A collaborative project aimed at developing a GMES-service for monitoring and forecasting subsidence hazards in coastal areas around Europe

Final Report Summary - SUBCOAST (A collaborative project aimed at developing a GMES-service for monitoring and forecasting subsidence hazards in coastal areas around Europe)

Executive Summary:
Subsidence in coastal lowlands can affect – in combination with other factors – flood risk in low-lying areas near the sea or rivers, appearance of water nuisance, groundwater quality, and planning or maintenance
of urban areas, infrastructure and water defence constructions. A service delivering so-called ‘Dynamic DEM’ (DDEM) information - time dependent elevation of the ground surface at a certain location or in a certain area - at local, regional, national and international levels would have significant value for public departments and other stakeholders (e.g. engineering companies, E&P industry) involved in subsidence issues in coastal lowland areas. In fact, the DDEM is a concept for a new generation (digital) elevation maps, enabling the provision of quantitative information about ground motion. This can be considered as baseline information for any further assessment of subsidence impacts and follow-up decision-making, planning or (risk) management. Therefore, SubCoast has focused on the development of components that make up the DDEM-methodology, parallel to deployment in four pilot areas (Rhine-Meuse area, coastal areas in the Baltic, Italy (coastal area in Emilia Romagna) and Europe as a whole).

For the Rhine - Meuse pilot (basically covering the area of the Netherlands), the development of a DDEM has been carried out to the most comprehensive and area wide extent, enabled by satellite data with more or less sufficient spatial and temporal coverage, availability of proper ground truth and in-situ data and advanced geodetic expertise. Other important drivers have been the clear presence of subsidence in large parts of the area, with different causes and impacts, and the long-term experience with the subject of different stakeholders and citizens in the area. The case studies in this area have delivered examples of possible services that could be built on DDEM-results, e.g. connected to water management and monitoring of ground settlements related to gas production. The other pilot areas (Italy, Baltic) had to build their DDEM’s on the basis of satellite data with lower spatial and temporal coverage, different sources or quality of ground truth data, and in a context of much less societal knowledge and awareness of subsidence impacts (being less obvious in these regions). Under the limitations the pilot studies have focused on different aspects of DDEM’s, e.g. making use of new opportunities of high resolution satellite data (3D ground motion monitoring) or specific geophysical interpretation of earth observation data for coastal erosion, tectonic movements or coastal infrastructure.

The European integration pilot has delivered harmonising approaches for the DDEM technology. This required frequent technical exchange between SubCoast partners, which consequently much advanced the expertise of institutes that can play a vital role in their countries regarding monitoring ground movement using earth observation techniques. The European integration pilot has also focused on the predictive component of the DDEM for all coastal areas of Europe, through estimations of subsidence susceptibility on the basis of the currently available digital geological map of Europe (OneGeologyEurope project).

Altogether, SubCoast has delivered an advanced manual and program for the ‘new generation elevation maps’, adding the time dimension which is crucial for monitoring ground movements. In addition, SubCoast has provided an advanced IT-framework for digital provision of such services. SubCoast also made clear that full development of DDEM’s requires advanced and substantial technological programs involving long term (satellite) earth observation, geophysical modelling, data management and validation activities. SubCoast concludes that continuous development and provision of DDEM’s is pre-conditional to develop relevant services for mainly public agencies involved with flood risk and water management in coastal lowlands where ground deformation occurs. Building forward on primary research in SubCoast, also applications for the E&P Industry can be envisioned, related to prediction and monitoring of production impacts at the surface.

In general, the new satellite missions (Sentinel) provide very good opportunities to extend application of the DDEM-technology worldwide, taking into account geodesy and geophysical modelling of the subsurface. It is recommended to initiate further research programs involving the most important
subsidence-prone coastal lowland areas.

Project Context and Objectives:
SubCoast is a three year project funded by FP7 Call Theme 9 – Space. It is a collaborative project aimed at developing a GMES-service for monitoring and forecasting subsidence hazards in coastal lowland areas around Europe. The project started in April 2010 and ended in September 2013. (The GMES (Global Monitoring for Environment and Security)-program is now renamed into Copernicus). The EC contribution of 3.1 million EUR is divided over 6 work packages (including 6 additional sub-work packages). The project consortium consists of 12 partners from 7 countries, including 5 geological surveys, 2 universities, 2 research institutes and 3 commercial companies (see table 1).

Coastal lowland areas are widely recognized as vulnerable locations exposed to extreme events, which can potentially have a large range of social, economic and environmental impacts. The vulnerability of coastal regions takes on two aspects: the diverse impacts from the sea (e.g. connected to climate change and sea level rise), rivers and anthropogenic impacts resulting from increased land use. Ground subsidence is a hazard that connects these issues and is the focus of the SubCoast project. Ground subsidence has many causes that can be divided into two broad categories; shallow causes due to, for example, peat oxidation, compaction and groundwater extraction, and deep causes due to, for example, tectonic phenomena and effects of mining and extraction activities (gas, salt). Although subsidence can be a direct hazard (e.g. landslides, sinkholes), more commonly it is the associated hazards that are exacerbated by subsidence, which are a greater threat to human land use. Subsidence is generally under-acknowledged as a geohazard, because it is generally too slow for human perception and effects are often invisible before structural damage appears. This makes subsidence an insidious threat, which may proceed undetected for decades, e.g. having significant cumulative effects on flood risk or the integrity of water defences and infrastructure.

Supported by advancements in space-based technologies and combining this downstream information with in-situ and other measurements of changes in land elevation, the main objective of SubCoast is to develop a user-centered downstream GMES/ Copernicus-service for delivering data and information on extent and impact of subsidence in coastal lowland areas around Europe and demonstrate its viability in various pilot services for a variety of geographical settings and applications. The resulting services should enable relevant local, regional and (inter-)national departments to deliver reliable information about subsidence, thus allowing them e.g. to design mitigation plans, to develop policies and programs for water management and land use, or to monitor flood defence infrastructure.

To achieve these results the SubCoast work program has been organized around the following topics:

- Deriving indicators of environmental and economic impact made by subsidence by making use of state-of-the-art scenario and impact models;
- Developing a coordinated data provision service for necessary terrestrial and satellite data, and input data streams from GMES Core Services and GMES Service Element Terrafirma and functioning as a portal for SubCoast-services;
- Testing the SubCoast-concept through dedicated pilot services making our approach viable and supportive;
- Demonstrate how the SubCoast-products will be integrated into current user practices and their working environment;
• Build service sustainability by developing a service delivery model which will transform the project into an operational downstream service and includes Service Provision Agreements (SPA) to ensure quality, standards and feedback as input to service improvement.

The work in SubCoast has been organized following the structure of figure 1 below.

Four pilot studies have been devised to develop SubCoast services (see figure 2). These include the Rhine Meuse Delta in the Netherlands, the Southern part of the coast of Emilia-Romagna region in Italy, and a part of the Baltic area (subdivided into 3 countries: Denmark, Poland and Lithuania). The fourth pilot is aiming to develop a ‘European integrated service’, through harmonizing methodologies and information at European level. Being distributed across several countries in Europe, the four pilots have a variety of factors influencing their vulnerability to hazards, but also a variety of data availability, technical standards and organizational frameworks.

Project Results:
1. Scenario’s, impacts and user requirements
Climate change and subsidence are hazards with a long time frame and a large spatial scale (up to global level). To be able to make decisions at an early stage on drastically adaptation measures a framework is developed to assess the current and future state of the natural environment and safe living environment with reasonable efforts, regarding the information needs for subsidence and decision making on impact of climate change in coastal areas.

The Assessment Framework (fully described in Report D1.1) gives an overview of the coastal system and it is a guideline how to structure the inventory of stakeholder information needs regarding scenarios, impact analysis, risk and the decision process on measures (figure 1.1)

Regarding the drivers of change, several scenarios should be taken into account for the impact analysis in order to deal with the uncertainty and possible consequences in the future under a variety of socio-economic and environmental scenarios. This gives important information for decision makers to select appropriate adaptation measures. This has been further elaborated towards a schematic overview of main indicators for drivers and pressures (figure 1.2) which can be used to identify risk level for several themes and hazards where subsidence is involved, specified for 3 spatial layers with different planning characteristics and dynamics (Occupation, Network, Base).

These frameworks regarding drivers, impacts and scenarios have been tested, exchanged and further analysed in the pilot areas of SubCoast, to identify user needs regarding information products, services and tools based on integration of various information sources within the scope of SubCoast. Several workshops with stakeholders and decision makers have been organized accordingly. The results have been summarized in tables 1.3a-b-c including reference to estimations of involved costs in the Netherlands.

2. Dynamic DEM
From further consideration of the results of WP1, ongoing discussions about SubCoast products and services and new experiences from the pilot studies it has been concluded that one core parameter is
required to deliver basic information for almost every policy or planning issue related to ground
subsidence: time dependent elevation of the ground surface at a certain location or in a certain area. This
information is required to derive any other information, model or service about impact or costs of
subsidence (e.g. increasing flood risk). Therefore, SubCoast has focused on development of one core
service: Dynamic DEM (DDEM) (see figure 2.1) a digital elevation model (DEM) that is time dependent,
including proper definition within a common geodetic datum and appropriate quality metrics. This concept
integrates many of the separate products and activities described in the DoW. The concept and
methodology of a DDEM is reported in the pilot harmonization report (D3.1.1) which also includes a
manual for development of a DDEM in the pilot areas. The methodology is applied to a full extent for the
nation wide area of the Netherlands (D3.2.1).

Description Dynamic DEM

The Dynamic DEM is defined as a digital elevation model (DEM) that is time dependent. In this context we
consider the DEM to be a terrain model (the bare ground, without buildings), and not a surface model
(following the outline of buildings). In order to satisfy the requirements in relation to flood risk, the Dynamic
DEM needs to be:
1. defined in a common geodetic datum, and
2. accompanied with appropriate quality metrics.

These two conditions reveal some important conceptual choices. First, in relation to what is popularly
implied by ‘relative sea level rise’, here we do not aim for direct relative measurements between the off-
shore (sea level) and the on-shore (land level) vertical. An example of such type of measurements would
be tide gauge observations, with a direct relative link between the off-shore and on-shore elevation.
Instead, we seek to estimate ‘absolute’ elevations, both on-shore as well as off-shore, defined in a well-
defined geodetic vertical datum. The rationale behind this approach is that it allows for the efficient
coupling between different data sources (on-shore and off-shore, in the past, now or in the future),
including quality control, and that it is independent of the various definitions used, e.g. for sea level with
Mean Sea Level, High-Tide levels, surges, etc. The requirement is that all types of input data should be
defined in such a geodetic datum, and that ‘datum connection’ (the transformation of coordinates from one
datum to another) is possible.

A conceptual choice related to the second condition (appropriate quality metrics) is that we do not
necessarily aim for the ‘best product’ at this time. A product which is perhaps not optimal, but which has a
realistic quality description, will still be useful for several applications, policy decisions, and useful to
concentrate resources to the weakest link in the chain. An example of such a product is a Dynamic DEM
based on input elevation data with poor precision and reliability. Such a product would perhaps not be
directly applicable for the finest flooding simulation studies, but the proper quality description allows for a
realistic assessment of its possibilities. Likewise, should there be a need for a better product, it will be
clear which data set should be improved.

The Dynamic DEM can be split in two parts: a contemporary (geodetic) part and a prospective
(geophysical) part. The contemporary part is based on all available surveys/observations performed until
the last campaign, whereas the prospective part aims to predict the future development of the elevation, in
order to facilitate adequate policy decisions. It should be noted that the contemporary part may also
include observations or inferences from, e.g. geological or geotechnical surveys, as long as (i) these are
quantitative and (ii) they are accompanied by appropriate quality metrics.
Both the contemporary as well as the prospective Dynamic DEM have uncertainties. The quantification of these uncertainties is perhaps the most important aspect of the entire product. In other words, if a product such as a Dynamic DEM would not be accompanied with quality metrics, it is essentially useless. Here we stress that any product, even with a poor quality level, can be useful as long as the quality metrics are appropriate. It is evident that the quality of the contemporary and the prospective DDEM may be very different, particularly for the realization/prediction of the D-DEM on very long time scales ahead.

The Dynamic DEM is an elevation, hence it is defined in the unit of meters, and it always needs to be ‘time-stamped’. On the spatial axes, it’s realization can have different forms, such as an inhomogeneously sampled set of points, a gridded set of observation, an interpolated grid (i.e. a map), or even the elevation at a single location, as long as it satisfies the two main conditions discussed above (geodetic datum and quality metrics). In the context of the project, it should be stressed that as the basic unit of the DDEM is meters, it is not a velocity or a rate (e.g. with the unit mm/year). This implies that velocities may be one of the core input observations needed to estimate the DDEM, but they are not useful when used autonomously, i.e. in the absence of real elevation data (in meters).

On the temporal axis, the D-DEM can be evaluated at a single epoch via a functional description of elevation (as a function of geographic coordinates and time), or static via a discrete time series. Both the spatial and the temporal axes combined indicate that a representation in a dynamic GIS (or web-GIS) would be optimal.

3. Dynamic DEM’s in pilot areas

The creation of the Dynamic DEM in a certain area relies on the availability of input data, availability governs what level can be created; five products have been identified, connected to the SubCoast pilot areas:

1. DEM + PSI + 1 GPS (Lithuanian case)
2. DEM + PSI + 1 GPS (Polish case)
3. DEM + PSI + GPS + levelling (Italian case)
4. DEM + PSI + GPS + levelling + gravimetry (Dutch case)
5. DEM + Modelling (European Integration case)

Necessary steps for each pilot to produce their version of the Dynamic DEM have been describes in report D3.1.1.

Dynamic DEM results from Lithuanian case (description report D3.4.6)
(see figure 3.1)

Dynamic DEM results from Polish case (description report D3.4.6)
(see figure 3.2)

Dynamic DEM results from Danish case (description report D3.4.6)
(see figure 3.3)

Dynamic DEM results from Italian case (description report D3.4.6)
(see figure 3.4)

Dynamic DEM results from Rhine-Meuse case (description report D3.2.1)
For the Rhine - Meuse pilot (basically covering the area of the Netherlands), the development of a DDEM has been carried out to the most comprehensive and area wide extent, enabled by satellite data with more or less sufficient spatial and temporal coverage, availability of proper ground truth and in-situ data and advanced geodetic expertise. This nation wide area product, elaborated up to significant high quality metric levels, has functioned as a methodological example for elaboration of the DDEM’s in other pilot areas.

By providing a framework that used least squares for an efficient integration of different geodetic techniques it was possible to disentangle Holocene and deep deformation sources, which exhibit different spatial variabilities. This resulted in maps of the absolute vertical rates that are caused by these two categories of deformation sources (see figure 3.5). The deformation of the absolute Dutch vertical Datum used for leveling could be established, which was $-1.1 \pm 0.3 \text{ mm/yr}$. A map of the total deformation was produced by summation of Holocene and deep deformation rates. The surface subsidence in the free field is not captured and sometimes differs considerably from the geomechanical sensitivity map, due to the lack of representative persistent scatterers. The drainage driven mechanism has a longer period than the observations and cannot be captured by the present data sets. This also holds true for the pilot areas. It is expected that with the development of the next generation satellites this can be overcome.

Dynamic DEM results from European Integration case (described in D3.5.6)

A main result from the European Integration product is the ‘potential subsidence map of European Coastline’ (see figure 3.6). This has been compiled according to a specifically designed methodology using digital geological data emerging from OneGeology Europe, calibrated with PSI-data where they are available (e.g. from the ESA GSE Terrafirma and EC FP7 PanGeo) and careful assessment by experts.

In order to fulfill the requirement to forecast potential flood risks along the European coastline it is necessary to have a dataset that contains the current absolute sea heights and a corresponding dataset that contains the current baseline land elevation i.e. a Digital Elevation Model (DEM) (see also figure 2.1). The report D3.5.6 outlines the methodology used to create those layers.

In order to satisfy the requirements in relation to flood risk, the baseline DEM (and therefore the Dynamic DEM) need to be:

1. defined in a common geodetic datum, and
2. accompanied by appropriate quality metrics.

The European Integration Product does not produce direct relative measurements between the off-shore (sea level) and the on-shore (land level) vertical. An example of such type of measurements would be tide gauge observations, with a direct relative link between the off-shore and on-shore elevation. Instead, we seek to estimate ‘absolute’ elevations, both on-shore as well as off-shore, defined in a well-defined geodetic vertical datum. The rationale behind this approach is that it allows for the efficient coupling between different data sources (on-shore and off-shore, in the past, now or in the future), including quality control, and that it is independent of the various definitions used, e.g. for sea level with Mean Sea Level, High-Tide levels, surges, etc). The requirement is that all types of input data should be defined in such a geodetic datum, and that ‘datum connection’ (the transformation of coordinates from one datum to another) is possible.

A datasets providing information on the rate of change of sea surface height was identified in the form of a global sea level trend grid produced by the National Oceanic and Atmospheric Administration (NOAA).
This grid details sea level rise or fall (in mm/yr) at a spatial resolution of 0.5° x 0.5°, and was produced using satellite altimetry measurements from 1992 to the present (see figure 3.7).

4. Other case results from pilot areas

Cases Rhine Meuse area
The pilot cases were chosen as examples based on current issues and projects of current stakeholders in relation to subsidence.

Full use was made of Persistant Scatterer-InSAR data, in combination with terrestrial data from national and local leveling and GPS networks. Where available, full use was made of results obtained in the GMES Terrafirma project. In addition, data were used to help explain the observed ground motion: geotechnical data, hydrogeological data on ground water levels from instrumented boreholes, and data on gas injection and extraction rates. The Geological Survey of the Netherlands provided a detailed 3D model of the subsurface that was used in the interpretation and forward modeling of subsidence (see figure 4.1).

As topographic reference datum the Netherlands has a full cover of airborne LIDAR-type altimetry data available. This reference was used as a starting point to construct a dynamic DEM, incorporating observed subsidence and forecast extrapolations of subsidence estimates, in order to provide a basis for the analysis of risks associated with subsidence.

SubCoast products aim to provide useful information necessary to understand and mitigate against the processes involved in coastal flooding risks. This was tested and achieved by constructing a nationwide subsidence map (figure 3.5) and by applying the full range of techniques to 6 cases study areas, grouped in two main areas, focusing on respectively, coastal and on-land subsidence.

The Dutch North Sea Coastal Region study uses the Absolute Wide-scale Subsidence Map in combination with other in-situ data sources, such as geo(hydro)logical data, data on gas extraction or injection, and information on buildings and building projects. The validation and interpretation is focused on subsidence forecast with respect to dike safety assessment, flood risk and impact and groundwater salinity. The pilot locations are Schouwen-Duiveland, Nijmegen and Harlingen. For the location Alkmaar a novel recursive algorithm was developed to enable the assessment of gas-reservoir and surrounding rock properties directly from line-of-sight PS- INSAR data, without the need for unraveling the data in horizontal and vertical components.

In the Zuid-Holland Region study the focus is on the influence of groundwater management and the shallow compaction in sensitive urban areas, largely below sea level. Here user-requirements and feedback from end-users of local authorities and water-board districts (Delft, HH Delfland) was used to tune the analyses in order to help end users to make better founded policy decisions. The locations are Delfland and Zuiderzeeland.

Within the Rhine-Meuse pilot 20 years of satellite radar imagery is used. The imagery is provided by the ERS-1/2, Envisat and RadarSAT-2 missions. For the interpretation of the PSI datasets, focus has primarily been on a surface covering analysis and not on a point-to-point explanation of the observed movements. The PSI datasets are used to look back in time, in order to pinpoint the major components in the surface movements. These data are subsequently confronted with the modeled subsidence in order to
be able to predict the future subsidence more accurately.

The cases provided the following developments and services:

Case Delfland (see figures 4.2 and 4.3)
PSI results obtained in Delfland show that radar interferometry is a suitable technique for obtaining very accurate deformation measurements and subsidence/uplift rates of ground and non-ground stable reflections. As expected, there is a marked difference between the densities of reflections from urban areas as opposite to the rural ones. A ground/building point separation was performed for a neighborhood in Delft. The quality of measurement points can vary locally but overall was in the sub-centimeter range. It was heavily influenced by the number of available images, which is at the lower limit in the case of the Radarsat-2 dataset. The analysis of the deeper geodetic benchmarks shows subsidence features that can be related to gas and water extraction.

Case Zuiderzeeland (see figure 4.4)
PSI results obtained in Zuiderzeeland show that the PSI technique provides extra information regarding subsidence (values and rates) in the urban area. The deformation in the rural area lacks representative reflectors. The AHN-2 Lidar data were validated against leveling at 20 points where long term subsidence data (since reclamation) were present. An inverse model was set up to quantify the compaction parameters from the observed subsidence. With these parameters the subsidence predictions were applied on a 250*250 m grid. Contrary to the soft soil areas elsewhere in the Rhine-Meuse delta, the relatively recently reclaimed areas are still influenced by a process of soil ripening, which complicates the forward model. This makes the forward model limited spatially to the calibration area.

Case Harlingen (see figure 4.5)
The deformation of the dikes near Harlingen was investigated as well as the deformation due to salt and gas extraction. Using both lines of sight it was possible to provide both horizontal and vertical deformation measurements with high point measurement density, thus exceeding the capabilities of traditional surveying techniques.

Case Schouwen-Duiveland and Case Nijmegen
The deformation of the dikes around Schouwen-Duiveland island and along the River Waal is of most importance for these pilots. The PSI results prove to be also in this case a powerful tool for dike inspection. Results with the C-band satellite data show that PSI can provide a limited amount of measurement points on river winter dikes which lack any hard grass cover.

Case Alkmaar/ Bergermeer gas field
An Ensemble Smoother with Multiple Data Assimilation on line-of-sight measurements of PSInSAR data was used to estimate subsurface parameters of the Bergermeer gas field. In this study we have for the first time used ascending and descending line-of-sight measurements in a data assimilation scheme without first unravelling vertical and horizontal components of the movement. Furthermore, the direct use of the line-of-sight measurements omits a possible source of uncertainty and is to be preferred when PSInSAR is used for the assessment of subsurface parameters.
In the limited feedback response, the added value of the technique was recognized, but the development
of improved techniques to monitor free field subsidence in rural areas was seen as a requirement for the application in water management.

Cases Baltic pilot area

Coastal erosion maps (neo)tectonic maps for Lithuania, Poland and Denmark case studies
Coastal erosion was analyzed using various datasets, the description of these analysis was presented in detail in D 3.4.4 “Coastal difference maps based on VHR-optical and TerraSAR-X data” (see fig. 4.6)

The (neo)tectonic products contain raster tectonic map that is the result of joining together all available tectonic, remote sensing, geophysical and geological structural information. This deliverable contains also result of the analysis tectonic map together with PSI data. The description of the product included also proposed requirements for using InSAR data for tectonic movements monitoring (see fig. 4.7)

Cases Italian pilot area

3D motion component estimation
Having access to 3 or more (satellite) datasets providing independent measurements of the 3D displacement vector projected along different LOS (Line of Sight) directions, it would be possible, at least in principle, to retrieve a full 3D displacement field affecting the area of interest (Coastal area Emilia Romagna).
For the Subcoast project, the available 2 C-band and 2 X-band datasets available have been used to assess the quality of the estimation of the full 3D deformation vector. The estimated vertical, East-West and North-South motion component, and the corresponding standard deviation values, are shown in Figures 4.8 4.9 and 4.10 below.

5. Validation and Product reviews
The acceptance of the SubCoast products by the end-users depends on the validation of the entire service chain and, therefore, a validation activity has been undertaken to provide the end-users with re-assurance on the quality, consistency and wider applicability of the SubCoast products.
The D3.6.2 report describes some of the validation activities carried out within SubCoast. Other important documents devoted to validation issues are D3.6.1 “Integrating Framework Document”, D3.6.3 “Final Product Review”, and the deliverables that describe the activities carried out within the different Pilot services.

Many of the SubCoast products are based on PSI and SAR-derived products. For the validation of these products, the results of the Terrafirma project, which carried out several validation activities of PSI and SAR-derived products, were taken as reference within the SubCoast project. Therefore, the PSI results generated during SubCoast were not validated in the strict sense of the word. In D3.6.2 the most important PSI validation results obtained during the Terrafirma (TF) Validation Project have been described with the aim of providing a concise summary of the PSI validation results. This includes: (i) the main objectives of the TF Validation Project; (ii) the description of the two main component of the TF Validation Project: the Process analysis (Crosetto et al. 2008a) and the Product validation (Hanssen et al. 2008); (iii) the test
sites of the project; (iv) and a summary of the most relevant project results. It is important to underline that in the TF Validation Project the SubCoast providers of PSI data (i.e. Telerilevamento Europa (TRE), Fugro NPA and Hansje Brinker), underwent a “certification process”, which is also valid for this project. Even though the PSI results were not meant to be validated in the SubCoast project, a kind of “intermediate validation” was carried out in SubCoast. This involved the inspection of the PSI data delivered to the Pilot services in charge of generating the SubCoast products. Specifically, it involved the analysis of the PSI results provided to the Baltic Pilot –Poland, Lithuania and Denmark. The main outcomes of the “intermediate validation”, are briefly described below.

Concerning the TerraSAR-X results (Poland and Lithuania), the presence of thermal expansion together with the noisy behaviour of the deformation map are solid arguments to advise against using these PSI results in the generation of the SubCoast products. This is a surprising conclusion because: (i) as mentioned above, PSI results were assumed to be well-known and validated. This is a correct assumption for ERS and Envisat data, but not for high-resolution X-band data, like TerraSAR-X and CosmoSkyMed; (ii) the TerraSAR-X data are the most advanced PSI input data in terms of spatial resolution and phase quality and, therefore, rich PSI deformation results are expected from them. However, their correct exploitation requires advanced data processing and analysis procedures, not available in this project. Additionally, a set of PSI results was rejected and not considered in the subsequent analyses (the ascending ERS dataset over Lolland, Denmark). Finally, the PSI results of the city of Klaipeda (Lithuania) carried out from both ERS and TerraSAR-X data, were analysed due to unexpected results as the presence of PSs on the dunes. In this case, the main issue is data interpretation, which mainly concerns the mechanism that allows several PSs to show a relatively high long-term coherence. This atypical behaviour requires new, ad hoc, analyses which, however, are outside the scope of the SubCoast project. The last part of this document focuses on a preliminary discussion concerning the validation of the DDEMs. The implementation of the DDEMs generated in SubCoast can be seen as a first preliminary effort to provide a DDEM solution, which was based on the DDEM input data available in each pilot. It is worth underlining that this preliminary effort already included an estimation of the quality of the DDEM input/outputs. This is fundamental because a product which is perhaps not optimal, but which has a realistic quality description, will still be useful for several applications. In this report a complete procedure to compute the uncertainty of any DDEM solution has been described. Besides, the above procedure assumes that the DDEM input data are already available. This is the case of the four DDEMs considered in this document. A more general case has been described, which could be included in a project that continues the SubCoast project by extending the use of the DDEM to all those strategic applications that need scientific and technically sound DDEM predictions.

References

The ‘Final Product Review’ report (D3.6.3) describes the comparison of the resulting deformation model for the European integration against the deformation model generated for the Netherlands. These deformation models (represented by the maps of figures 3.6 and 3.5) are closely related to the DDEM, which is a time dependent digital terrain/ elevation model, i.e. it is defined as an elevation as a function of time and location. The implementation of the DDEM requires two main parameters: heights (DEM) and rates (deformation model).

Potential Impact:
6. Data Provision Service
The architecture design of the information infrastructure and functionalities of the database and web portal have been developed in such a way that it can build DDEM-maps and elevation profiles at locations from the available basic data. It includes translation of the developed methodology concerning calculations, datum references, etc. in the portal structure and database technology. Much attention has been paid to the development of the interface and structure of the portal. However the DDEM is rather clear-cut as a concept, the translation to an IT-infrastructure involved components, calculations and tools that were far from trivial: new tools and visualisations had to be designed and handling large datastreams required special expertise and design. The Rhine-Meuse ‘wide area’ pilot has been used as pilot case for implementation in the portal, because for this area the DDEM has been developed to the furthest extent; components of the DDEM’s of other pilots have been added in the next stage, as well as other results and maps from pilot cases that were no particular part of DDEM’s.

The portal has been developed up to the stage of a prototype. At the end of the project it was concluded that the maximum DDEM-information output that could be delivered (for the Rhine-Meuse pilot) is not yet sufficient to use in real policy, planning and risk or water management. This was also obvious for the other pilot studies that could be developed to a less comprehensive extent than the Rhine-Meuse pilot. Although SubCoast has made very substantial progress towards delivery of DDEM information, the current constraints regarding availability of data and models, time coverage and status of technological development of the DDEM-methodology require expert knowledge to interpret the information from the portal. Because in several coastal areas subsidence information could be rather sensitive the SubCoast team decided to provide only restricted access to the portal to avoid misinterpretation.

From the perspective of dissemination and public data provision these restrictions are important topics that need to be addressed in follow-up developments. It is required to dissolve such constraints for the involved organizations regarding the current unclear (legal) responsibilities with regard to the provision of potentially sensitive hazard information, as well as other legal limitations towards the data provision in various countries. In the last stages SubCoast has engaged with the consortium of the EGDI-Scope project (a feasibility study for a European Geological Data Infrastructure (EGDI), which aims to provide the backbone for serving interoperable, pan-European geological data, and data from past, ongoing and future European projects) to exchange about these topics. At the same time, SubCoast has been included as one of the priority projects to be included in the Implementation phase of the Roadmap for the EGDI, which considerably advances the chances for sustainability and development of an appropriate framework for public dissemination.
Under control of the Consortium partners, the current prototype can be used for communication and demonstration purposes, e.g. to explain the possibilities of comprehensive DDEM information and required elements of follow-up research & development. Further development of the portal will depend on the further development of DDEM technology and service applications.

In order to serve all available data a complete hardware infrastructure has been built, containing the following components which runs on 4 independent servers:

- ARC GIS Server (WMS, WFS)
- Alfresco Document Management (Project data and project results)
- Database server (Postgres and Postgis) to provide the queried DDEM location and area maps (currently including up to 300 million records for DDEM);
- Geonetwork Application Server for:
  - Query
  - Search Metadata
  - Visualisation

The basic functionality covers zoom, map transparency, export, etc. Towards the more advanced tooling for the portal a more customized tooling environment has to be developed, connected to user requirements that are evaluated in work package 1 and subsequent activities in the pilots (work package 3). Additional functionality (see figure 6.1):

- Focus on 1 map, or compare 2 or 4 maps simultaneously;
- Browse the map library, categorized per region;
- Linear calculation of future subsidence rates from historic deformation rates (based on SubCoast methodology to determine subsidence rates);
  (From the geophysical viewpoint this option is of course controversial, because one cannot assume that future subsidence rates are similar to trends in the past; however, presenting the functionality in the portal can make clear that further development of the service should go in this direction, including geophysical modelling of subsidence)
- Scroll through 2010, 2025, 2050, 2100 and 2200 for each elevation or deformation map;
- View historic data and future trends in one graph for each grid point;
- Compute new elevation or deformation maps for a specific moment in the future for small regions;
- The ‘base elevation’ (DEM connected to a certain baseline year, representing current height levels, e.g. DEM 2010) and it’s uncertainty levels (error bars) together on one screen (side by side);
- 4 map viewing areas, with interconnected zooming functionality;
- Functionality to view and compare maps at different points in time (2005 – 2010 - 2050 – 2100 - 2200)
- Selection of one point of interest (see figure 6.2)
- Selection of array of interest (see figure 6.3)

The relevant datasets were available from the activities in the pilot areas. Within the framework of the integral design of the portal functionality and layout, the portal has been updated after finalization of different components of DDEM’s in the case studies in pilot areas, and the corresponding reports (D3.2.3 D3.3.9 D3.4.6 and D3.5.2/ D3.5.3).

The following categories have been included in the portal:
7. Service sustainability and market development

A fundamental issue with regard to service sustainability and market development is that at this stage of development of the core SubCoast product, the Dynamic DEM and its components, it cannot be easily transferred into specific products and services for dedicated markets. Fully elaborated Dynamic DEM's clearly need a lot of extra surveying and research. Once available, this will result into a basic, generic service delivering geographic information about height levels of areas and locations over time, producing a clear parameter that can be incorporated in work flows of potential user groups. From this perspective the DDEM approach produces baseline information, on top of which other services could be built. In most cases this requires combined analysis including other information sources, e.g. status of coastal defence infrastructure, regarding population, economic activity, land use, etc. However this was touched in some cases these more comprehensive analyses were outside the scope of the SubCoast project. In combination with the status of Dynamic DEM’s as a prototype baseline service, becoming available at the end of the project, this means that it was basically too early to establish concrete service delivery models and specifications with certain dedicated end users. In other words, there is a gap between the development stage of services that could be achieved within SubCoast, and fully developed products and services that could actually be ‘sold’ to certain ‘markets’, predominantly departments of public bodies and water boards.

From the cost analysis in the Rhine Meuse study (D1.3 section 4.4) it may be concluded that market potential for subsidence information must certainly be there, regarding the estimated annual 3.5 billion damage costs of subsidence impacts in the Netherlands alone. The character of this potential market will be connected to avoidance of damage costs and flood risk protection (more indirectly, because subsidence represents a smaller component of flood risk). Both topics are primarily connected to the public domain.

First steps towards possible applications and services for private parties, predominantly E&P industry, have also been addressed (D3.2.3.1) but market development is really premature, and requires substantial
multi-annual efforts. This perspective is more or less the same in case of the other services defined in the SubCoast project. These findings changed the perspective of a number of deliverables within work package 4; therefore the contents of these deliverables have been adapted as appropriate as possible, but within the framework of the original work plan. Some results from these studies are listed below:

- D4.1. Catalogue of User Services
- D4.2. Service Portfolio Specification (SPS)
  This includes the outline of four types of products; core (full Dynamic DEM product), partial (partial elements of the Dynamic DEM), other products such as flood risk maps, and also other products not directly related to subsidence phenomena but providing useful coastal information.
- D4.3. Service Provision Agreement
  The SPA provides a basic service agreement template between a SubCoast service supplier and an end recipient. The SPA outlined five specific functions; collect information relevant to the area of interest, specify the service to be provided, enable the release of the SubCoast service to the recipient, ensure minimum level of feedback from the recipient to assist the development and improvement of the SubCoast Service, and help stimulate further interest and investment to increase coverage of SubCoast Services. The high-level of definition of the SubCoast service, i.e. Dynamic DEM, did not allow for a more specific agreement to be drawn up at this time.
- D4.5. Service Delivery Consultation Note
  This document outlines the methods used to consult potential end users and obtain stakeholder views on the SubCoast service. It was found that interest in SubCoast products and services had different economies of scale, i.e. from small businesses to governmental organisations from the local to national scale. However, interest in SubCoast was not backed by a willingness to pay for such a service, partly because of the view that this type of information (ground deformation) should be provided by public bodies. The difficulty in gauging customer interest and achieving financial backing was due to a number of issues, the alteration in the view of SubCoast towards service development and its subsequent definition only in the latter stages of the project, was likely a contributing factor.
- D4.6. Service Delivery Model
  Because the core SubCoast (prototype) service achieved a demonstrable status only at the very end of the project, composing an economically sustainable service delivery model was challenging. In addition to this obstacle, at this stage there was no apparent potential for the SubCoast service to be privately funded based upon the findings of the stakeholder consultation that took place. The Service Delivery Model therefore took into account a number of scenarios and considerations that were deemed important to any potential continuation of a SubCoast service.

It was identified that in its current state the SubCoast service is not yet sustainable as a working service due to lack of investment potential from envisaged end users. For this, further development towards a mature product for market application needs to be covered by follow-up funding programs. SubCoast and the Dynamic DEM were of great interest, but it needs to be shown how the Dynamic DEM could be incorporated into workflows of companies and departments and the tangible cost/benefit showcased. In this stage, it can be concluded that the type of services and products that could be built on SubCoast results will be valuable primarily for public purposes; applications for the private sector are further ahead.

For a part, the situation can be compared to DEM’s: no-one would question the need for elevation maps and DEM’s for society, but no-one will earn money from selling them .... the same could be the case for
DDEM’s in the future.

Future outlook and research agenda
Based on results and experience of the project – and exchanges with stakeholders at diverse occasions such as the final SubCoast symposium - SubCoast concluded that continued development and provision of DDEM’s is pre-conditional to develop relevant services for mainly public agencies involved with flood risk management, water management and planning in coastal lowlands. The new satellite missions (Sentinel) provide very good opportunities for this. A future outlook and research agenda includes the following items:

- Broader ‘DDEM-coverage’ in Europe
- Geological/ Hydrological modelling to enable ‘forecasts’ component of DDEM
- Include scenario’s (socio-economic, land-use, climate) connected to modelling
- Monitoring over longer time periods; continuity
- Higher resolutions/ point densities
- Improve land/sea transitions from satellite monitoring
- Improve geodetic datum connections
- Improve service delivery and data provision

8. Dissemination activities and results
Further dissemination activities and results, in addition to website, portal and market development, are described below.

Santorini Forum and ESA publication
To anticipate on the necessary further development of services and products for relevant target groups on the longer term, much effort has been put into development and dissemination of a common perspective on future research and services with regard to earth observation for subsidence and flood risk management. These activities were mainly connected to the International Forum on Satellite Earth Observation and Geohazards in Santorini (May 2012), in close co-operation with the TerraFirma consortium. SubCoast contributed a full chapter to the subsequent ESA publication (publication title: The International Forum on Satellite EO and Geohazards; SubCoast/ Terrafirma contribution: Chapter 5; Perspectives Concerning Satellite EO and Geohazard Risk Management: coastal lowland subsidence and flood defence). It is expected that this publication, under the auspices of ESA, can support significant dissemination of SubCoast and Terrafirma topics to research communities and stakeholder communities connected to GMES/ Copernicus, GEO and Horizon 2020. This publication could set the agenda for broader European and global application of the developed methodologies in subsidence prone areas (see figures 8.1 and 8.2)

Engagement with European Environment Agency
Within the framework of the development of European integration products (WP3.5) SubCoast has regularly engaged with representatives of the European Environment Agency. Two workshops have been attended in Copenhagen, and the Potential Subsidence Map of the European Coastline (figure 3.6) its explanation and a short description of SubCoast have been included in EEA-report “Balancing the future of Europe's coasts — knowledge base for integrated management (2013)”.

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Final SubCoast symposium Delft

Taking the advice of the Commission connected to the midterm review, substantial efforts have been applied to organize the final SubCoast symposium (see figure 8.3) connecting the research community (SubCoast partners and comparable institutes) with representatives from public agencies and departments involved in civil protection and emergency response and their technical consultants. This was organised in Delft (Netherlands) and it was well-visited (see table 8.4 for list of participants). The final seminar resulted in a number of follow-up activities for different consortium partners regarding follow-up DDEM-research in their own areas, as well as dissemination of developed methodologies and market development activities in Asian countries, where subsidence risks related to flooding are much more prominent.

Television broadcastings (Netherlands)

SubCoast partners have contributed twice to television broadcastings in the Netherlands:


Banner

For dissemination purposes, a SubCoast banner has been designed, and taken to various events and conferences (see figure 8.5).

Posters

Some examples of SubCoast posters are included below (see figures 8.6)

List of dissemination activities (conferences and events)

1st Reporting period
- Toulouse Space Show, Toulouse, June 2010
- ESA Living Planet Symposium, Bergen, July 2010
- GEO 5th User Workshop, London, Feb 2011

2nd Reporting period
- AEGEE-delegation, 28th July 2011 (presentation)
- GRSG (Geology & Remote Sensing Group), Frascati, 6th December 2011 (presentation)
- ESA-GEO Santorini Forum, 21-23 May 2012 (4 presentations, workshop)
- EUREGEO, Bologna, 12-15 June, 2012 (poster + presentation)

3rd Reporting period
- European FLOODRisk Conference, 21 November 2012, Rotterdam (workshop, presentations)
- Monitoring Matters; In-situ coordination in support of Copernicus operations, EEA, Copenhagen, 10-11 April 2013 (poster)
- EGU Assembly 2013, Vienna, 7-12 April 2013 (presentation, poster)
- GEO European Projects Workshop, 15-16 April, Barcelona (presentations)
- 6th EARSeL Workshop on Remote Sensing of the Coastal Zone, Matera, 7-8 June 2013 (poster)
- ESA Living Planet Symposium, Edinburgh, 9-13 September 2013, (poster)
- SubCoast final symposium, Delft, Waterboard Delfland, 25th September 2013, Delft (fully organised by SubCoast consortium)

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