Remote Sensing of Environment xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A Copernicus downstream-service for the nationwide monitoring of surface displacements in Germany

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ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 11 April 2017
Accepted 14 May 2017
Available online xxxx

Keywords:
Copernicus downstream-service
Ground Motion Service Germany
Persistent Scatterer Interferometry
Wide-Area-Product
ERS-1/2
Sentinel-1

ABSTRACT

Advanced interferometric SAR processing techniques (Persistent Scatterer Interferometry, Small Baseline Subset) are able to detect and monitor various surface displacements caused by e.g. gravitative mass movement, subrosion, groundwater extraction, fluid injection, natural gas extraction. These processes can e.g. cause damage to buildings and infrastructure, affect ecosystems and agriculture or affect the economic use of the geological underground by influencing the hydrogeological setting. Despite the maturity and operational readiness of the PSI technology it is rarely used in operational workflows of the German user community (e.g. from responsible authorities).

In order to support the operational use of this technique a "Ground Motion Service Germany" has been designed by the Federal Institute for Geosciences and Natural Resources (BGR) in collaboration with the user community, land surveying agencies, SME and research institutions. A major outcome of this collaboration is the user request regarding a PSI-WAP (Persistent Scatterer Interferometry Wide-Area-Product) dataset of the entire nation (approx. 360,000 km^2) based on Sentinel-1 data. For this reason the PSI mapping coverage is increased by mosaicking PSI data products from adjacent SAR data stacks. Several case studies has been performed to demonstrate the design of the service. Within this paper one case study regarding the PSI-WAP technique and the calibration/validation scheme is presented.

The pilot study is focusing on the built up of an officially approved PSI-WAP dataset. The study area covers an area of >30,000 km^2 and is located in the Northwest German Basin. This is the first time a PSI-WAP analysis is performed in this area. Several natural processes (e.g. compaction of marine sediments, peat growth/shrinkage) and anthropogenic activities (e.g. natural gas extraction, rock salt mining) are causing surface displacements in the study area. The PSI-WAP analysis is based on six adjacent ERS-1/-2 data stacks covering the timespan from 1992 until 2001. Each data stack consists of 49 to 73 acquisitions. A comparison of the PSI results with thematic data (e.g. cumulated volume of extracted natural gas and location of natural gas fields) indicates that a part of the detected land subsidence is caused by natural gas extraction.

To summarize, this paper shows i) the design of the "Ground Motion Service Germany" and ii) a pilot study to exemplarily demonstrate a PSI-WAP, the calibration/validation scheme and value-added-products.

1. Introduction

It is clear, that fast surface displacements due to earthquakes or landslides are geohazards. But also relatively slow surface displacements can cause damage to buildings and infrastructure, influence the hydrogeological setting or increase the vulnerability of flooding in coastal lowlands. Slow displacements can even be a precursor to fast movements or an indicator for looming earthquakes (Bekaert et al., 2015). Mass movements can even lead to loss of live. In order to mitigate these hazards, accurate information regarding the displacement of interest are mandatory. Surface displacements phenomena are mainly detected and monitored by geodetic techniques (optical leveling campaigns, tilt meters, GNSS). Spaceborne SAR-Interferometry (InSAR) is gaining increasing attention because of its unique characteristics (large spatial coverage, dense sampling grid, high temporal measurement density, independence of accessibility). InSAR has been used to detect surface displacements of the earth surface since >20 years (Massonnet et al., 1993) and reached maturity in recent years (Adam et al., 2009).

Advanced interferometric SAR processing techniques, e.g. Persistent Scatterer Interferometry (PSI) (Ferretti et al., 2000, 2001; Kampes and Adam, 2003; Werner et al., 2003), Small Baseline Subset (SBAS) (Berardino et al., 2002; Lanari et al., 2004) or combinations of PSI and SBAS (Ferretti et al., 2011; Hooper, 2008) allow the detection of surface

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http://dx.doi.org/10.1016/j.rse.2017.05.015
0034-4257/

displacements with a high precision in the order of mm per year. In this manuscript, the term Advanced DInSAR (A-DInSAR) technique is used as a generic term to summarize these sets of techniques. Several studies have shown the successful measurement of surface deformation and mass movements by using A-DInSAR techniques for e.g. landslide (Calò et al., 2014; Del Ventisette et al., 2014; Notarnicola et al., 2014), coastal subsidence (Gruijters and van der Krogt, 2013), karst processes (Chang and Hanssen, 2014; Galve et al., 2015), ground water overexploitation (Tomás et al., 2010), mining (Abdikan et al., 2013; Guéguen et al., 2009), natural gas production (Chaussard et al., 2013; Ketelaar, 2009), geothermal energy production monitoring (Lubitz et al., 2013; Lubitz et al., 2012) or earthquake induced displacements (Bekaert et al., 2015; Kobayashi et al., 2015). Depending on the application, the range of velocities and spatial extent varies strongly (mm/year to m/month, hundreds of m^2 to hundreds of km^2). Modern SAR sensors like Sentinel-1 A/B (S-1) (Torres et al., 2012) can provide precise phase measurements with large coverage (250 km wide swath) while preserving a spatial resolution of 5 × 20 m (Interferometric Wide Swath mode, IW). Very high spatial resolution SAR data are provided by e.g. the TerraSAR-X (Werninghaus, 2004) or Cosmo-SkyMed (Covello et al., 2010) missions (3 × 3 m with the Stripmap mode), but with smaller coverage (swath width 30 km). All mentioned SAR missions offer a fast revisit cycle (6-, 11- and 4-days respectively) which is mandatory for the monitoring of fast non-linear displacements (e.g. landslides). Furthermore, the high repeat cycle enables the fast buildup of image stacks, which are required for e.g. the PSI technique. S-1 is designed as a "mapping mission" providing complete coverage in particular over Europe, every 6 days. With a PSI analysis based on S-1 IW datasets, an operational nationwide surface displacement monitoring (millions of PS – Persistent Scatterer with mm a^{-1} precision) becomes technically feasible.

The demand for operational InSAR based surface displacement products and in particular a German nationwide surface displacement monitoring product was articulated by the German national user community during so called "National Fora" in 2011, 2012, 2014 and 2015 (DLR, 2016). Several EU projects were aiming at the creation of user-driven products based on A-DInSAR analysis, e.g. ESA-Terrafirma (2003 − 2012) (Adam et al., 2009), EU-FP7-PanGeo (2011–2014) (Capes, 2012) and EU-FP7-SubCoast (2010 − 2013) (Gruijters and van der Krogt, 2013). These projects established product standards based on user requirements and demonstrated the operational readiness of the PSI technique. A validation scheme of PSI processing and value added products was proposed by (Agudo et al., 2006) and (Adam and Kampes, 2008). This includes displacement products like the geocoding-, mean velocity accuracy and quality control aspects during interferometric SAR processing like missing lines check of the SAR imagery.

Based on the requirements of numerous stakeholders of the German user community and the operational readiness of the A-DInSAR techniques a "Copernicus downstream-service for the nationwide monitoring of surface displacements in Germany" is designed by the Federal Institute for Geosciences and Natural Resources (BGR). Copernicus (before 2012 called GMES, Global Monitoring of Environment and Security) is the European Earth Observation program coordinated by the EC (European Commission) in collaboration with the ESA (European Space Agency), EUMETSAT (European Organization for the Exploitation of Meteorological Satellites), ECMWF (European Centre for Medium-Range Weather Forecasts), EEA (European Environment Agency) and Mercator Ocean. Copernicus aims at the support of European environmental, climate and security policies (EC, 2013). It provides information products for public policy makers (e.g. atmosphere monitoring service: European air quality; land monitoring service: CORINE land cover; emergency management service: burnt area map, flooded area map) based on remote sensing and in-situ data. As an extension of these European Copernicus core services a national Copernicus downstream service regarding A-DInSAR based information products to monitor surface displacements is requested by the German national user community (government agencies, public authorities, industry and general public).

This manuscript outlines the concept for a Copernicus downstream service (Fig. 2) with standard and value added products of different Levels (L). In order to demonstrate the feasibility and usability of the standard level 2A Product (L2A), results from ERS-1/2 based PSI-WAP analysis are presented and discussed. Subsequently the L2A product is described from the processing, calibration/validation perspective. Furthermore, a potential level 3 (L3) product is presented. The conclusion focuses on potential challenges within the designed workflow and current applied research themes.

2. User requirements

User workshops and inter-ministerial meetings dedicated to the preparation of a national Copernicus service regarding displacement monitoring were performed in 2014 and 2015 by the BGR (Kalia et al., 2014; Lege, 2014; Kalia et al., 2016). End-users from German governmental agencies (e.g. state geological surveys, mining authorities and ordnance surveying), remote sensing experts/companies and researchers were participating at these workshops. Besides the identification of relevant displacement processes also technical aspects like the tradeoff between spatial measurement density vs. coverage or preferred data formats were discussed. In addition to these workshops, a user survey, based on a questionnaire, was performed in order to support the identification of required applications and rank the importance of specific data and processing characteristics. The user community identified ten displacement phenomena (Table 1).

These anthropogenic and natural displacement phenomena occur in spatial relation to the geological, hydrogeological, pedological, geomorphological setting and anthropogenic activities. Fig. 1 shows a nationwide generalized overview of areas with a potential occurrence of particular displacement processes where local/regional displacement areas might appear. This nationwide overview shows e.g. the location of major natural gas reservoirs or carbonates and thus indicates areas with the potential of subsidence caused by natural gas extraction or karst processes. Fig. 1 highlights that regions, potentially affected by surface displacements, are located throughout Germany. However, some processes are clustering in certain areas of Germany, e.g. subsidence caused by natural gas extraction, salt tectonics, dewatering of organic soils is mostly present in the North of Germany, while mass movements, karst collapse are mostly present in central and Southern Germany. In some regions, several displacement processes can be present at the same location, challenging a correct interpretation of the associated displacement process.

In order to cover all potential displacement areas in Germany, a nationwide map of surface displacements is requested by the national user community. Key user requirements are the consistency of the PSI-WAP dataset with other measurements (e.g. GNSS, leveling) and the reliability of the PSI-WAP dataset. Thus, the PSI processing chain as well as the calibration/validation workflow are important parts of the national Copernicus downstream service.

Table 1
Surface displacement phenomena were identified by the user community.

Crude oil and natural gas extraction/storage	Karst processes
(Abandoned) mining	Landslides
Groundwater extraction (management)	Coastal subsidence/sediment consolidation
Geothermal energy production	Salt tectonics/subrosion
Dewatering of organic soils	Settlement of infrastructure

Please cite this article as: Kalia, A.C., et al., A Copernicus downstream-service for the nationwide monitoring of surface displacements in Germany, Remote Sensing of Environment (2017), http://dx.doi.org/10.1016/j.rse.2017.05.015