a follow-up meeting during EGU in April 2012. The scientific focus of these events was then complemented by the more applied focus of the Santorini Conference. A combination of excellent science, a strong observing system, applied projects approaching their sustainable, operational phase and major industrial players will be critical to plan a more consolidated approach to dealing with seismic hazards, globally, and the GHCP aims to join efforts up across the community to achieve this goal.

7.3 Volcanic Hazards

Space-based observing systems play an important role in building GEOSS, together with the surface-based observing networks. Indeed, the EO satellite missions have largely proved their reliability and capacity to observe phenomena directly or indirectly related to volcanic processes with suited spatial and temporal accuracy, often complementary to surface-based systems. Given GEOSS objectives, upcoming EO missions have to be as integrated as possible with the observing systems, based on the volcano observatories, from both operative (e.g. revisit times) and technical (e.g. used bands of the electromagnetic spectrum) points of view.

Considerable effort has been put into the global aspects of volcanic hazards over the past decade, ranging from the setting of strategies for mitigation and observation to the sharing of experiences from different continents. One of the four pillars of the IGOS Geohazards Theme was volcanic monitoring. Within GEO, the community building process continued through the establishment of the GHCP which, like for seismic hazards, was influential in setting out a Roadmap for the Disasters SBA based on the four recognised stages of the disaster response cycle; preparedness, early warning, response and recovery. There are also activities related to the ESA and EC initiative on GMES that could fit within this framework, including those in the ESA GlobVolcano project, the GMES emergency response core service, the GMES Downstream FP7 project EVOSS and within the GEM, which has an evolving offshoot activity related to volcanic hazards.

The combination of excellent science, a strong observing system, applied projects approaching their sustainable, operational phase and major industrial players will be critical to plan a more consolidated approach to dealing with volcanic hazards globally.

7.4 Landslide Hazards

The IGOS Geohazards Theme Report set out a long-term strategy for the better observation and monitoring of landslides. One of the main strands was to build a stronger global geohazard community and this has been taken forward for landslides by the International Consortium on Landslides, principally through the World Landslide Forum. The IGOS Partnership was an excellent forum for designing strategy. With the renwed impetus the community found through GEO, the strategy has been integrated with the broader Disasters Roadmap and is being implemented through the Disasters SBA. The GEO Work Plan has a series of Tasks or Sub-Tasks focused on different elements of the disaster response cycle, though not specifically on landslides but rather for multiple hazards. There are also activities related to the ESA and EC initiative on GMES that could fit within this framework, including those in the GMES emergency response core service and within the GMES Downstream FP7 project DORIS.

7.5 Inactive Mine Hazards

Initially, little effort was put into the global aspects of mining hazards in comparison to other geohazards. They were considered a local issue and were not part of the International Strategy and then Decade for Disaster Reduction in the 1990s and early 2000s. This changed when CEOS joined with the UN agencies and the science programmes under the International Council for Science to form the IGOS Partnership. The IGOS Geohazards Theme specifically addressed subsidence as one of its main pillars. This included subsidence that related to mining and resource extraction. The IGOS Geohazards community that had developed the subsidence theme worked within the GEO community and as a result, in its VIII Plenary, in November 2011, GEO adopted a new Work Plan which included minerals as specific theme for the first time under a new Energy and Geo-resources Management Task, EN-01. This Task aims to develop tools and information for the resource assessment, monitoring and forecasting of geological resources (including mineral and fossil resources, raw material and groundwater). In addition, the GEO 2012-2015 Work Plan includes a Task on Impact Assessment of Human Activities, SB-05, which aims to develop an impact monitoring system for geo-resource exploration and exploitation.

An InSAR-based mapping and monitoring service may be offered into this GEO activity as a significant new contribution and the techniques developed in a European context thereby extended to global application. An initial approach may include contributing data to GEOSS. The European Project EO-MINERS, which was funded under FP7 to implement these GEO tasks, is a precursor.

Within GEO, the Roadmap and the Work Plan, which now has specific SBA Tasks related to mining, provide a potential framework for defining new activities on mining hazards that could be supported and delivered by Terrafirma partners and ESA. Minerals of growing importance within the EC agenda, and the Raw Materials Initiative (RMI) is starting to explore ways in which GMES could provide the observations necessary for the minerals-related issues.

7.6 Coastal Subsidence

IGOS included a specific theme looking at issues in the coastal zone. One of the main strands was to build stronger global geohazards and coastal zone communities and initially this was taken forward through cooperation between these two IGOS Themes, which shared a co-Chair. GEO has been responsible for implementing the geohazard and coastal zone strategies through its Disasters and Water SBAs and also through activities related to the Oceans. The former has a series of Tasks or Sub-Tasks focused on different elements of the disaster response cycle. Most are not specifically focused on the coastal zone but rather on multiple hazards. However, one of the main relevant Tasks relates to the establishment and improvement of early warning systems for tsunamis. This work is related to coastal subsidence, though not directly. Within GEO, the community building process has continued through the establishment of Communities of Practice for both Geohazards and the Coastal Zone. The GEO Work Plan now has specific SBA Tasks related to the Oceans provide a potential framework for defining new activities on coastal hazards. There are also activities related to the ESA and EC initiative on GMES that could fit in this framework, including those on flooding in the GMES emergency response core service, the GMES core service for the Oceans and especially the GMES Downstream FP7 project SubCoast.

It is clear from the overview of the five thematic areas above that a significant amount of progress has been accomplished over the last few years in bringing the GHCP together and establishing objectives and agendas for each thematic area that builds on the collective strength of the community while recognizing the specificities of each area. The impressive work achieved in the Santorini Community Papers, now reflected in the thematic chapters of this report, would not have been possible without the efforts and success of the past decade.

A Listing of Research and Development Issues for Satellite Earth Observation Related to Geohazards

Lead authors: Michele Crosetto and María Cuevas, Institute of Geomatics, Spain

1. Introduction

Mitigating the risk of natural disasters can be supported by understanding our environment and the fundamental mechanisms that drive change within it. The field of EO is an important element, which can potentially contribute to this challenge by assisting different components of the risk management cycle, including hazard identification, quantification and monitoring, preparedness, emergency response, etc. (Giannopapa, 2011; BRGM, 2007; Respond, 2011; Deichmann et al., 2011).

This listing of R&D issues aims to provide a concise review of the satellite EO R&D activities related to geohazards. The R&D activities are treated at a general level, identifying main R&D fields, describing the EO techniques used in each field, highlighting main achievements or limitations, and indicating the areas where substantial progress is expected in the future. This paper complements other thematic chapters addressed in this report:

— Seismic hazards;
— Volcanoes;
— Landslides;
— Inactive Mines; and
— Coastal lowland subsidence & flood defence.

These themes were chosen by the different geohazard risk communities represented at the Santorini Conference. The chapters consider the state-of-the-art concerning applications and services based on EO data, examine how to consolidate these applications and services, and address key issues like handling large volumes of imagery from new satellite EO missions, the need for standardized and widely-accepted methodologies and the integration of satellite EO data into everyday practices for risk management.

This annex complements the thematic community papers by exclusively addressing the main fields of R&D associated with four targeted geohazard themes. This topic basically includes three main pillars:

— satellite EO, which is currently based on a wide range of satellite platforms and sensors;
— EO-data added-value, which includes data processing and analysis procedures needed to transform the raw EO data into products;
— the risk management sector, which exploits or can potentially make use of the above products in different phases of the risk management cycle.

This annex mainly focuses on the second pillar and, in particular, on the R&D activities aimed at exploiting EO data to derive products related to geohazards. All types of EO data and techniques are virtually addressed, even though, as it is explained later, special emphasis is given to the interferometric SAR techniques.

By contrast, the document does not address the first pillar, satellite EO, neither describes the available EO systems, nor considers the specification of technical requirements for new EO missions. Likewise, it does not explicitly treat the third pillar, risk management and how it can take advantage of EO-based products, which are already discussed in the thematic chapters.

Section 2 provides a concise overview of the main satellite EO techniques, while sub-section 2.1 describes the main characteristics of PSI, a technique which plays a special role in each of the abovementioned themes. Sections 3 to 6 are devoted to four geohazard themes, namely seismic hazard, volcanoes, coastal lowland subsidence and flood defence, and landslides.

2. Satellite EO techniques

There are several ways of classifying satellite EO techniques. This section briefly recalls the available techniques that are relevant to the geohazard themes addressed in this paper, proposing a classification based on five main groups of sensors.

- Optical sensors working in the visible bands. They usually acquire panchromatic and colour imagery. The EO techniques based on this type of sensors are, by far, the more consolidated ones, mainly due to the remarkable heritage of more than one century of R&D in airborne photogrammetry and to the major step forward in image quality obtained by VHR optical sensors since the late 1990s. Some of the most significant products based on optical sensors are widely used in geohazard risk management. Some of the main application fields of optical sensors are briefly outlined below.
  - Cartographic production is an important and mature discipline, which shares most of its tools and procedures with the cartographic production based on photogrammetric data. A large part of the production process requires manual operators. Thus, a great deal of the R&D effort is focused on increasing the degree of automation of the whole cartographic process, e.g. automatic cartographic feature extraction, using image analysis and computer vision techniques.
  - DEM and ortho-image generation are also mature disciplines, which are largely based on fully automated procedures. The main reason is that they basically exploit the geometric properties of optical imagery, while cartographic production involves image interpretation.
  - Thematic mapping by image classification includes a wide range of techniques to generate thematic maps usually exploiting optical and infrared imagery. Ongoing R&D in this field is particularly aimed at improving the quality and reliability of image classification.
  - Finally, there is an endless list of applications that exploit optical imagery using different types of techniques, including the oldest and probably still the most widely used, i.e. photo interpretation.
- Infrared (IR) sensors are sensible to electromagnetic radiation with a wavelength longer than that of visible light. They include near IR (NIR), short-wave IR (SWIR), mid-wave IR (MWIR) and long-wave IR (LWIR) bands that are sensible to the thermal radiation emitted by the Earth surface. A key example of IR sensor is the series of Advanced Very High Resolution Radiometer (AVHRR). Most of the EO IR sensors are used together with optical sensors to get multispectral sensors, e.g. the Landsat and SPOT series, Ikonos, etc. The most important applications of IR sensors include:
  - Thematic mapping using optical and IR imagery. As mentioned above, there is an active R&D field on automatic image classification algorithms. NIR is sensitive to green biomass and moisture in vegetation, and is useful for distinguishing between land and water. It is used for land use and vegetation studies as well as geomorphic and landform applications.
  - Sensors such as the Advanced Very High Resolution Radiometer (AVHRR) have used these properties of the NIR to produce maps showing the changes in vegetation and land use since the 1970s.
  - In volcanic studies IR sensors are used to monitor surface or near-surface thermal manifestations of internal changes in the state of volcanoes.

- Hyperspectral sensors have the ability to acquire images in many narrow spectral bands that are found in the electromagnetic spectrum from visible, NIR, MWIR to thermal IR. Hyperspectral remote sensing is a relative new technology: most hyperspectral sensors are mounted on aerial platforms. An example of satellite-based sensor is the Hyperion EO-1, launched in 2000 by NASA. The most important applications of hyperspectral sensors are:
  - Agriculture, forestry and environmental monitoring, e.g. monitoring chemical concentrations in leaves, vegetation stress, mapping the expansion of different species of plants, identify surfaces contaminated by mining waste and other pollutants, etc.
  - In geology, detection and identification of minerals (mineral mapping), study of soil properties, including moisture, organic content, salinity, etc.
- Weather sensors are primarily used to monitor the weather and climate of the Earth. They typically use sensors working in the visible and IR spectra, which are carried out by either polar orbiting (e.g. the NOAA series) or geostationary satellites (e.g. the Meteosat series). They acquire low resolution imagery with high temporal resolution. The EO techniques based on weather sensors are among the most advanced and mature: most of the weather sensors are exploited at operational level. Their most important applications directly related to the geohazards treated in this paper are:
  - Monitoring at global scale of volcanic emissions.
- SAR represents an important class of EO sensors, which has complementary characteristics with respect to the previous types of sensors. SAR sensors are active imaging sensors that work in the microwave spectrum. They have remarkable key characteristics, like the all weather capability, the day and night operation, the sensitivity to specific properties (dielectric properties, surface roughness, etc.) and the capability to measure and exploit the signal phase (interferometry). Major SAR sensors include ERS-1/2, ASAR-Envisat, Radarsat (all of them in C-band), JERS and ALOS-PALSAR (L-band), and the VHR sensors TerraSAR-X and CosmoSkymed (X-band). Among the future SAR missions it is worth mentioning the Sentinel-1 sensor (C-band). The main fields of application of SAR are briefly described below:
  - Applications based on the SAR amplitude include lake and river ice monitoring, glacier monitoring, cartography, land use and forest cover mapping, soil moisture mapping, monitoring of coastal erosion, urban planning, rapid mapping of forest fires, floods, earthquake damage, volcanic eruptions, oil spills, etc. Some of the applications take advantage of the polarimetric property of some SAR imagery. In addition, some applications make use of coherence images to complement the information coming from amplitude imagery. The potential of SAR-amplitude has grown considerably with the advent of VHR SAR sensors.
  - Interferometric SAR is a technique to generate DEMs, which exploits the phase difference of at least a pair of SAR images acquired from slightly different viewpoints. This technique was used by the Shuttle Radar Topography Mission (SRTM) to generate a 90-m DEM on a near-global scale. An improved global coverage DEM is expected by the TanDEM-X mission.
  - Differential interferometric SAR (DInSAR) is a class of techniques to measure and monitor the displacements and deformation of the Earth surface. Its potential has been largely demonstrated in the last two decades on a wide range of applications related to seismic and volcanic activity, glacier dynamics, landslides, land subsidence, etc. (InSAR, 2004). An advanced DInSAR technique is PSI, which makes us of large stacks of SAR images (data redundancy) and advanced procedure to estimate deformation. Given the major role of PSI in the four geohazard themes treated in this paper, the following section is devoted to discuss in detail the main characteristics of PSI.

  - Besides the interferometric techniques, it is worth mentioning the methods (image matching, pixel tracking) that exploit the information contained in the SAR amplitude to derive deformation measurement and monitoring.
- It is worth mentioning that there are many other available EO sensors, e.g. LiDAR and radar altimeters, microwaves radiometers (e.g. SMOS), radar scatterometers, gravity gradiometers, etc. They are not directly treated in this paper because have a weak relation to the geohazards considered in this paper.

Persistent Scatterer Interferometry

PSI has demonstrated its unmatched deformation measurement and monitoring capabilities in a wide range of application fields and, specifically, in four of the geohazard themes considered in this report: seismic hazard, volcanoes, coastal lowland subsidence and flood defence, and landslides. For this reason, a specific section is devoted to briefly discuss the main PSI characteristics, which are essential to understand both the potential and the structural limitations of this technique. Note that some properties are valid for any DInSAR technique. There are different initiatives to enhance the capacity of PSI-based motion mapping in particular new supply chains available or in development able to provide wide area motion measurements. TRE Europe have processed very large surfaces and so has Technical University Delft; in Germany, DLR is developing the WAP product that provides automated PSI measurements over footprints of very large extent, equivalent to several datastacks (e.g. spatially the WAP product over Greece is equivalent to 10 temporal stacks of SAR data).

- Coherence. PSI is able to exploit only a small fraction of the pixels contained in a SAR image, i.e. only those pixels which interferometric phase is good enough to get reliable deformation estimates can be used. The pixels that satisfy this condition are often called coherent pixels or Persistent Scatterers (PSs). PS density is usually low, if not naught, in vegetated and forested areas and over low-reflectivity areas (very smooth surfaces and steep terrain). By contrast, PSs are usually abundant over built-up areas, infrastructures, etc. The potential lack of PSs is the most important limitation of PSI, which makes it an "opportunistic deformation measurement method", able to measure deformation only where there are available PSs. This issue has a direct impact on the four geohazard themes.

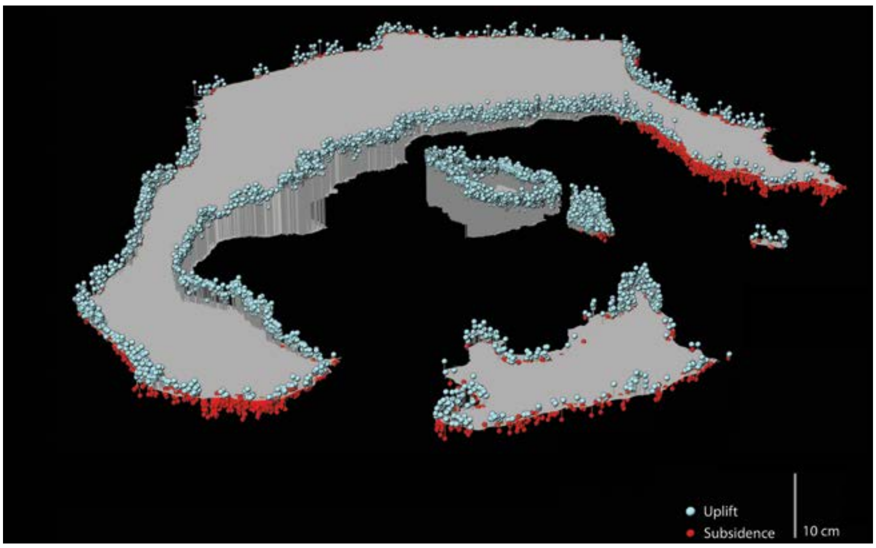

Figure 1. PS-InSAR based deformation map of Nea Kameni volcano in Santorini; Credits: Harokopio University of Athens, ENVISAT ASAR data over Mar 2011 - Feb 2012, Copyright ESA.

- Spatial sampling. The PSI spatial sampling capability is considerably inferior to the spatial resolution of the used SAR imagery. This is a direct consequence of the previous point. The impact of this largely depends on the spatial extent of the deformation phenomenon of interest: the smaller, the more critical is spatial sampling. For instance, this is potentially critical for many types of landslides.
- Temporal sampling. The PSI temporal sampling capability depends on the SAR data availability, which in turn is related to the revisiting time capabilities of the SAR sensors. The importance of this aspect is basically related to the type of temporal evolution of the deformation phenomenon at hand. In addition, it is worth recalling that PSI usually requires a large number of SAR scenes acquired over the same area: typically more than 15–20 images are needed. This is another potential limiting factor because this amount of images is currently unavailable in several areas of the world.
- Type and rate of deformation. The PSI performances in measuring deformation strongly depend on the type of deformation temporal variation and deformation rates. This is an intrinsic limitation, which is due to the ambiguous nature of the PSI observations, i.e. the interferometric phases, and the need of the so-called phase unwrapping. PSI and any DInSAR technique suffer limitations in the capability to measure "fast" deformation phenomena. It is difficult to quantify what "fast" means exactly, because it depends on different parameters: the PS spatial density, the temporal SAR sampling, the deformation temporal and spatial pattern and the used SAR wavelength.
- Deformation model. The previous point is further complicated by the fact that many PSI methods perform the phase unwrapping by assuming a linear model for deformation. This assumption can have a negative impact on the PSI estimates for all deformation phenomena characterized by non-linear temporal deformation behaviour, i.e. where the assumption is not valid. In such cases the PSI products may lack PSs, due to the fact that the PSI observations do not fit the (incorrect) linear model. This is a critical limitation because PSI may be unable to provide deformation measurements precisely over the most interesting deformation area.
- High sensitivity to displacements. PSI is highly sensitive to small land displacements. This has been largely demonstrated in the literature for L-band, C-band and X-band data. In the case of VHR X-band the sensitivity is so high that thermal dilation can represent a significant component of PSI observations, which needs to be properly handled to perform deformation monitoring of urban areas (Monserrat et al., 2011).
- Relative deformation measurements. All estimates provided by PSI (deformation velocity maps, deformation time series, residual topographic error, etc.) are relative measurements that usually are referred to a given or arbitrarily used reference point, where all estimates are known or are conventionally set to zero.
- Low frequency deformation components. PSI deformation products (deformation velocity maps and time series) over large areas may contain spatial tilts or trends, which can be due either to uncompensated orbital errors or low frequency residual atmospheric effects. In some applications, deformation patterns with similar characteristics can be due to real geophysical signals. Using only PSI data and standard PSI processing it is usually not possible to discriminate and separate low-frequency geophysical deformation signals from the above-mentioned spurious residual effects with. One of the following opposite situations may happen. Either a tilt results in the PSI products that can be interpreted as geophysical signal, while in fact it is simply due to residual processing errors; or a tilt-free product results, which is interpreted by a geophysicist as no signal, e.g. quiescence of a given phenomenon, while in fact the site may have undergone significant geophysical low-frequency deformations that have been removed (together

with the other residual effects) during the PSI processing. Any PSI application covering wide areas (e.g. the Wide Area Product mentioned later in this paper) and focused on spatial low-frequency deformation signals should properly address the above impact.

3. Seismic hazard

Earthquakes are responsible, together with volcanoes, of 9% of the disasters caused by natural hazards. EO data can be used as a complement to seismic networks, continuously-operating stations and in-situ data available in developed countries. However, developing countries, which usually lack such sensor networks, can hugely benefit from EO data. In fact, in developing countries, sometimes the main source of information during the first days after an earthquake derives from satellite images.

In the field of seismic hazard, satellite EO is mainly used to measure and monitor terrain motion and to help characterize the geophysical process of tectonic phenomena. In particular, the following three main EO research fields have been identified:

— Mapping of surface features associated with faulting;
— Terrain motion measurement and monitoring;
— Earthquake damage mapping.

Mapping of surface features associated with faulting

Surface features (lineaments) associated with faulting can be mapped using high-resolution imagery and elevation data. These features, which can be alignments of vegetation and topography, may be a manifestation of active faults and evidence of seismicity (CEOS, 2002). Specifically, high resolution optical (generally visible and IR imagery) and topographic data sets are used for investigating tectonic geomorphology, paleo-seismology, etc. (Walker et al., 2003). Although SAR imagery may also be used, the geometric characteristics of these data can make these tasks difficult (CEOS, 2002).

Lineament mapping from satellite EO imagery is a regularly used initial step in tectonic studies, which is usually followed by field verification. The regular procedure for extracting surface features associated with faulting from satellite EO data usually involves initial digital image enhancement followed by manual interpretation. Although there have been notable progress for the evaluation and automatic detection of lineaments and curvilinear features from satellite images, the human expert judgement still remains to be an asset for lineament detection and interpretation (Solomon and Ghebreab, 2011).

Terrain motion measurement and monitoring

Satellite EO data have made a significant contribution for seismology in surface deformation mapping. In fact, surface deformations generated at all phases of the earthquake cycle, including co-seismic, post-seismic and inter-seismic, can be measured and monitored using DInSAR techniques. Co-seismic deformations can be up to meters and tens of meters, while pre-seismic and post-seismic movements amount up to centimetres, although subsequent landslides can increase post-seismic deformations to meters (Tronin, 2010).

DInSAR techniques have proven to be effective tools to measure and monitor terrain motion over seismic areas. Among the benefits of using these techniques the following are worth to mention: wide area coverage which allows monitoring seismic activity over wide areas, large archives that can be exploited to study historic events, relatively inexpensive compared to field campaigns, sensitivity to displacements as small as a few millimetres. Moreover, the development of advanced DInSAR techniques, such as PSI, has widened the field of seismic applications due to the opportunity of measuring even slower displacements, including the phenomena caused by active tectonics as aseismic creeping or inter-seismic movements. DInSAR and PSI techniques have been exploited, among others, to measure surface displacement due to earthquakes, from moderate to strong, up to mega-earthquakes, to observe deformation caused by the accumulation of strain within the crust along active fault zones, and to investigate the temporal evolution of surface deformation phenomena. However, a variety of open issues need to be addressed, such as standardization of procedures for DInSAR analysis, development of standard modelling procedures, an assessment of significance and uncertainty of model results, etc.

Some of the most promising ongoing and future R&D activities related to terrain motion measurement and monitoring are briefly outlined below.

- Making use of high-resolution DEMs and optical imagery for tectonic geomorphology.
- Fusing VHR SAR and VHR optical data for change image analysis.
- Combining DInSAR and GPS to estimate large scale velocity fields. SAR data can be fused with data from seismic networks and GPS permanent stations. The GPS data can be used to estimate the long-wavelength deformation, while DInSAR enables velocities to be determined on a dense mesh.
- Studying inter-seismic strain accumulation using DInSAR provided effective results. The outcomes could be used together with GPS to define global strain rate models and to provide a contribution to the estimation of seismic hazard.
- Increasing the automation of the PSI processing chains, to cope with the high throughput of Sentinel-1.
- Earthquake cycle modelling capabilities today integrate EO measurements too. However further developments are needed for inter-seismic phase.

The demonstrated capability of PSI to monitor the spatial and temporal variations in the fault zone properties should be exploited systematically and extensively by generating Wide Area Products (WAPs). These products should be transnational, covering at least the most active seismic regions. This might provide valuable information about the fault evolution through the earthquake cycle. In order to get these products there is a need to increase the processing capacity and reduce the production costs. The WAP should become a standard product for the upcoming Sentinel-1 mission. However, it is worth considering that the value and usability of such wide-area products can be severely limited by the issue of “low frequency deformation components” discussed in Section 2.1. We recommend analysing this aspect thoroughly, making R+D efforts to properly address it. This could probably involve fusing, systematically and using a rigorous approach, SAR and Global Navigation Satellite System (GNSS) data.

Earthquake damage mapping

EO satellite imagery is a useful tool in several phases of the seismic risk management cycle in developing countries and remote regions. In particular, EO data can help provide asset and exposure mapping during the mitigation and preparedness phases and rapid access to satellite optical imagery can support rapid mapping and damage assessment during the emergency-response and recovery phases.

The field of earthquake damage assessment has hugely benefited from the research done using High Resolution (HR) and VHR optical imagery. Image differencing techniques using pre- and post-seismic optical images or classification of post-seismic images have been used to map damage. Moreover, recently developed methods reveal that operative damage mapping exploiting EO data are close to reach the operational level. Specifically, a new fusion approach between SAR and optical data carried out in real-time after the earthquake which stroke L'Aquila (Italy) in 2009 seems to be very promising (Dell'Acqua et al., 2011).

4. Volcanoes

Volcanoes create two distinct types of hazards related to the spatial coverage of the volcanic activity. On one side, there is the risk related to populated areas near erupting volcanoes due to proximal hazards such as lava flows, ash fall, etc. On the other side, volcanic activity produces dense plumes of volcanic ash and gases that can travel thousands of kilometres and endanger aircrafts. Historical analysis using EO data can help identify and characterise eruption types and their probability of occurrence. EO data is currently used to support the characterisation of the state of volcanoes, including terrain elevation and deformation measurements, to monitor the thermal output of an eruption and to estimate the height, behaviour, movement and extent of the ash cloud.

In the field of volcanic hazards, satellite EO can come into play only when the magma is near enough the surface to produce changes that can be monitored from space. In particular, the EO volcanic community is currently involved in three main research fields:

— Surface volcano deformation measuring and monitoring;
— Enhanced heat flow monitoring;
— Gas emissions observation.

Surface volcano deformation measurement and monitoring

Volcanic activity can induce ground deformation at different spatial and temporal scales. Changes to the surface of a volcano can provide clues about what is happening below the surface, e.g. subsurface flow of magma. DInSAR and PSI have been successfully used to measure and monitor terrain motion and topographic changes to characterise the state of a volcano: they are recognized techniques in the early detection of magma injection and in monitoring the stability of the underlying structure of a volcano.

However, there are still some limitations that need to be solved if the full capability of the DInSAR technique is to be exploited. Volcanoes in the tropics are a great challenge in this regard because the abundant vegetation causes severe coherence loss. Note that L-band radar performs better in such environments than C- or X-band radars. Another limitation is the lack of observations in steep slopes, which is due to the slant-range geometry of SAR imagery. This limitation can be largely surpassed if ascending and descending datasets for the same areas are used jointly. The temporal sampling can be an additional problem, which limits the PSI capability to monitor the temporal evolution of deformation. Finally, the limitation of DInSAR and PSI to measure "fast" deformation phenomena, mentioned in Section 2.1, can be a critical aspect considering the magnitude range of surface volcano deformation. One way around this problem is using image matching techniques of pairs of optical or SAR images.

Increased superficial heat flow monitoring

Heat associated to volcanism can be observed from space. Fumaroles fields, lava lakes, lava flows or pyroclastic flow deposits are some of the volcanic features that have distinctive thermal characteristics. From an EO perspective, a thermal anomaly can be defined as an unexpected increase in the radiant temperature compared to background values (Dehn et al., 2000). Temperature difference between middle IR and thermal IR satellite imagery are often created to search for thermal anomalies. These anomalies can support volcanic research by detecting surface or near-surface thermal manifestations of internal changes in the state of a volcano and to parameterise and validate numerical models of volcanic activity (Wooster et al., 2000). Increased superficial heat flow is a recognized precursor to volcanic eruptions (CEOS, 2002) and the height reached by a plume in the atmosphere is fundamentally related to the flux of material that is ejected.

However, inadequate spatial and temporal resolutions of the EO systems are a limitation to the development of remote sensing tools for thermal monitoring of volcanoes. Spatial resolution problems arise because extremely hot regions on active volcanoes represent usually sub-pixel size for most sensors but are hot enough to saturate a pixel much larger than the emitting area (CEOS, 2002). Besides, low temporal frequency limits the use of satellite data for volcanic routine monitoring. Higher spatial and temporal resolution in thermal imaging will be needed in the future.

Volcanic emissions

Volcanic gases and ash released into the atmosphere during eruptions can be a threat to persons near the erupting volcano and can also travel thousands of kilometres from the source and be a hazard to aircrafts. The scientific community is investing a substantial amount of effort to improve the capabilities for monitoring and forecasting the movement, extent and dispersion of the volcanic ash cloud. In this regard, satellite data is an essential source of information for a network of VAACs created as a global system of detection and tracking of the airborne products of explosive volcanic eruptions.

Satellite EO is mainly used in the volcanic field to observe volcanic ash and sulphur dioxide (SO_2). Ultraviolet, visible and IR data are used in three main ways in volcanic emissions research: observing the eruption, observing the movement and extent of the ash (height, thickness/depth, location and concentrations) and SO_2 cloud, and validation of numerical model predictions of ash cloud extent. Regarding volcanic gases, satellite derived measurements of SO_2 have proven to be a very reliable indicator of volcanic activity and pre-eruptive degassing measurements are potential early warning tools (Zehner, 2010).

Although the use of EO data for volcanic ash observation is quite mature, there are still some issues that need to be solved. Currently there are problems to initialize the dispersion models due to uncertainties related to the ash cloud height, the concentration of ash being expelled and the ash cloud concentrations. In order to solve these limitations, efforts are focused on the integration of observation sources (ultraviolet, visible, IR and thermal IR) for SO_2 and volcanic ash monitoring and forecasting. Specifically, a set of near real-time volcanic ash products need to be developed to improve ash plume dispersal forecasting including ash cloud height, ash cloud concentration, ash effective radius and mass loading (Zehner, 2010).

Ad hoc attempts at exploiting redundancy of geostationary telecommunication sources that continuously transmit in the C, X and Ka,u bands of the microwaves are promising, however further R&D efforts are required before interferometry from geostationary platforms become feasible.

5. Coastal lowland subsidence and flood defence

Many coastal lowland and deltaic plains are underlain by compressible soils vulnerable to subsidence (Milliman and Haq, 1996). Coastal areas and river basins concentrate densely populates cities and human activities, such as industry, agriculture and infrastructures, with high economic value. Human activities, such as the extraction of natural resources like groundwater, salt, oil or gas, also cause subsidence at surface level. Moreover, coastal lowlands are exposed to the effects of storm surges and extreme discharges in rivers. The combination of subsidence with an increase in sea level rise and extreme weather conditions will result in an increase in flood risk. Therefore, there is need "to assess whether any water courses and coastlines are at risk of flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk" (EC, 2007).

Satellite EO might be an effective tool for flood hazard applications. Currently, EO satellite applications for flood hazard are mainly concentrated on multispectral optical and SAR images. In particular, DInSAR and PSI techniques can be exploited in order to understand terrain movement in flood prone areas, providing estimates of subsidence rates as well as the temporal behaviour of the displacement. Moreover, DInSAR and PSI data can be used as input in models to better understand the process of subsidence and to predict the results of possible non-regret measures. The backscatter of the SAR signal and multispectral optical images are also used to map inundated areas by flood events. Two main EO research fields related to the topic at hand, have been identified:

— Subsidence measurement and monitoring;
— Flood monitoring.

Deformations measurement and monitoring

Subsidence related to compressible soils or/and extraction of natural resources, mainly groundwater, can be precisely measured and monitored with satellite EO imagery. Conventional techniques to measure subsidence such as levelling and GPS can be complemented by DInSAR and PSI techniques. Some of the advantages of using PSI compared to conventional techniques are: (i) the availability of historical SAR archives confers to PSI the ability to measure and monitor ground motion that occurred in the past and for which no other survey data are available, (ii) the combination of wide area coverage, usually associated with high spatial resolution and revisit time, and sensitivity to small deformation phenomena, and (iii) the ability to analyse the temporal behaviour of ground motion.

The combination of PSI ground measurements with conventional in situ data is proving effective for some applications. For instance, a wide area map of ground motion has been recently produced in the Netherlands from integration of DInSAR, levelling and GPS data. This map provides an overview of the displacement phenomena affecting the country, including subsidence processes related to compressible soils or gas extraction (Caro-Cuenca et al., 2011). In this regard, PSI wide area products are expected to be a standard product for the upcoming Sentinel-1 mission and, thus, the scientific community is intensifying the effort toward this objective.

Relative sea-level rise might exceed the global average in coastal lowland areas affected by subsidence, with the subsequently increase for potential inundation, coastal erosion, habitat disruption and salt water intrusion. Flood prone areas with high economic or human value are often protected by flood defence structures and if these structures are subsiding the probability of a flood event increases, even more in a sea level rise scenario. In this regard, PSI proved to be an effective for monitoring flood defence structures (Hanssen and Van Leijen, 2008). However, several improvements are required in this field: (1) very high resolution SAR images are needed to better monitor water defence structures such as sluices, dams, levees, etc.; (2) shorter revisit times are required to increase the effectiveness of PSI to detect levee failure.

The following high-level conclusions can be drawn from the discussion above:

— The PSI deformation monitoring should be exploited systematically by generating transnational and wide-area coverage products, covering at least the low land costal regions. As already mentioned in the Seismic Hazard section, we recommend addressing the issue of "low frequency deformation components", making R+D efforts to properly address it, e.g. by fusing systematically SAR and GNSS data.
— Efforts are needed to derive deformation products with uniform spatial coverage, especially in areas with vegetation such as grass covered levees and agricultural fields in rural areas.
— A thorough exploitation of PSI results requires comprehensive quality reports containing metadata, quality checks, processing steps and identification of PS.
— Combining subsidence mapping with flood mapping when subsidence is related to plain flood; plain flood services primarily concern hazard mapping (historical mapping for risk assessment and crisis mapping for emergency response).
— Combining subsidence mapping with storm surge applications when subsidence is related to storm surge in coastal zones; concerns both tropical and extra-tropical storm surges around the world; storm surge applications include modelling, forecasting and hind-casting, ensemble approaches, development of effect-oriented products such as inundation maps and GIS-based tools.

6. Landslides

Landslide events are one of the most common geological hazards and their occurrence is closely linked with intense or prolonged rainfall, earthquakes, volcanic eruptions, rapid snowmelt and permafrost thawing. Landslides represent a major hazard in mountainous and hilly regions as well as along steep riverbanks and coastlines. They pose a serious threat to settlements and infrastructures and their impacts depend largely on the involved area and volume, the motion velocity and intensity, number and distribution of the elements at risk, their vulnerability and their exposure value.

In the field of landslides, satellite EO research is mainly aimed at generating and upgrading landslide inventory maps at regional scale, and at characterizing and monitoring unstable slopes. Optical images are preferred for landslide detection and mapping, while SAR images are used to detect and monitor surface deformation produced by slow moving landslides (Guzzetti et al., 2012). In this sense, this community paper deals with two main EO research fields:

— Landslide mapping and inventory;
— Landslide monitoring and characterization.

Landslide mapping and inventory

Keeping an updated inventory of landslides is essential to document the extent of the landslide phenomena in a region, to investigate the distribution, types, patterns, and recurrence of slope failures, and to determine landslide susceptibility, hazard, vulnerability and risk. Conventional methods for landslide mapping, such as geomorphologic field mapping and visual interpretation of aerial photographs or satellite images (Brabb, 1991; Galli et al., 2008), are giving way to new methods and techniques for landslide mapping.

Satellite EO imagery has made a significant contribution to landslide monitoring and characterization. In particular, EO satellite data have been used to identify indicators of slope instability, such as terrain features and landforms, and the spatial distribution of mass movements using optical imagery interpretation, and to measure slope motion with DInSAR and PSI techniques.

The advent of satellite optical sensors providing increased spatial, temporal and spectral images and the improvement of computer software and hardware are being exploited by the landslide community. A wide range of techniques and methods show great potential for landslide detection and mapping using panchromatic and multispectral images. These methods include automatic or semi-automatic classification pixel and object-oriented classification for landslide inventory mapping, change detection methods for landslide inventory updating, and imaging spectroscopy techniques for retrieval of hydrological and geomorphologic features, such as soil properties, land use and rainfall fields, used in many landslide predictive models as indicators of slope instability (van Westen et al., 2008).

Regarding SAR imagery, the new satellite-based techniques and methods provide essential information about the morphology, land use and geology of landslides. In this sense, DInSAR and PSI have demonstrated their suitability to provide detailed slope information, which is essential to analyse surface morphology for reliable landslide inventory maps generation, including landslide motion estimates (Farina et al., 2006). For instance, landslide motion estimates can be used to detect landslides that had not been previously documented or to update the existing ones.

Landslide monitoring and characterization

Landslide monitoring and characterization has been hugely benefited by the DInSAR and PSI techniques. These techniques are predominantly used in the field of landslides to obtain estimates of landslide-induced motion and to investigate the temporal evolution of the moving slope. Due to the ambiguous nature of their observations, see Section 2.1, PSI suffers limitations in the capability to measure "fast" deformation phenomena. For this reason, PSI is mainly used to detect and monitor deformation of the topographic surface produced by slow moving landslides (Guzzetti et al., 2012). PSI can support the geological and kinematic interpretation of the slope instability, especially in built-up and densely urbanized slopes, where landslide indicators are difficult to recognize due to the presence of the urban fabric.

Besides the use of PSI, conventional DInSAR allows analyzing not only motion rates exceeding the limitation of PSI (in C-band usually below 10 cm/yr, even though this depends on the spatial deformation pattern), but also deformation trends significantly differing from the linear deformation model usually assumed in PSI processing. A supplementary advantage of DInSAR is the spatial coverage and the ability to detect the landslide limits with lower costs than with PSI. However, DInSAR analyses are generally less accurate than PSI and requires additional work load.

Although DInSAR and PSI have demonstrated their suitability for the study of extremely to very slow moving slopes, several limitations prevent the use of these techniques to monitor the whole deformation field or landslides located in vegetated areas. Firstly, they can only measure deformation in the satellite line-of-sight, which is an important limitation to study unstable slopes. In this sense, the availability of ascending and descending SAR datasets providing two geometries of acquisition are required to increase the coverage of the study area and to estimate the vertical and East-West components of displacements. Secondly, as already discussed in Section 2.1, they can measure displacement in vegetated areas only if coherent targets (corresponding to coherent pixels or PSs) are available in the area of interest. The use of L-band SAR could benefit the landslide applications.

Finally, it is worth mentioning that image matching or correlation techniques based on optical imagery have show good performances to quantify motion and to monitor landslide activity.

The following high-level conclusions can be drawn from the discussion above:

— The PSI deformation monitoring should be exploited systematically by generating transnational and WAPs, covering the most landslide prone regions. The systematic and wide-area exploitation of WAPs will fully take advantage of the opportunistic nature of DInSAR and PSI: a systematic exploitation can maximize the number of landslides detectable and that can be monitored by PSI. It is worth noting that, given the rather localized nature of landslides, in this case the issue of "low frequency deformation components" is negligible.
— Perform validation and assessment of the performances of WAPs for landslide hazard and risk studies, considering real, near-real and deferred time applications. The WAP processing strategies will possibly be unsuitable for applications in Alpine environments, but will likely contribute to landslide mapping in built-up and urban areas.
— To overcome the problem of temporal de-correlation (coherence loss) of interferometric data, which severely limits the PSI monitoring capability, we recommend: (i) to systematically exploit the 16-day temporal sampling of Sentinel-1; (ii) systematically exploit the L-band capabilities of any SAR forthcoming mission.
— Standardization of the methodologies employed for the implementation of EO-based landslide services, creating guidelines for the interpretation of EO data and PSI products aimed at landslide mapping, monitoring and modelling. Key PSI limitations related to the rates of deformation, PSI data loss due to non-linear deformation patterns, etc. should be properly addressed in the guidelines and communicated to end users.
— Development and further enhancement of the emerging techniques for EO-based landslide modelling and early warning purposes.

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Acronyms

AATSR	Advanced Along-Track Scanning Radiometer (ENVISAT)
ADB	Asian Development Bank
AIRS	Atmospheric Infrared Sounder (Aqua)
ALI	Advanced Land Imager (NASA's EO-1)
ALOS	Advanced Land Observing Satellite (Japan)
AOA	Airport Operators Association
ASAR	Advanced SAR (ENVISAT)
ASI	Italian Space Agency
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer (Terra)
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BIRA-IASB	Belgisch Instituut voor Ruimte-Aeronomie · Institut d'Aéronomie Spatiale de Belgique
BGR	German Geological Survey
BGS	British Geological Survey
BRGM	French Geological Survey
CEOS	Committee on Earth Observing Satellites
CIESIN	Center for International Earth Science Information Network
CNES	Centre National d'Etudes Spatiales
CoSA	Collaborative Spatial Assessment
CSA	Canadian Space Agency
DEM	Digital Elevation Model
D InSAR	Differential InSAR
DGGT	Deutsche Gesellschaft für Geotechnik (Germany)
DLR	Forschungszentrum der Bundesrepublik Deutschland für Luft- und Raumfahrt (German Aerospace Centre)
DMT	Deutsche Montan Technologie für Rohstoff, Energie, Umwelt e.V. (DMT GmbH & Co. KG, Germany)
DMSG	Disaster Management Support Group (CEOS)
DMV	Deutscher Markscheider-Verein (German Mine Surveyors Association)
DORIS	Downstream Observatory organised by Regions active In Space - Network
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
EEA	European Environmental Agency
EFG	European Federation of Geologists
EGDI	European Geological Data Infrastructure
ENSP	Ecole nationale superieure polytechnique
EO	Earth Observation or Earth Observations
EOMD	Earth Observation EO Market Development programme element (of EOEP)
EOEP	Earth Observation Envelope Programme (ESA)
EPOS	European Plate Observing System
EPRS-E	Extraordinary Plan of Environmental Remote Sensing (Italy)
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESF	European Science Foundation
ESFRI	European Strategy Forum on Research Infrastructure
ETM	Enhanced Thematic Mapper (Landsat)
EU	European Union
EUDAT	EUropean DATa
EURAC	European Academy (Italy)
EVOSS	European Volcano Observatory Space Services
EWS	Extra Wide Swath mode (Sentinel-1)
FP7	7th Framework Programme (EU)
HRG	High Resolution Geometrical (SPOT-5)
GDLND	Global Landslide Hazard Distribution
GDP	Gross Domestic Product
GEM	Global Earthquake Model
GEO	Group on Earth Observations
GEOSS	Global Earth Observing System of Systems
GFDRR	Global Facility for Disaster Reduction and Recovery
GHCP	Geohazards Community of Practice
GIO EMS	GMES Initial Operations Emergency Management Services
GMES	Global Monitoring for Environment and Security
GSE	GMES Service Element programme
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GOME-2	Global Ozone Monitoring Experiment
GPS	Global Positioning System
GSE	GMES Service Element
GSNL	GeoHazard SuperSites and Natural Laboratories
GSRM	Global Strain Rate Model
HH	Horizontal/Horizontal – polarizations for SAR
HV	Horizontal/Vertical – polarizations for SAR
IASI	Infrared Atmospheric Sounding Interferometer (MetOp-A)
IATA	International Aviation Transport Association
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
ICAO	International Civil Aviation Organisation
ICSU	International Council for Science
IGOS	International Global Observing Strategies

INGV	Istituto Nazionale di Geofisica e Vulcanologia (Italy)
InSAR	Interferometric Synthetic Aperture Radar
INSPIRE	Infrastructure for Spatial Information in the European Community
IPGP	Institut de Physique du Globe de Paris (France)
IRPI	Institute for Geo-Hydrological Protection (Italy)
ISPC	Institute for the Security and Protection of the Citizen (JRC/EU)
IT	Information Technologies
IUGG	International Union of Geodesy and Geophysics
IWS	Interferometric Wide Swath mode (Sentinel-1)
HR	High Resolution
JAMI	Japanese Advanced Meteorological Imager
JAXA	Japan Aerospace Exploration Agency
JICA	Japan International Cooperation Agency
JRC	Joint Research Centre (EU)
LDCM	Landsat Data Continuity Mission (Landsat-8)
LiDAR	Light Detection And Ranging
LOD	Linked Open Data
LOS	Line of Sight
LSM	Landslide Monitoring
LSMd	Landslide Modelling
METS	Ministry of Environment and Territory of the Sea (Italy)
MIR	Mid Infra red
MODIS	Moderate Resolution Imaging Spectroradiometer
MORFEO	MOnitoraggio e Rischio da Frana mediante dati EO (Italy)
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
MWO	Meteorological Watch Office
NAFS	North Anatolia Fault System
NAFZ	North Anatolian Fault Zone
NASA	National Aeronautics and Space Administration (USA)
NERA	Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation
NILU	Norwegian Institute for Air Research (Norway)
NIR	Near Infra Red
NOAA	National Oceanographic and Atmospheric Administration (USA)
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	National Polar-orbiting Operational Environmental Satellite System Preparatory Project
NSF	National Science Foundation (USA)
OECD	Organisation for Economic Cooperation and Development
OMI	Ozone Monitoring Instrument
PGI	Polish Geological Institute (Poland)
POLIMI	Politecnico di Milano
PSHA	Probabilistic Seismic Hazard Assessment
PS	Persistent Scatterer
PSI	Persistent Scatterer Interferometry
RCM	Radarsat Constellation Mission (Canada)
REAKT	Strategies and tools for Real time EArthquake risK
RMI	Raw Materials Initiative
SAFER	Service and Applications For Emergency Response
SAR	Synthetic Aperture Radar
SBA	Societal Benefit Area
SCIAMACHY	Scanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY instrument (Envisat)
SEVIRI	Spinning Enhanced Visible and Infra Red Imager (MSG)
SHARE	Seismic Hazard Harmonization in Europe
SLAM	Service for Landslide Monitoring
SME	Small and Medium-Sized Enterprise
SMOS	Soil Moisture and Ocean Salinity
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SWIR	Short wave Infra Red
TIR	Thermal Infra Red
TMPA	Multi-satellite Precipitation Analysis
TOPS	Terrain Observation with Progressive Scans in azimuth (Sentinel-1)
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
UN	United Nations
UNAVCO	University Navstar Consortium (Boulder, Colorado)
UNIFI	University of Florence (Italy)
UNITAR	UN Institute for Training and Research
UNOSAT	UNITAR'S Operational Satellite Applications Programme
USGS	United States Geological Survey
VAACs	Volcanic Ash Advisory Centres
VACs	Value-Adding Companies
VERCE	Virtual Earthquake and seismology Research Community in Europe e-science environment
VHR	Very High Resolution
VIR	Visible Infra Red
VIIRS	Visible Infrared Imager Radiometer Suite
VV	Vertical/Vertical – polarizations for SAR
WAP	Wide Area Processing
WOVO	World Organisation of Volcanic Observatories
WMO	World Meteorological Organisation