1 Summary

1.1 Executive summary

DORIS is an advanced downstream service for the detection, mapping, monitoring, and forecasting of ground deformations caused by natural and human-induced phenomena. Natural phenomena investigated by DORIS include landslides, riverbank erosion, rock glaciers, and the melting of permafrost. Human induced causes include coal mining, the exploitation of groundwater for human and agricultural consumption, and construction works. DORIS integrates traditional and innovative Earth Observation and ground-based data and technologies to improve our understanding of the complex phenomena that result in ground deformations, at different temporal and spatial scales, and in various physiographic and environmental settings. DORIS integrates state-of-the-art technological and scientific capabilities with existing services to deliver innovative, user-driven services and products expected to be beneficial for different communities. Primary users of the downstream are Civil Protection authorities, and environmental and planning agencies operating at different geographical and organizational scales, from the local to the national scale. Secondary users of DORIS include the mining industry, builders, utilities, road and rail companies, and other businesses involved in the assessment or the mitigation of the risks posed by the ground deformations, including the insurance industry. DORIS advanced the state-of-the-art of the science and technology used to detect, map, monitor, and forecast ground deformations. New techniques were developed to exploit fully the unique ESA ERS-1/2 and ENVISAT C-band, Synthetic Aperture Radar (SAR) archives, obtaining time-series of ground deformations, and associated maps, of unprecedented length. The high-resolution X-band SAR data brought by COSMO-SkyMed and TerraSAR-X satellite sensors were used to produce deformation maps and time series of unparalleled spatial and temporal densities. DORIS moved forward the multi-frequency joint analysis of DInSAR products obtained processing data captured by multiple sensors (C, X, L-band) for the same area, and the combined application of satellite and ground-based differential SAR interferometry, coupled with in situ thematic data and geophysical probing, for improved monitoring and modelling of landslides. DORIS processed more than 2000 SAR images in 13 study areas in Hungary, Italy, Poland, Spain and Switzerland. Collectively, the study areas represent a wide range of physiographical and environmental settings, and include all types of ground deformations for which the service is suited. This guarantees that the downstream service will work in Europe, and in other areas. Based on a thorough evaluation of the potential markets, and on a realistic sustainability assessment, DORIS designed a business model and an appropriate strategy for the long-term self-sustainability of the downstream service.

1.2 Summary description of DORIS context and objectives

Landslides and ground subsidence are serious and largely underestimated problems, in Europe and in other areas of the world. Where they occur, landslides and subsidence pose a major threat to public and private properties, structures and infrastructures, and the population, with significant economic, environmental, and societal consequences.

A "landslide" is the movement of a mass of rock, debris, or earth down a slope, under the influence of gravity. Different phenomena cause landslides, including intense or prolonged rainfall, earthquakes, rapid snow melting, volcanic activity, and multiple human actions. Landslides can involve flowing, sliding, toppling, or falling, and many landslides exhibit a combination of two or more types of movements, at the same time or during the lifetime of a landslide. Landslides are present in all continents, and play an important role in the evolution of landscapes. They also represent a serious threat to the population. The International Disaster Database EM-DAT reports as many as 20,000 people killed in the last 20 years by major landslide events, with a major event killing ten or more persons. Every year, there are between six and 20 major landslide events in the world, with at least one of these major landslides occurring in Europe, on average. These figures are known to be vastly underestimated, and the number of landslides causing less than 10 fatalities and providing significant damage and disruptions is several orders of magnitude higher. In Italy, a country for which detailed information exists on the societal and economic impact of landslides, at least 5190 people were killed, went missing, or were injured by landslides in the 50-year period 1963–2012. In the same period, the number of evacuees and homeless people caused by landslides exceeded 150,000. The cost of geo-hydrological events in Italy, including landslides, in the period 1950–2012, was estimated at € 60-billion, with an average yearly cost exceeding € 2-billion in the last years. Although Italy is a country particularly affected by landslides and related geo-hydrological hazards (e.g., debris flows), the extent of the landslide problem is severe in several other European countries, including Austria, Czech Republic, Croatia, France, Greece, Hungary, Norway, Poland, Portugal, UK, Slovakia, Slovenia, Spain, and Switzerland.

Ground subsidence has many natural and human-induced causes, and it is most severe and widespread in areas where mining and other sub-surface exploitation activities take place. According to Swiss Re, in some parts of Europe subsidence is now the costliest natural hazard, comparable to flooding. In Great Britain, over the last ten years subsidence has cost an estimated € 3.6-billion, making subsidence the most damaging geo-hazard in the region. In the Ruhr region of Germany, a large number of litigation cases towards mining companies have emerged, with more than 35,000 damage claims filed each year. The claims are in the hundreds of millions of euros. In France, subsidence-related claims have risen by more than 50% in the past 20 years, costing the affected regions € 340-million every year, on average. In 2003 a single mining subsidence accident caused by a French mining company's caused damage assessed at € 10-million in France and Germany. In Poland, coal mining causes vast subsidence and produces significant damage to public and private properties and the infrastructure. In Italy and Spain, excessive water withdrawal for human consumption and agriculture uses produce subsidence of large to very large geographical areas, producing widespread damage and considerable costs.

In this phenomenological and economic context, **DORIS** is an advanced **downstream service for the detection, mapping, monitoring, and forecasting of ground deformations**, including **landslides** and **ground subsidence**, at different temporal, spatial and organizational scales, and in various physiographic, climatic, and environmental settings. The downstream integrates traditional (consolidated) and modern (innovative) Earth Observation (EO) and ground based (non-EO) data and technologies to improve the understanding of the complex phenomena that result in ground deformations, chiefly landslides and ground subsidence, and to foster the ability of Environmental and Civil Protection authorities to manage the risks posed by ground deformations. DORIS delivers innovative products tailored on the needs of national, regional, and local authorities integrating state-of-the-art national technological and scientific capabilities. DORIS complies with general guidelines provided by the EU Emergency Response Core Services, and benefits from a unique partnership of leading research institutes, commercial providers, and experienced end-users.

The **mission** of DORIS was to establish an **operational Copernicus** (formerly GMES) **downstream service** capable of:

- Strengthening the operational exploitation of satellite data and technology for the detection, mapping, monitoring and forecasting of ground deformations caused by landslides and subsidence phenomena.
- Integrating effectively satellite and ground-based data and technologies to improve the understanding and forecasting of ground deformations caused by landslides and subsidence.
- Raising the awareness of landslide and subsidence and their actual and potential impacts, and of the possibility of using space data and technology to monitor and manage the ground deformations.

Specific goals of DORIS included:

- To design and deliver innovative products relevant to Civil Protection and Environmental authorities, for all the phases of a typical risk management cycle.
- To exploit the unique ESA ERS-1/2 and ENVISAT, C-band Synthetic Aperture Radar (SAR) archives, to generate very-long time-series of ground deformations, and associated deformation and deformation velocity maps.
- To evaluate quantitatively the improvements brought by the high-resolution COSMO-SkyMed and TerraSAR-X, X-band SAR sensors, for the production of innovative DInSAR products.
- To explore the combined application of satellite and ground-based DInSAR technologies and products for the improved monitoring of local-scale landslides and subsidence phenomena.
- To define and test innovative, quantitative validation procedures for an improved exploitation of DInSAR services and products. Lacks of standards for the assessment of the quality of DInSAR products, including deformation maps and time series, limits the use of the services and products, and the thrust of the end-users on the consolidated and the innovative services and products.

- To design an efficient interface between the "user domain" (represented by a diversified audience of end users with different levels of knowledge and expertize), the European level core services, and the DORIS downstream, exploiting national resources and specific technical expertise on ground deformations.
- To execute innovative research on the use of remote sensing technologies for the detection, mapping, monitoring and forecasting of landslides and subsidence.
- To evaluate private and public markets for the DORIS services and products, and to design an appropriate business model for the long-term sustainability of the downstream.

DORIS has obtained a number of significant results, which are of potential interest to a large and diversified audience of **service providers**, **operational users**, and **research scientists**.

- For 13 test sites in Europe, DORIS produced accurate deformation and deformation-velocity maps, and associated time series of unprecedented length obtained processing very-large stacks of C-band SAR data captured by the ESA ERS-1/2 and ENVISAT satellites. We expect that service providers can use the new DInSAR techniques experimented by DORIS to offer innovative services and products to a range of costumers. Operational users can exploit the accurate deformation maps and the very long time series to better understand the ground deformations and the drivers of the deformations. Scientists have new information to study the long-term behaviour of landslides and subsidence. This is particularly relevant to investigate the relationships between precipitation and ground movements, and the expected impact of the on going or the predicted climatic and environmental changes on the pattern and rate of the natural and the human induced deformations.
- Extensive processing of X-band SAR data taken by the Cosmo-SkyMed and TerraSAR-X satellites, exploiting the significantly higher spatial resolution and the considerably shortened repeat time of the new advanced sensors. We expect that service providers will expand their portfolios offering new services and products based on the advanced processing of the high resolution X-band SAR data. Operational users will benefit from the improved temporal and spatial resolutions of the X-band sensors, being able to use significantly denser and more accurate deformation maps and time series. This will prove particularly useful in urban and sub-urban areas and along major infrastructures. Scientists can use deformation maps and associated time series of unmatched spatial density to study in greater detail the kinematics of landslides and subsidence phenomena. We further expect that operational users and scientist will use the denser maps to constrain and/or validate numerical (e.g., FEM) models of landslides and subsidence phenomena.
- Innovative use of SAR interferometry to investigate fast moving slope processes, including landslides, glaciers, rock glaciers, areas with permafrost, and human induced subsidence in active mining areas. The service providers can offer new services experimented by DORIS to monitor rapid ground deformations. These previously unavailable services and products are of potential interest to operational users and scientists that can use new tools to detect, monitor, and investigate active

landslides and subsidence phenomena moving at fast to very-fast rates that previously could not be investigated effectively using SAR data and related processing technologies.

- Novel validation procedures for DInSAR services and products. Service providers can offer better-validated products, and operational users benefit from the use of validated products. We expect that these results will contribute to expand further the use and the confidence on DInSAR-based services and products by a large audience of end-users.
- Innovative framework for the semi-automatic recognition and mapping of fast-moving landslides exploiting optical (multispectral) images. Service providers can now offer innovative rapid mapping services, which are particularly effective for mapping event landslides. Operational users and scientists can obtain accurate landslide maps shorty after an event. The capabilities for the semi-automatic recognition and mapping of event landslides are further expanded in the FP-7 LAMPRE project (**www.lampre-project.eu/**).
- An assessment of the sustainability of the downstream service has shown that, if certain conditions were met, DORIS could evolve towards a successful operational service. The DORIS services and products were initially planned for a few categories of users, chiefly Civil Protection and Environmental authorities, local government agencies, national and regional governments and municipalities. These remain the primary users of DORIS. There are other entities potentially interested in the DORIS benefits, including e.g., mining industry, builders, utilities, road and rail companies. These are secondary users in the DORIS value chain.