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Localising deformation along the elevation of linear structures: An experiment with space-borne InSAR and RTK GPS on the Roman Aqueducts in Rome, Italy

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A B S T R A C T

We map and monitor the condition of linear structures using Measurement Points (MPs) from satellite Interferometric Synthetic Aperture Radar (InSAR), and deal with the uncertainty of localising the detected deformation along the building elevation. We combine spatial information of the MPs with elevation measurements collected by Real Time Kinematic (RTK) GPS surveying to understand where structural motions occurred. The MPs are geolocated along the z-direction by exploiting their height information (h_{MP}) compared to the elevation of the surveyed buildings and surrounding ground (h_{GPS}). This approach aims to find a good compromise between the required accuracy and repeatability, and the advantages of reduced time-consumption and cost-effectiveness offered by RTK GPS. Reliability of the method is proved via the experiment on the Roman Aqueducts in the southern peri-urban quarters of the city of Rome, Italy. We focus on the linear man-made structures of the ancient to modern aqueduct systems. These are challenging anthropogenic features to monitor with InSAR due to their huge extent, variety of condition and architectural complexity. Of the total 13,519 MPs retrieved from SqueeSAR™ processing of 87 RADARSAT-1 Fine Beam Mode 3 ascending scenes (2003–2010), the MPs spatially attributed to the local linear features and the surroundings are analysed with regard to: (i) their densities against building type, structure planimetric orientation and vegetation coverage; and (ii) their height distribution against RTK GPS micro-topographic surveying in seven sample areas. Numerical analysis of h_{MP}–h_{GPS} pairs result in high correlation (R^2 equals 0.970), and their cross-comparison allows validation of 3D geolocation of the MPs, also demonstrating the usefulness of complementary surveying by laser distance meter device whenever RTK GPS is not feasible. Cross-referenced h_{MP} values are then used to reclassify the MPs and generate final map products to support the design of in-situ inspection activities. We discuss beneficial impacts for condition monitoring and assessment at the scale of single building through the examples of the medieval tower Torre del Fiscale and the Roman arcades of the Claudian Aqueduct. The MP height information improves the understanding of the deformation estimates, and also contributes to address hazard mitigation measures and restorations.

Introduction

Building surveying in urban areas is among the fields of geographical application that has benefitted greatly from the advent of new remote sensing technologies from space and their increasing use in the last decade (Mcnally & Mckenzie, 2011; Sever, 2000), in addition to the well established aerial photography and free-access imagery from optical satellites (e.g., Google Earth). Applications at the scale of single building included, but were not limited to: cadastre updating (e.g., Ali, Tuladhar, & Zevenbergen, 2012), identification of urban features (e.g., Bhaskaran, Paramananda, & Ramnarayan, 2010), assessment of urban sprawl (e.g., Jat, Garg, & Khare, 2008; Xu & Min, 2013), and damage mapping in emergency contexts (e.g., Dong, Li, Dou, &Wang, 2011; Witharana, Civco, & Meyer, 2013). As found in affine geographical sciences such as land cover change detection and mapping (Liu &

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Yang, 2015 among the latest research), key factors that make these Earth Observation technologies highly advantageous compared with traditional surveying methods are the cost-effectiveness and reduced time-consumption.

Such aspects are nowadays of high concern for individual surveyors, as well as authorities in charge of built environment management. Professionals and technical officers seek for sustainable solutions to undertake ordinary activities of building inspection, in a period when reduced human resources and funds allocated are being drastically reduced due to financial cuts and economic constraints (cf., for instance, English Heritage, 2011 and Cecchi & Gasparoli, 2010, 2011, with specific regard to English and Italian current contexts). This also aligns with recommendations at international level, including those proposed by the European Parliament (2007) and recalled in the European Commission decision (2013/743/EU) in the framework of the Horizon 2020 initiative. The current trend is indeed to encourage the development of feasible methods of surveying, data collection and mapping in GIS environment to support cultural heritage monitoring and damage assessment.

There is recent literature demonstrating that satellite Interferometric Synthetic Aperture Radar (InSAR) ground motion data from multi-interferogram processing can help building surveyors, heritage conservators and geographers to achieve this purpose. Persistent Scatterer Interferometry (PSI; Crosetto, Monserrat, Jungner, & Crippa, 2009) in particular is suitable to monitor the condition of buildings, man-made structures and infrastructure (e.g., Bianchini et al., 2014; Bock, Wdowinski, Ferretti, Novali, & Fumagalli, 2012; Cigna, Del Ventisette, et al., 2012a; Kourkouli, Strozzi, & Wegmuller, 2012; Parcharidis, Foumelis, Kourkouli, & Wegmuller, 2009a). It was also proved valuable for diagnostic investigation in historical urban and rural sites (Cigna, Lasaponara, Masini, Milillo, & Tapete, 2014; Iadanza et al., 2013; Parcharidis, Foumelis, Pavlopoulos, & Kourkouli, 2009b; Pratesi, Tapete, Terenzi, Del Ventisette, & Moretti, 2015; Tapete & Cigna, 2012a, 2012b), in a way that allows early detection of surface deformation as indicator of structural instability of the building and/or instability of foundations and underlying bedrock (Tapete, Fanti, Cecchi, Petrangeli, & Casagli, 2012).

The spatial dimension of this type of analysis relates to understanding where the deformation that has been recorded in the satellite time series occurs. To this scope in this paper we combine satellite InSAR data from PSI processing with topographic measurements by GPS surveying, to solve the uncertainty related to the spatial interpretation of the geolocation information associated to deformation patterns.

PSI-based condition assessment relies specifically on the provision of sparse grid of Measurement Points (MPs) with associated time series of surface deformation which allows (1) distinction of stable and unstable areas, (2) analysis of the temporal evolution of deformation and (3) recognition of deformation trends.

Among the spatial properties of each MP, we stress in this paper the importance of the height information. Some studies have paid attention to this parameter, mainly to: better identify the object(s) on the ground (e.g., Perissin & Ferretti, 2007); map topographic changes of urban features (e.g., Delgado Blasco, Hendrickx, De Laet, Verstraeten, & Hanssen, 2012); geolocate precisely MPs via the aid of LiDAR Digital Surface Models (DSM) with regard to buildings and infrastructure under sinkhole risk (Chang & Hanssen, 2014).

By using the MP height we want to identify the object the MP deformation estimate refers to. If the MP is spatially located over a building, we aim to define the architectural component/portion of the object investigated that is subject to deformation (the latter depending on the spatial resolution of SAR imagery, i.e. the extent to which the SAR sensor is capable to spatially resolve two neighbouring elements on the ground).

Answers to the above questions are specifically sought by surveyors of linear structures (e.g., viaducts, aqueducts, colonnades, terraced buildings), the elevation of which predominates with respect to the other two dimensions. Location within urban, peri-urban and rural areas can be challenging, since the proximity of unrelated objects (e.g., light poles) can cause difficulty to the spatial attribution of the identified MPs. Consequently, deformation patterns can be misinterpreted, with detriment to the reliability of PSI results.

To address this practical issue, we explored the feasibility of using Real Time Kinematic (RTK) GPS (Featherstone & Stewart, 2001; Hofmann-Wellenhof, Lichtenegger, & Collins, 2001) to survey samples of a wider region of interest (ROI) and solve the 3D geolocation of the MPs, taking advantage of the good compromise between reduced time-consumption, accuracy, cost-effectiveness and flexibility offered by RTK GPS surveying technique (Morelli, Segoni, Manzo, Ermini, & Catani, 2012; Morelli et al., 2014). We tested the method in the southern quarters of the city of Rome, Italy, owing to its variety of urban layout and landscape, focusing on the kilometre-long aqueduct system which dates back to Roman up to modern times. The choice of this test site allows us to demonstrate the sustainability of the method we propose, thereby offering an alternative to the traditional approaches of regular monitoring (e.g., visual inspections and in-situ spot measurements) to deal with huge ROIs. We spatially investigated PSI data obtained from multi-interferogram processing of 7-year long C-band RADARSAT-1 Fine Beam Mode 3 imagery by means of SqueeSAR™ algorithm (Ferretti et al., 2011).

Section 'Methodology' describes how to exploit PSI height information by combining the GIS-based preliminary assessment of the MPs with RTK GPS and ancillary topographic measurements. We also illustrate how surveyors and geographers can use this combined spatial information to feed into mapping products. Land cover characteristics and features of the study area are then introduced, alongside the technical parameters of the RADARSAT-1 data. Reliability and effectiveness of the method is demonstrated via the discussion of the experiment we undertook in Southern Rome. The final mapping product summarising the outcomes of the sample survey is presented in Section 'Results and discussion', followed by selected examples of linear features and historical structures to discuss the benefits that can be achieved for condition assessment of building environment and heritage assets.

Methodology

Flowchart in Fig. 1 illustrates the methodological approach that we implemented, mainly consisting of the following phases:

1. GIS-based data integration and preliminary assessment (Fig. 1a);
2. Topographic survey with in-situ elevation measurements by RTK GPS (Fig. 1b), coupled with complementary surveys (Fig. 1c) whenever physical obstacles, logistics constraints, conservation needs and/or safety issues limit the accessibility for object geolocation with RTK GPS;
3. Deformation analysis and condition assessment (Fig. 1d and e).

GIS-based data integration and preliminary assessment

The sparse grids of MPs that are obtained from the PSI processing of a sufficiently long time series (at least 15–20 images in the case of C-band SAR imagery acquired with monthly frequency from the same satellite and geometry) are handled in a GIS environment (Fig. 2) and spatially analysed by using the following properties: