MONITORING SUBSIDENCE OF COASTAL LOWLAND AREAS BY SATELLITE RADAR INTERFEROMETRY

Rob van der Krogt [1], Gabriele Bitelli [2], Chris Bremmer [1], Ren Capes [3], Michele Crosetto [4], Jolante Cyziene [5], Marek Granizcki [6], Ramon Hansen [7], Freek van Leijen [8], Stuart Marsh [9], Fabrizio Novali [10], Stig Schach Pedersen [11], Rogier Westerhoff [12]

1. TNO, Netherlands; rob.vanderkrogt@tno.nl
2. University of Bologna, Italy; gabriele.bitelli@unibo.it
3. Fugro-NPA, United Kingdom; r.capes@fugro-npa.com
4. Institut de Geomàtica, Spain; michele.crosetto@ideg.es
5. LGT, Lithuania; jolanta.cyziene@lgt.lt
6. PGI, Poland; mgra@pgi.gov.pl
7. Delft Technical University, Netherlands; r.f.hanssen@tudelft.nl
8. Hansje Brinker, Netherlands; f.j.vanleijen@hansjebrinker.com
9. BGS, United Kingdom; shm@bgs.ac.uk
10. Tele-Rilevamento - TRE s.r.l., Italy; fabrizio.novali@treuropa.com
11. GEUS, Denmark; sasp@geus.dk
12. Deltares, Netherlands; rogier.westerhoff@deltares.nl

ABSTRACT

Coastal lowland areas may be affected by various geohazards; one of them is the subsidence that, when combined with sea level rise and extreme weather events, aggravates flood risk, deteriorating the flood defence and increasing the exposure, with a potential large range of social, economic and environmental impacts.

Space-based techniques can be today used for monitoring this phenomenon, in addition to traditional geodetic methods; in particular PSI (Persistent Scatterer Interferometry) data from radar satellite sensors can provide detailed information to assess with high precision the terrain motion for long periods and at different scales of investigation: local, regional, national.

Within the EU FP7 framework, the ongoing SubCoast project aims to provide data on changes in land elevation for coastal lowland areas combining the information coming from PSI processing with other kind of data, providing services for stakeholders dealing with issues pertaining to hazard management, monitoring and policy development (e.g. water boards, departments of ministries, provinces, regions and municipalities throughout European coastal regions, as well as authorities at European scale such as the European Environment Agency).

Three pilot studies have been devised to develop the SubCoast service, together with a fourth pilot comprised of a parallel 'European integration' of services.

INTRODUCTION

Coastal lowland are the most populated areas in the world and of great economic importance. Utilization of the coast increased dramatically during the 20th century, a trend that seems certain to continue through the 21st century. It has been estimated that 23% of the world's population lives both within 100 km distance of the coast and <100 m above sea level, and population densities in coastal regions are about three times higher than the global average.

Several factors relate coastal lowland areas and deltas to risk, and one of the most important, although often hidden, is land subsidence. The shallow subsurface in lowland areas frequently contains compressible soils which are vulnerable to subsidence. Furthermore, these deposits have a substantial spatial variability due to sedimentation and erosion processes, introducing a spatial component in the vulnerability to subsidence. In addition to natural processes of ripening,

compaction and peat oxidation, human factors also influence the terrain level: the extraction of natural resources like groundwater, salt, oil or gas in deeper layers (ranging from tens of meters up to thousands of meters) may cause subsidence at the surface.
Many coastal areas are suffering from subsidence, and it results in:
- increased flood vulnerability
- changing groundwater levels, disruption of the water management and related effects (water nuisance, increased salt water intrusion, reduced crop yields, droughts and related water supply etc.)
- damage to buildings, foundations, infrastructure (roads, dikes) and subsurface structures (drainage, gas pipes etc.)
- disruption of the water management and related effects (water nuisance, increased salt water intrusion, reduced crop yields,droughts and related water supply etc.)
- increased CO2 emissions due to accelerated oxidation of peat areas
- nutrient leaching
- reduction in biodiversity and ecological value.

Land subsidence can have immense socio-economic impacts in coastal areas and urbanized deltas (figure 1). The floods that took place in Europe over the recent decades have shown an increase in economic losses. This is the result of increased populations and wealth in the affected areas. The total damage worldwide is estimated at billions of dollars.

Figure 1 - Coastal lowland areas (solid blue) and deltas (green points) in Europe, from (1)

Coastal lowland areas are furthermore widely recognized as highly vulnerable to the impacts of climate change, particularly sea-level rise and changes in runoff, as well as being subject to stresses imposed by human modification of catchment and delta plain land use (2). Global sea level has reached an annual average rise of approximately 3 mm during the last two decades (1), although regional differences exist (mean sea level has fallen in some locations). Combining this information with measurements of downward changes in land elevation would allow easier identification of Local and Regional Authorities exposed to increasing flood risk - area prone to flooding could increase 50% during 21st century - thus allowing them to design mitigation plans. Existing mitigation measures such as flood defenses can also be monitored to determine their efficacy over time; infrastructure failures due to reduced budget allocation or ground subsidence beneath flood defenses usually carry large costs and increasing risks if left unchecked.
Because of the complex and multi-sectorial aspects of subsidence, these situations are easily denied and hence a problem owner is lacking. Awareness raising and good decision making on appropriate adaptive strategies and measures are needed based on an integrated approach. This involves technical, social-economic and especially governance aspects (3).
The Directive 2007/60/EC on the assessment and management of flood risks (EU-Flood Directive)

is being introduced for mapping Flood Risk on a European scale and to harmonize Flood Risk management plans, specifically in case with cross border impacts of flooding (4). The Directive entered into force on 26 November 2007 and will be implemented in the Member States in three stages, starting with a preliminary flood risk assessment/vulnerability for flooding (due in 2011), followed by the development of flood hazard and risk maps for flood-prone zones (2013), and flood risk management plans (2015). This Directive now requires Member States for all watercourses and coastlines to assess risk from 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 (flood risk management plans). It also reinforces the rights of the public to access this information and to have a say in the planning process of adaptive strategies and measures.

THE SUBCOAST PROJECT

Considering the problem of subsidence for coastal lowland areas, there is firstly the need of:

- adequate data and information to assess spatial variations in subsidence in relation to sea level rise and its impact on flood risk;
- adequate data and information to assess geographical and temporal variations in subsidence and its impact on the geomorphological, ecological and hydrological systems in order to anticipate necessary adaptive measures;
- monitoring of the rate of settlement and movement of water defense structures and engineered constructions in order to detect any significant weaknesses in time.

In order to provide an appropriate monitoring of the phenomenon, geodetic techniques have been applied:

- spirit leveling is a well-established technique providing very precise results with a well-known error budget (providing redundant observations for detection and removal of eventual erroneous data), but it is labor intensive and expensive for large regions; the spatial density of the data available is not homogeneous but mainly dependent on the existence of roads in the area of interest, along which the leveling lines can be established;
- GNSS systems (e.g. GPS) are today mainly related to the availability of networks of permanent stations recording data for long acquisition periods: they are nevertheless mainly indicated for pointwise monitoring, showing high costs for their institution and management;
- in addition to these traditional geodetic methods, the PSI (Persistent Scatterer Interferometry) technique derived from the interferometric analysis of radar satellite images is emerging to provide detailed information to assess with high precision the terrain motion, for long periods and at different scales of investigation: local, regional, national. Each point scatterer is associated with a velocity (mm/year).

A first objective of the GMES (Global Monitoring for Environment and Safety) downstream service SubCoast (www.subcoast.eu), funded from the EU 7th Framework Program, is precisely to develop a service for monitoring the extent and impact of subsidence in coastal lowlands and demonstrate its capability in various pilots for a variety of settings around Europe; the surveying technique principally applied is PSI, following a previous experience in 'TerraFirma' project. Via the project partners there is a strong link between 'Terrafirma' and SubCoast, thus guaranteeing that 'Terrafirma's' products will be available for further downstream service development on a European scale. Other relevant partnerships and collaborations are brought in through partners involved in national and European programmes (figure 2).

The SubCoast Downstream service integrates leading GMES-services in the field of earth observation and interferometric SAR-analysis with state-of-the-art geoscientific models for coastal lowland areas both on a regional scale as well as on a European scale (figure 3). This ongoing project is not only related to the development and setup of appropriate monitoring techniques of subsidence, but aims to consider that this phenomenon involves many policy fields and therefore requires an integrated approach for risk management.

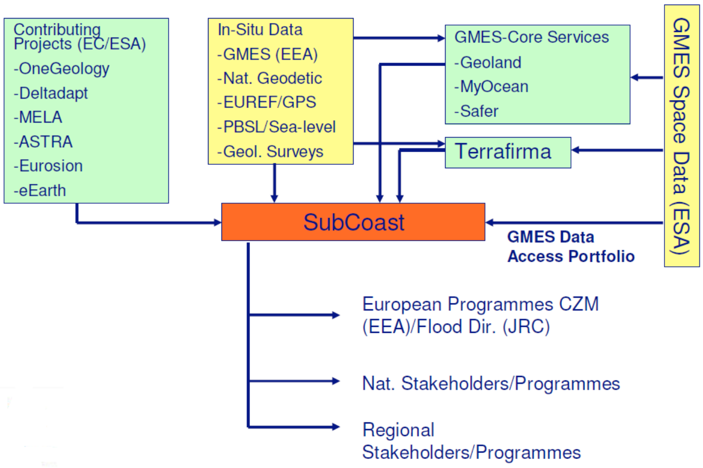

Figure 2 – Connection of SubCoast with European programs, projects and data

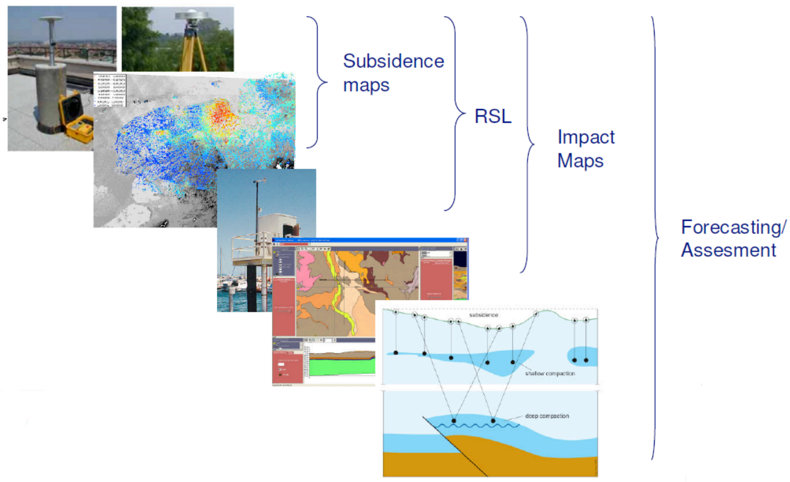

Figure 3 – Basic elements for the project

A project objective is in fact to support decision making on policy, adaptation strategies and operational measures dealing with subsidence on coastal lowland. User communities with a potential interest in SubCoast services are those principally interested in monitoring risks which may threaten human life or put infrastructures at risk. Users of the project services include stakeholders dealing with issues pertaining to hazard management, monitoring and policy development (e.g. water boards, research institutes, infrastructure departments of ministries, provinces, regions and municipalities throughout European coastal regions, as well as authorities at European scale such as the European Environment Agency). There are varying levels of geohazard awareness within the user community, and large regional differences in the institutional configuration for mitigation and response activities. Specialised companies and research centres today generate PSI maps, but 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 (1).

EO TECHNIQUES AND MAIN ISSUES

EO techniques can play a fundamental role with regard to area wide subsidence mapping and monitoring (1); this is achieved primarily in the form of subsidence rates derived from PSI processing, suitably combined with levelling, GNSS data, geological modelling.
Crucial points to be considered are related to several factors:

- Regarding the data, the systematic acquisition of SAR images in coastal areas is worthwhile: wide-swath SAR satellites are useful for regular monitoring over large coastal areas, high resolution and frequent acquisition for specific sites. 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; improved access to SAR data from new sources such as TerraSAR-X, Radarsat-2, and COSMO SkyMed constitute an important innovation (1).
- Regarding R&D, issues concern the use of dedicated InSAR processing with non-linear techniques to increase density of measurement points (deltas, flooded regions and soft soils are not good candidates for the application of classical InSAR techniques), detection of semipersistent scatterers, and furthermore the monitoring of flood defence systems by frequent high resolution acquisition and specific tools. Finally, the absolute subsidence versus sea level: 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, that may require the use of innovative technology or processing to merge data. The appropriate connection to geodetic reference systems is generally a crucial aspect of these applications.
  A specific topic of the research currently carried out by the SubCoast project is to relate subsidence rates to Digital Elevation Models (DEMs) of the areas in a dynamic mode, that is dealing with the elevation as a function of time, at high precision and high resolution scale (5).
- Regarding services and infrastructure, the dissemination of the data (maps and time series for single points) may require the creation of specific service infrastructures, including access to data, possible control for access and additional data. Ground motion and subsidence forecasts can be provided by a Web portal where dynamic models are implemented. The approach requires of course clear quality descriptions, being the results depending on the characteristics of the various available datasets.

PILOT SERVICES

Central to the whole SubCoast-project is the development of pilot-services, since these will be both the testing environments for the proposed services as well as the deliverers of primary derived output to share with the stakeholders and end-users (6).
The pilot services implement the concept of the SubCoast downstream-service and the appropriate validation procedures for the most important coastal lowland setting around Europe. The main concept is that the different pilot services should have the capability of testing the different functions of the downstream-service and demonstrate its viability for the most important issues related to subsidence in a coastal lowland setting.
In SubCoast four pilot areas have been chosen to test the services (figure 4).

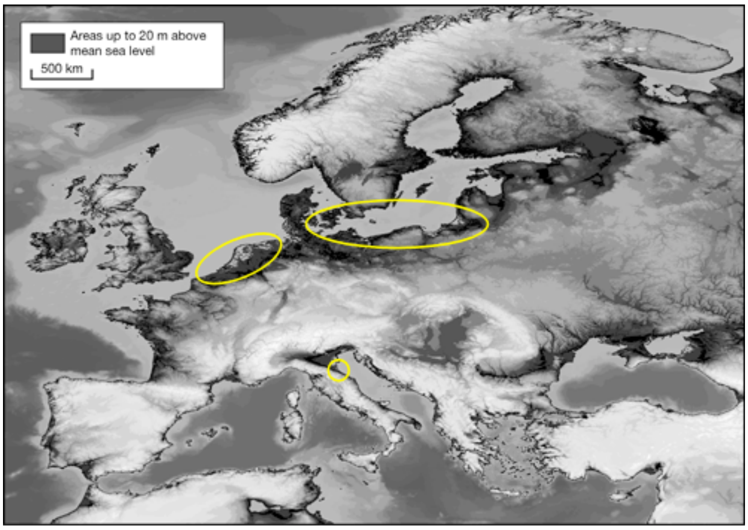

Figure 4 – SubCoast pilot areas

These pilots 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 that was subdivided into 3 countries: Denmark, Poland and Lithuania. The fourth pilot is comprised of a parallel 'European integration' of services. The different scales of analysis can demonstrate the service capability to various stakeholders operating at various levels. All pilot services actively involve end-users (Table 1).
Based on the experience of the four pilot services, a product portfolio will be developed which can be delivered by the consortium throughout Europe and eventually worldwide, supporting GMES ambition as a European initiative for Global environmental monitoring.

Pilot	***End-users***
Rhine-Meuse Delta	• Ministry of Transport, Public Works and Water Management / Rijkswaterstaat
Southern Emilia Romagna	• ARPA Emilia-Romagna • Regione Emilia-Romagna
Baltic	• Maritime Office in Gdynia • Department of Regional and Spatial Development of Pomorskoie Voivodeship • Coastal Research and Planning Insitute, Klaipeda University
European	• European Environmental Agency (EEA)

Table 1 – Pilot services end users

CONCLUSIONS

SubCoast project aims at connecting local, national and European policy requirements, together with existing GMES Services and auxiliary data-streams, with a dedicated service for monitoring the extent and impact of subsidence in coastal lowland areas to a level where sustainable information services can be delivered.
The project involves four European pilot services where PSI datasets are used for subsidence monitoring at different scales, with integration with available geodetic databases, aiming to realize dynamic DEMs useful for assessment and forecasting of the phenomenon.
SubCoast and related research provide important first steps for the development of more comprehensive monitoring services, consisting of a complete chain of data collecting, processing, interpretation, modelling, and the release of this information through interactive portals, for integrated services for risk management.

ACKNOWLEDGEMENTS

The research has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 242332-SubCoast.

REFERENCES

1 Gruijters S., P. Kruiver, R. van der Krogt (2012): Perspectives Concerning Satellite EO and Geohazard Risk Management: coastal lowland subsidence and flood defence. In: Bally P. (2012), Scientific and Technical Memorandum of The International Forum on Satellite EO and Geohazards, May 21st - 23rd, 2012, 91-110, Santorini Greece, doi:10.5270/esa-geo-hzrd-2012.

2 IPCC (2007): Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

3 van Ruiten C.J.M., T.H.M. Bucx, G. Bitelli (2012): Subsidence in coastal lowlands-hidden floodrisk (EU-FP7-SubCoast), in: Comprehensive Flood Risk Management: Research for Policy and Practice, edited by Klijn F. and T. Schweckendiek, CRC Press.

4 Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (2007), Official Journal of the European Union, L 288/27.

5 Hamersley D. & van der Krogt R. (2012): SubCoast: Preparing services for monitoring changes in land elevation in flood-prone coastal lowlands. In: Window on GMES – Special Issue, ISSN 2030-5419, 114-119, GMES4Regions, GRAAL Project.

6 van der Krogt R., C. Bremmer, G. Bitelli, R. Capes, M. Crosetto, J. Cyziene, M. Granizcki, R. Hansen, F. van Leijen, S. Marsh, F. Novali, S. Schach Pedersen, V. Hopman (2012): SUBCOAST: a collaborative project aimed at developing a GMES-service for monitoring and forecasting subsidence hazards in coastal lowland areas around Europe, In: 7th European Congress on Regional GEOscientific Cartography and Information Systems (EUREGEO), 12-15 June 2012, Vol. I, 343-344, Emilia-Romagna Region - Geological Seismic and soil Survey.