remote sensing

MDPI

Article

Detecting Slope and Urban Potential Unstable Areas by Means of Multi-Platform Remote Sensing Techniques: The Volterra (Italy) Case Study

Teresa Nolesini *, William Frodella, Silvia Bianchini and Nicola Casagli

Department of Earth Sciences, University of Florence, Via G. La Pira 4, Florence 50121, Italy; william.frodella@unifi.it (W.F.); silvia.bianchini@unifi.it (S.B.); nicola.casagli@unifi.it (N.C.)

* Correspondence: teresa.nolesini@unifi.it; Tel.: +39-055-205-7770

Academic Editors: Rosa Lasaponara, Soe Myint, Richard Gloaguen and Prasad S. Thenkabail
Received: 4 July 2016; Accepted: 30 August 2016; Published: 9 September 2016

Abstract: Volterra (Central Italy) is a town of great historical interest, due to its vast and well-preserved cultural heritage, including a 2.6 km long Etruscan-medieval wall enclosure representing one of the most important elements. Volterra is located on a clayey hilltop prone to landsliding, soil erosion, therefore the town is subject to structural deterioration. During 2014, two impressive collapses occurred on the wall enclosure in the southwestern urban sector. Following these events, a monitoring campaign was carried out by means of remote sensing techniques, such as space-borne (PS-InSAR) and ground-based (GB-InSAR) radar interferometry, in order to analyze the displacements occurring both in the urban area and the surrounding slopes, and therefore to detect possible critical sectors with respect to instability phenomena. Infrared thermography (IRT) was also applied with the aim of detecting possible criticalities on the wall-enclosure, with special regards to moisture and seepage areas. PS-InSAR data allowed a stability back-monitoring on the area, revealing 19 active clusters displaying ground velocity higher than 10 mm/year in the period 2011–2015. The GB-InSAR system detected an acceleration up to 1.7 mm/h in near-real time as the March 2014 failure precursor. The IRT technique, employed on a double survey campaign, in both dry and rainy conditions, permitted to acquire 65 thermograms covering 23 sectors of the town wall, highlighting four thermal anomalies. The outcomes of this work demonstrate the usefulness of different remote sensing technologies for deriving information in risk prevention and management, and the importance of choosing the appropriate technology depending on the target, time sampling and investigation scale. In this paper, the use of a multi-platform remote sensing system permitted technical support of the local authorities and conservators, providing a comprehensive overview of the Volterra site, its cultural heritage and landscape, both in near-real time and back-analysis and at different scales of investigation.

Keywords: radar interferometry; infrared thermography; instability phenomena; city walls

1. Introduction

The protection and preservation of cultural heritage from natural hazards represent key issues, requiring a specific monitoring strategy which should be planned considering: (i) the site characteristics (topography, geological setting); (ii) the features of the related instability phenomena (kinematics, magnitude and velocity); and (iii) the typology of the hazards affecting each specific area of interest [1]. In the field of landslide studies, basic disaster-prevention strategies and urban planning involve the detection and mapping of the most unstable areas at different scales, ranging from the whole municipality up to the single structure. Such issues are currently of high concern for all the authorities in charge of urban and landscape management: rapid and cost-effective solutions are increasingly required by professional operators in order to perform environmental and building inspection activities to be applied in different urban contexts [2,3]. Remote sensing technologies have become effective tools in order to safely monitor and analyze the criticalities affecting urban and cultural heritage structures, especially in case of fast and non-invasive detection purposes [4,5]. Satellite PS-InSAR (Persistent Scatterer Synthetic Aperture Radar Interferometry) technique can be profitably used in cultural heritage applications and in landslide risk management, for its capability to measure surface displacements over wide areas during pre- and post-event phases through long time deformation series [6,7]. GB-InSAR (Ground-Based Interferometric Synthetic Aperture Radar) technique represents a powerful remote sensing terrestrial technique for detecting fast structural deformation [8,9] and ground displacements at a slope scale [1,10–15]. Infrared Thermography (IRT) has gained increasing relevance in civil engineering and cultural heritage applications, being a versatile, non-destructive and contactless testing technique, capable of detecting the properties or the interior conditions of a structure from its surface temperature changes [16–20].

Volterra is a valuable cultural heritage site built on a tableland and wholly embraced by a defensive wall enclosure composed by Etruscan, Medieval and Renaissance sections, with a present overall length of about 2.6 km and height up to 5 m [21] (Figure 1a). During the winter of 2014, after a period of intense rainfall, the pressure of undrained water caused significant collapses of two wall sectors (Figure 1b,c). Furthermore, in the Spring of 2014, slope instability phenomena occurred in an uninhabited area, west of the urban center (*Le Balze* geosite, Figure 1d), worsening this hazardous situation [22].

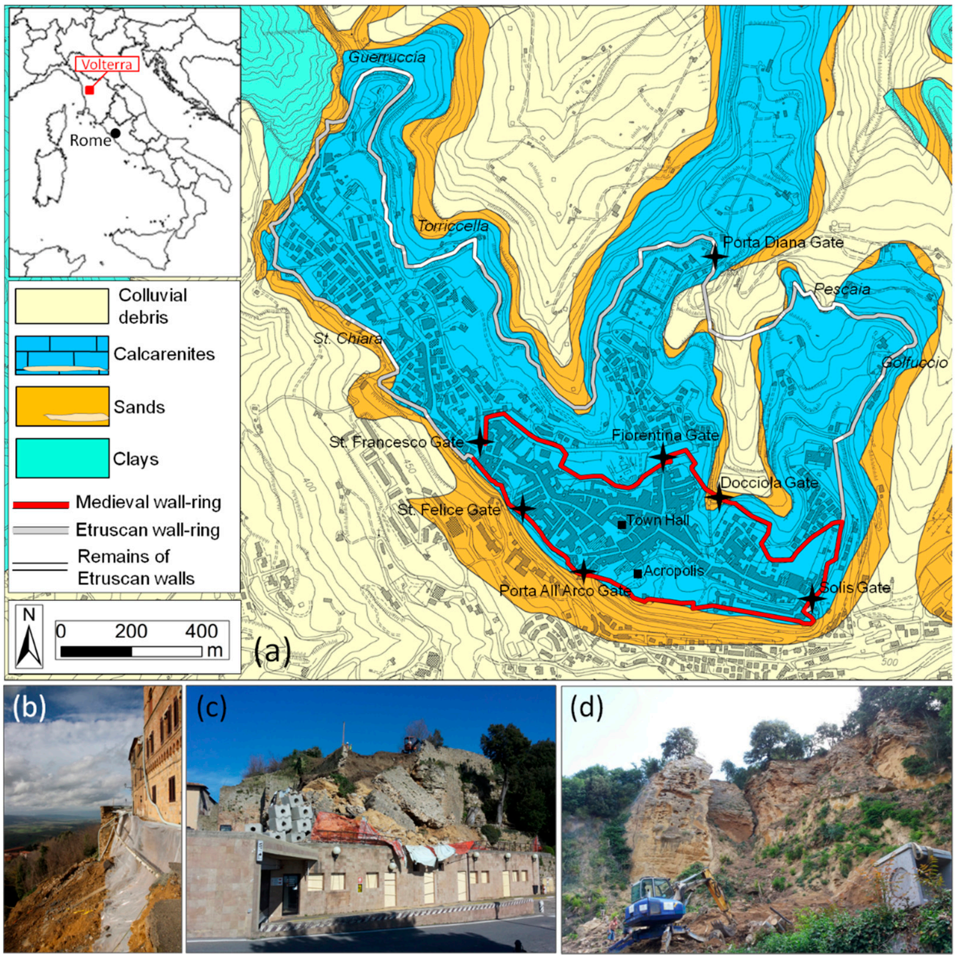

Figure 1. (**a**) Volterra study area: geological map and wall-ring; (**b**) January 2014 wall collapse; (**c**) March 2014 bastion collapse; (**d**) June 2014 slope failure.

Following these events, a multiplatform monitoring system was implemented in order to monitor possible displacements and detect critical sectors with respect to instability phenomena, with the final aim of managing the emergency and planning safety and mitigation measures (Figures 2 and 3). In particular, a PS-InSAR long-term analysis was carried out at an urban scale area [6], whereas GB-InSAR monitoring was applied at a slope scale area by means of two radar systems: the first one focusing on the city wall's southwestern sector (GB-InSAR 1) [9], and the second system on the *Le Balze* geosite sector (GB-InSAR 2). In this framework, IRT was applied at a building scale for mapping the city wall's surface temperature, with the aim of detecting potential weakness sectors within the wall enclosure, such as moisture and seepage areas, cracks and structural anomalies. Field inspections were also performed in order to validate the remotely sensed data. In this work, the outcomes of the performed monitoring activities are presented, consisting in a pre- and post-event analysis of unstable hotspot areas within the urban center and the surrounding slopes, leading to a comprehensive overview of the Volterra site and its cultural heritage and landscape.

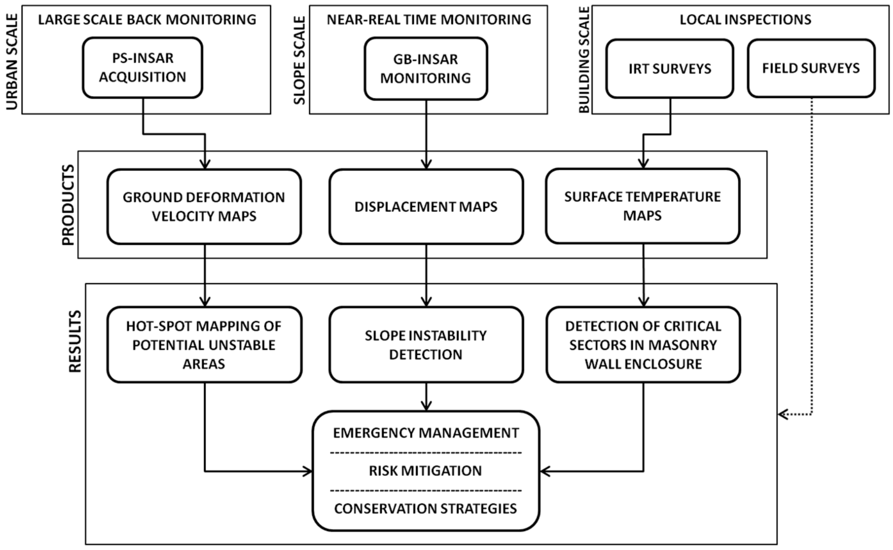

Figure 2. Logic scheme of the applied multiplatform monitoring system.

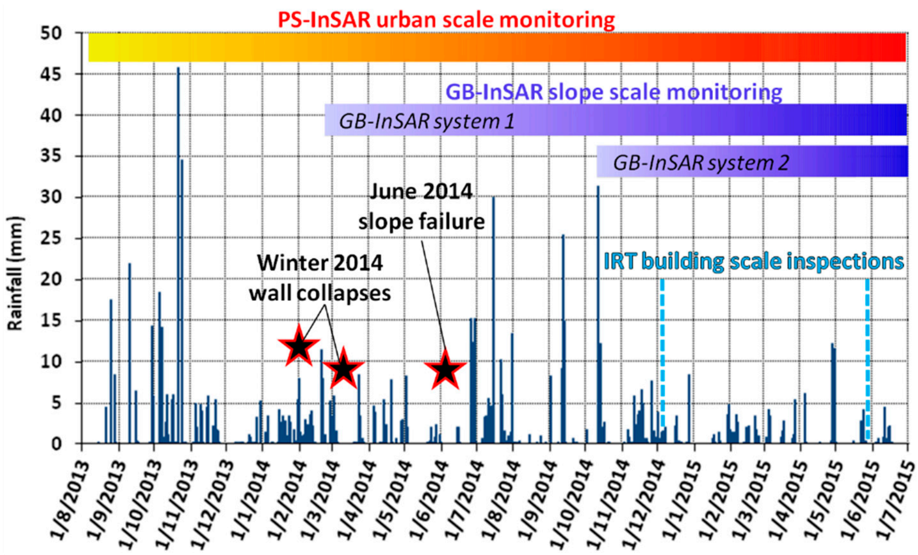

Figure 3. Time line of the employed multiplatform monitoring system, with city area rainfall data. Date format: dd/mm/yyyy.

2. Study Area and Description of 2014 Failure Events

The city of Volterra is located in Tuscany Region (Central Italy) at 550 meters a.s.l. on a tableland mostly made of Pliocene marine sedimentary successions (Figure 1). Three principal sub-horizontal layers characterize the stratigraphic sequence of the area (from bottom to the top): the Blue Clay Formation, which is a thick marine blue-grey clayey formation (Early-Middle Pliocene), the Villamagna sands formation that includes alternating layers of well-cemented sandstones and conglomerates (Middle-Late Pliocene) and the Volterra calcarenites (Late Pliocene), upon which the historic city was built (Figure 1a) [21]. The Volterra surroundings have a typical hilly landscape and the geomorphology is deeply influenced by the geological settings and the geotechnical properties of the outcropping formations. Clayey, poorly vegetated hills are affected by rapid geomorphological processes such as soil erosion (rills, gullies and badlands) and shallow landslides (flows and slides), triggered by heavy rainfall and freezing-thaw cycles [22]. Moreover, the different geotechnical properties between the impermeable clays, the upper erodible Villamagna sands and the well-cemented Volterra calcarenites determine the undermining of the clayey bases at the foot of the hill, and consequent retrogressive slope failures which generate very steep, sub-vertical cliffs (*Le Balze* geosite) around the tableland [6,22].

Volterra is widely known as one of the most important Etruscan settlements, which then developed as a Roman centre and later as a medieval city [23,24]. The present town wall configuration, about 2.6 km long, is the result of significant and repeated restorations across time, from the Middle Ages up to the present, especially during the 18th century AD [25,26]. Many sections of the old great Etruscan wall-enclosure and ancient gates (Porta all'Arco Gate and Diana Gate) are partially preserved, representing an invaluable element of cultural heritage (Figure 3a). Two main factors actually threaten the wall's conservation: the slope instability mainly due to the sub-vertical cliffs bordering the walls [6] and the inadequate maintenance both of the masonry structures and of the adjacent hydraulic plants. During the last 30 years, scaffolding holes were blinded and fissure connections between the stones were grouted, preventing the rainfall water to be drained. On 31 January 2014 the accumulation of water on the back side of the walls triggered the sudden collapse of a 35 m long and 9.5 m high portion of the southwest wall sector, along *Lungomura dei Pratini* (Figure 3b). The event caused huge damage with reparation costs up to 2 million euro, ultimately drawing the attention of the scientific and public community. On 3 March 2014, the bastion along *Martiri della Libertà* square, at the entrance of a public underground parking lot (Figure 1c) failed and was completely disrupted. The structure was sustaining a portion of the Roman acropolis and its failure was probably due to the uncontrolled accumulation of water in the underground Roman tanks. A few months later, in June 2014, slope instability phenomena occurred in the badlands and crags area west of the urban center (*Le Balze* geosite; Figure 1d), characterized by the collapse of a wide sub-vertical sandy cliff slab (about 15 m in height and 8 m width) delimitated by open and persistent fractures. The involved material blocked a local spring, interrupting the water flow and causing widespread moisture and water stagnation, subsequently representing a critical sector in an area particularly prone to landsliding due to its geomorphological setting.

3. The Applied Remote Sensing Monitoring Techniques

3.1. Persistent Scatterer Synthetic Aperture Radar Interferometry (PS-InSAR)

PS-InSAR technique is capable of measuring displacements with millimeter precision, dense spatial sampling, wide area coverage and systematic temporal updating. The technique's basic principles rely on the detection of stable radar targets within SAR images, the so-called persistent scatterers (PS), which can be anthropic (buildings, metallic structures) or natural objects (rock outcrops) characterized by a stable phase signal [27–29]. The PS-InSAR approach allows measuring the movements of each PS along the satellite line of sight (LOS) with respect to an assumed stable reference point [30]. This technique turns out to be particularly suitable in urban/peri-urban areas, which contain many potential coherent PS such as buildings and road lines [27,31–35]. Satellite SAR sensors acquire right-side looking and following an approximately North-South oriented orbit. Thus, the technique is useful to detect ground deformation located on prevailing east- or west-facing slopes. The SqueeSAR^{TM} algorithm is a new advanced multi-temporal PSI technique which measures ground displacements using both PS and the distributed scatterers (DS) [36]. The latter ones correspond to homogeneous areas spread over a group of pixels in a SAR image (rangeland, pasture, shrubs and bare soils). This innovative approach allows increasing the point target density with respect to the traditional PS-InSAR technique, especially in case of sparse vegetation landscapes [37–39].

3.2. Ground-Based Radar Interferometry (GB-InSAR)

This technique is based on interferometric techniques (InSAR), originally developed for earth observation from satellites [40,41]. A GB-InSAR system consists of a computer-controlled microwave transceiver, characterized by transmitting and receiving antennas, which are capable of synthesizing a linear aperture along the azimuth direction by moving along a mechanical linear rail. A SAR image is obtained by combining the spatial resolution along the direction perpendicular to the rail (range resolution, ΔRr), and the one parallel to the synthetic aperture (azimuth, or cross-range resolution; ΔRaz) [14], containing amplitude and phase information of the observed objects' backscattered echo within the investigated scenario in the acquiring time interval. The working principle of the GB-InSAR technique is the evaluation of the phase difference, pixel by pixel, between two pairs of averaged sequential SAR images of the same scenario, which constitute an interferogram [42]. In the time elapsed between the acquisition of two or more subsequent coherent SAR images, it is possible to derive from the obtained interferogram a map of the displacements occurring along the sensor line of sight (LOS), with metric or sub-metric resolution, submillimeter accuracy and sampling frequency of a few minutes [10,11,43–46].

The area covered by a GB-InSAR system depends on the distance between the sensor and the point of observation, but it is usually limited to a few hundred meters up to a few kilometers. According to the specific acquisition geometry, only this component of the real displacement vector can be estimated, whereas the displacements occurring along a direction perpendicular to the LOS are missed, representing the main limitation of the GB-InSAR technique.

3.3. Infrared Thermography (IRT)

IRT is a type of infrared imaging accomplished with calibrated infrared thermal cameras allowing the detection of thermal radiation differences on a surface object [47,48]. IRT has been successfully employed for the detection of delamination and subsurface cracks in concrete structures [49], for the location of near-surface defects or water infiltrations in masonry structures [50–52], non-homogeneity of materials or constructive technique [53,54], for the detection of structural damages [55], surface weathering [56] and plaster detachments [57] in historical buildings. The product of a thermographic survey is a pixel matrix (thermogram) collected through the thermal camera array detector, which after the correction of the sensitive parameters (object emissivity, path length, air temperature and humidity) represents a radiant temperature map of the investigated object. An IRT building inspection provides the mapping of surface temperature, which is a function of heat flow crossing the analyzed structure and local boundary conditions [58]. The presence of any inhomogeneity within the material (i.e., a thin coating delamination, cracks and fractures, subsurface voids, detachment layers, moisture or seepage zones) highly modifies the material thermal parameters (density, specific heat and thermal conductivity), reducing the heat transfer and adding its signal to that given by the structure [59], therefore displaying in the analyzed structure's surface temperature map as a thermal anomaly (an irregular thermal pattern).

3.4. The Multiplatform Monitoring System

PS-InSAR analysis was applied to the Volterra study area, extended up about 24 km^2 (Figure 4), in order to perform a back-monitoring of the city center, as well as to check the stability scenario over the urban fabric and geosite at a large scale (Table 1). In the study area, 55 ascending and 25 descending SAR scenes acquired by the Italian satellite COSMO-SkyMed (CSK) in 2010–2015 and processed with the SqueeSAR^{TM} approach [36], were used, producing 34,136 PS benchmarks.

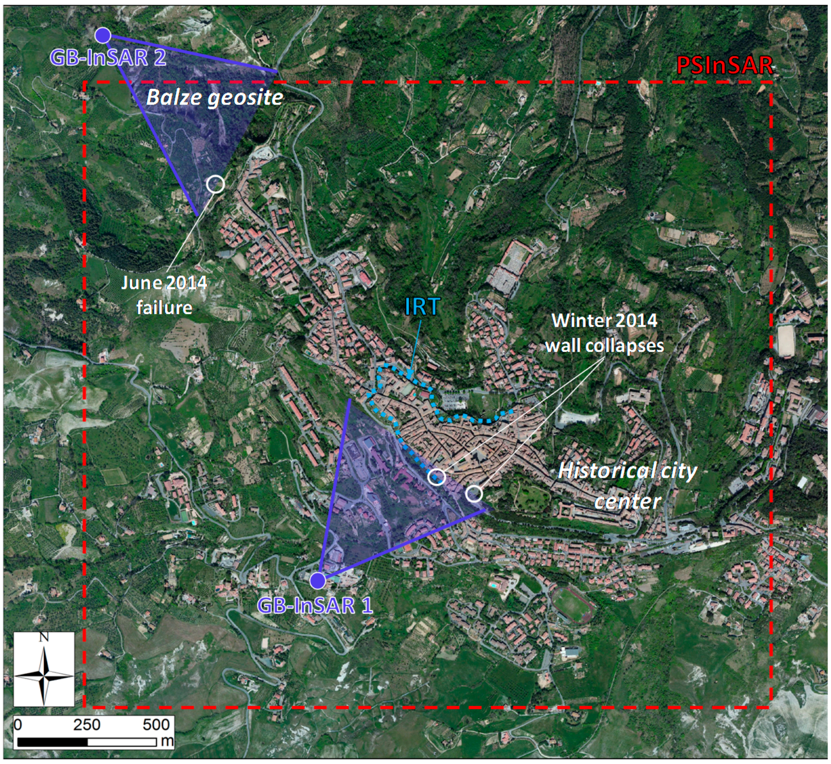

Figure 4. PS-InSAR-analyzed area (red dashed square). GB-InSAR system location and monitored areas (violet triangles) (GB-InSAR-1 system monitoring the mediaeval walls, GB-InSAR-2 system monitoring the slope instability phenomena in correspondence of *Balze* Geosite). IRT-surveyed wall sectors (dashed blue line).

Table 1. Characteristic of the employed technologies. Date format: dd/mm/yyyy.

Feature	PS	GB-InSAR-1	GB-InSAR-2	IRT
Wavelength	X-band (3.1 cm)	Ku band (1.35 cm)	Ku band (1.35 cm)	LW-IR (7.5–13 μ)
Revisiting time	16 days	≈4 min	≈1 min	2 surveys/year
Image resolution	3 × 3 m	0.3 (@100 m) × 0.75	0.8 (@100 m) × 1	0.65 mrad
Coverage/Maximum distance/Range	24 km^2	800 m	1050 m	(−40 + 500 °C)
Accuracy	±1–5 mm	<1 mm	<1 mm	±2 °C
Acquisition date	24/02/2010–07/01/2015	19/02/2014–26/11/2015	27/01/2015–26/11/2015	25/05/2015–02/12/2015

GB-InSAR radar post-event analysis was performed in specific critical areas within the Volterra municipality, in order to detect instability phenomena both in correspondence of the structures within the historical city center and of the natural unstable areas in the municipality surroundings. Two different radar systems were employed to monitor and to detect the displacements on the southwestern sector of the wall enclosure and on the western area of Le Balze geosite, respectively (Figure 4). Both the radar systems, patented by the Joint Research Center by the European Commission, work in Ku band, with a central frequency of 17.2 GHz and bandwidth of 200 GHz. The radar antennas moving along a 1.60 m rail simulate a 3 m synthetic aperture radar. GB-InSAR systems acquire images of the same scenario, covering different time periods (11 min, 2, 8, and 24 h) and producing cumulated displacement maps of selectable time spans (Table 1).

In order to rapidly detect potential critical sectors within the masonry wall enclosure, a double survey campaign was performed by using a FLIR SC620 infrared thermal camera, characterized by an uncooled microbolometric sensor (Table 1). In order to provide information about the thermal transfer efficiency of the examined structure in different seasonal conditions, thermograms were acquired in the post-emergency phase, on 2 December 2014 and 25 May 2015, during the daily warmer period (between 12 a.m. and 2 p.m.). A total of 65 thermograms were acquired during the first day of survey covering 23 different sectors of the town walls (Figure 4). The second survey was focused on the wall enclosure sectors where thermal anomalies were detected during the previous inspection. Although the thermal camera FOV was often limited due to the small distance between the sensor-acquiring point and the wall surface, thermograms were acquired from a distance ranging from 5 to 50 m, leading to a thermogram spatial resolution ranging between 3.3 mm and 3.3 cm. In order to picture a scenario wider than the camera field of view (FOV), adjacent thermograms were mosaicked by means of a specific software. Within this work, the mosaicking was carried out using FLIR Reporter 9 Professional software [60], while thermographic image correction, thermal focusing and analysis were performed by means of FLIR ResearchIR 3.4 sp3 software [61]. Field inspections were also carried out during the monitoring campaign in order to validate the outcomes of the remotely sensed data.

4. Results

4.1. Persistent Scatterer Interferometry (PSI) Analysis and Results: Large-Scale Urban Detection

The PS satellite LOS ascending and descending velocities (V_{LOS}) were projected along the local steepest slope, for obtaining V_{SLOPE} values, according to [39]. The estimation of V_{SLOPE} velocities is related to the scaling factor used for the downslope projection, which depends on the local topography (slope and aspect derived from DTM with 10 m cell resolution) and on the angle between the steepest slope and the LOS direction. Following Bianchini et al. (2013) [62], for this angle, we set the absolute maximum value of 72° as threshold, which corresponds to the condition number of 15 for the inversion matrix solving the algebraic system in the projection process, consequently making the V_{SLOPE} be no higher than 3.33 times the V_{LOS}. This procedure allows a more reliable data interpretation, since ground motions are mostly localized on W-facing slopes and LOS measurements, especially the ascending ones, would not have been very representative of real movements as they are minimized by the combination of acquisition geometry and local topography. The spatial distribution of V_{SLOPE} velocities shows that the city center appears to be almost stable within the four-year acquisition period (Figure 5). No precursor of the wall collapses is retrieved. The highest ground motion rates are recorded on the SW slope of the Volterra hilltop, where clayey soils crop out, overlapped by extensive colluvial debris from the gradual weathering of the upper geological formations upon which the city itself is built. The stability scenario over the Volterra urban fabric and the *Le Balze* geosite was scanned through PS-InSAR data in order to identify the most critical areas with respect to ground displacements. To this aim, the methodology proposed by Bianchini et al. (2013) [62] for deriving "active clusters" was exploited (Figure 6). In order to account for those impact motions that can potentially cause damages on manufactured and urban structures, PS outliers derived from ascending and descending datasets and characterized by $V_{SLOPE} > |10|$ mm/year were firstly selected, according to the damage threshold proposed by Mansour et al. (2011) [63]. Furthermore, these outliers were clustered by deriving the PS buffers from the 3 m CSK spatial resolution and grouped by amount of at least 4 PS [64–66]. Results permitted to derive 19 "active clusters" of PS with $V_{SLOPE} > |10|$, defined as the most moving and potentially hazardous sites over the Volterra study area at the large scale (Figure 6). An active cluster is located on unstable areas over the *Le Balze* geosite, nearby the site of failure occurring in June 2014 (Figure 1e; Figure 6, close-up 1).

Most of the active clusters are located in the southwestern peri-urban zone, where shallow translational landslides and soil erosion phenomena occur, including mean V_{SLOPE} rates ranging 12–15 mm/year. These terrain deformations determine severe damages to buildings, as validated by on-site observations (Figure 6, close-up 3 and 4) and are recorded in literature [6]. Three active clusters are located nearest the city center and show slightly slower V_{SLOPE} velocities, about 11–12 mm/year. The ground displacement's hotspot validation, carried out through field inspections and photo-interpretation, shows that one active cluster located in relation to the *Filosofi Avenue* (Figure 6, close-up 3) corresponds with slow-moving ground deformation, while another two active clusters are related to temporary land cover change due to anthropogenic activity (Figure 6, close-up 2).

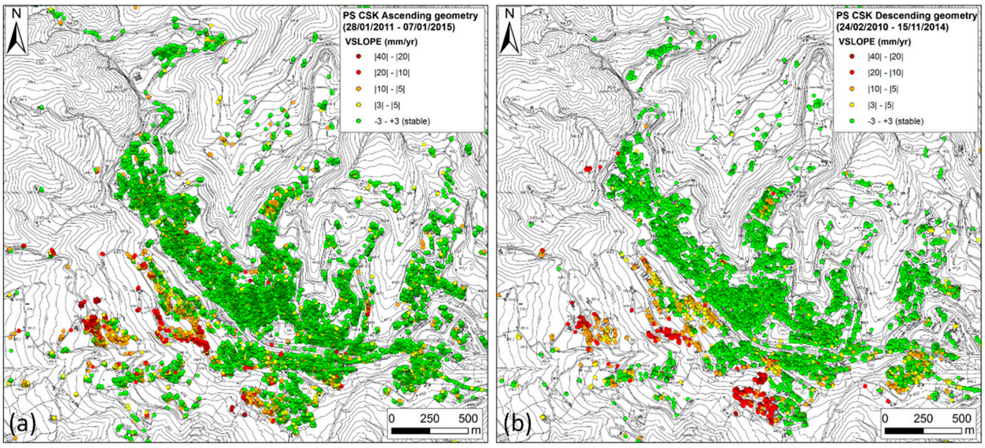

Figure 5. Persistent Scatterers (PS) CosmoSky-Med (CSK) data over Volterra area overlapped on a topographical map: (**a**) Spatial distribution of PS data classified by absolute values of V_{SLOPE} velocity in ascending geometry; (**b**) Spatial distribution of PS data classified by absolute values of V_{SLOPE} velocity in descending geometry.

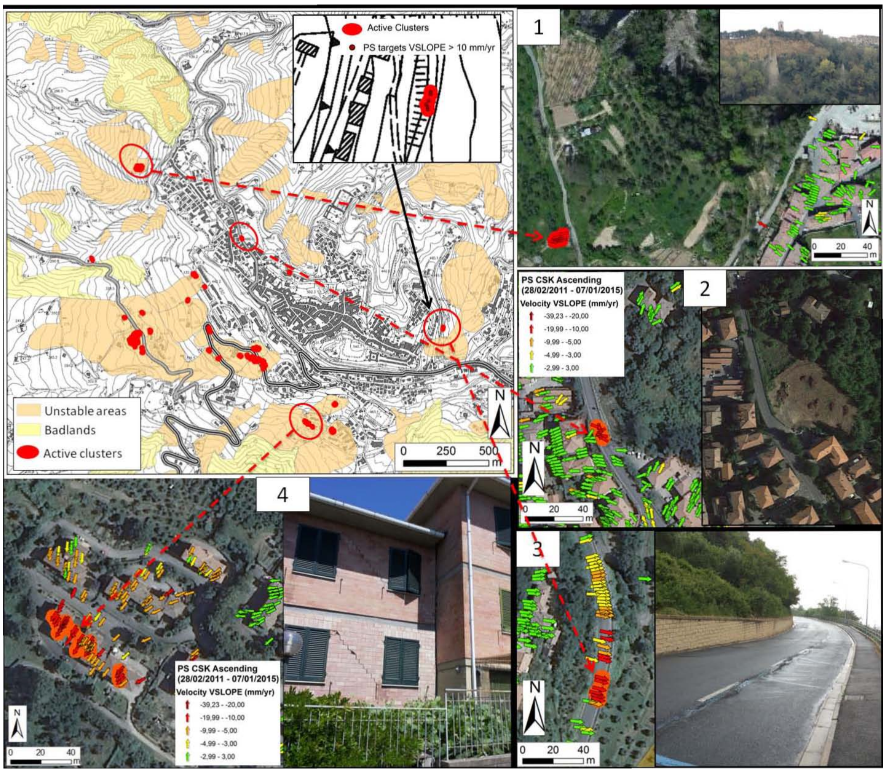

Figure 6. Detected "active clusters" [62] over Volterra area, overlapped on the spatial distribution of mapped unstable areas and badlands. The four close-up windows show four chosen examples of "active clusters" including the velocity map (V_{SLOPE} data are displayed as colored arrows) and photos of each chosen site.

4.2. GB-InSAR Monitoring of the Medieval City Walls (Slope Scale Analysis)

The GB-InSAR 1 system was able to monitor a 800 m long stretch of the southwestern city wall enclosure and some of the most important historical buildings (Dome, Baptistery) (Figure 7a). Pratesi et al. (2015) [9] describe in detail these GB-InSAR monitoring activities, carried out following the January 2014 wall collapse, prior to the March 2014 failure of a bastion sector (Figure 1b). GB-InSAR 1 system data revealed a general stability of the analyzed structures, except for a wall bastion area displaying velocity of about 2 mm/day, located in the area corresponding to *Piazza dei Martiri della Libertà* (Figure 7b). The latter area, comprising a pedestrian path and access both to a public park and the Etruscan Acropolis, represents a strategic and critical point of the city's public activities (Figure 1c). Within this sector, the displacement progressively increased from early to late February 2014, with displacement values reaching peaks of 4.11 mm/day. On 2 March 2014, a rapid acceleration was detected by the GB-InSAR system, where the displacement reached 1.7 mm/h [9]. As a consequence, the local authorities were immediately warned, and as a safety measure, public access to *Piazza dei Martiri della Libertà* area was interdicted. On 3 March 12 h after the early warning, the detected unstable bastion sector completely collapsed, destroying the underground parking access and the pedestrian path (Figure 3c).

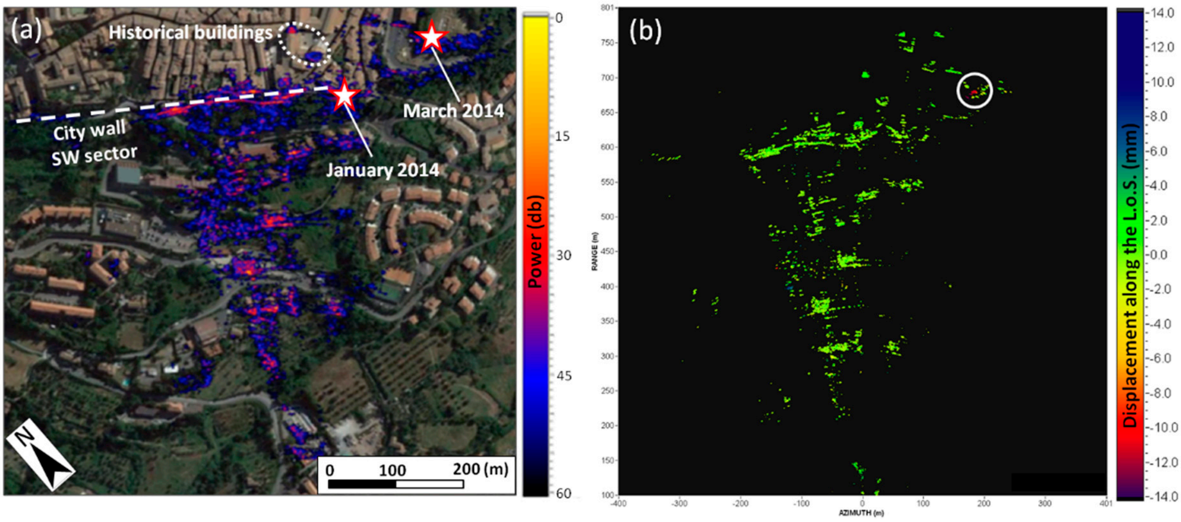

Figure 7. GB-InSAR 1 monitoring data: (**a**) geo-rectified radar power image on ortophoto, displaying the main structures monitored and the winter 2014 collapses (stars); (**b**) cumulated displacement map highlighting the unstable bastion sector (white circle): stable areas in light green, areas characterized by displacement toward the sensor LOS (colors from yellow to purple), areas characterized by displacements away from the sensor LOS (colors from dark green to blue).

The second GB-InSAR system (GB-InSAR 2) was installed in order to monitor the *Le Balze* geosite following the slope failure, with the aim of analyzing the morphodynamic evolution of the area, with special regard to precursors of further potential failures, such as displacements of the sand cliffs and shallow landsliding in as a result of the underlying clayey badlands [22]. The acquired displacement maps show a general stability of the monitored area, with special regards to the San Giusto Church and the subvertical sandy crags typically affected by instability phenomena, such as falls and toppling (Figure 8). Widespread clayey outcrops in the monitored area determine a very rapid evolution of the slopes, mainly related to gully erosion, small and shallow landslides and small earth-flows within the badlands [22]. Due to both the rapid and continuous evolution of these slopes, and their widespread vegetation cover, radar signal is strongly affected by decorrelation and atmospheric noise, giving the typical speckle effect to the displacement maps (Figure 8b).

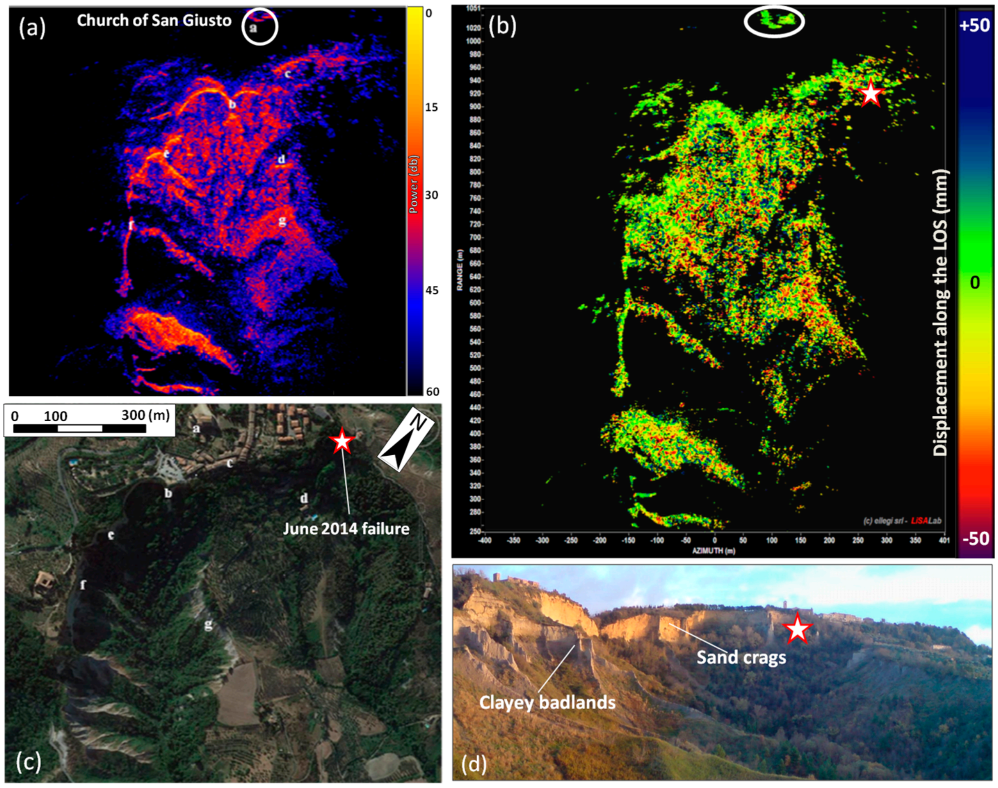

Figure 8. GB-InSAR 2 monitoring data. (**a**) SAR power image of the scanned area: a = Church of San Giusto; b, c, e, f = crags sandy cliffs; (**b**) monitoring period SAR cumulated displacement map: stable areas in light green, areas characterized by displacement toward the sensor LOS (colors from yellow to purple), areas characterized by displacements away from the sensor LOS (colors from dark green to blue); red star highlights the sand-cliff failure; white circle locates the Church of San Giusto; (**c**) geographical location of the monitored *Le Balze* geosite, letters same as in (**a**); red star = sandy wall collapse on June 2014 (**d**) Picture of *Le Balze* geosite.

4.3. Building Scale IRT Survey

The outcomes of the thermographic survey were synthesized in a "thermographic conservation criticalities map" (Figure 9a), which displays in detail the surveyed wall enclosure sectors, including the location of the detected thermal anomalies (areas with temperature pattern differing from the surrounding wall structure). The shown surface temperature maps are represented by means of a color scale, in which the higher temperatures are displayed by the lighter colors, and the lower temperatures by the darker ones (Figure 9b–f). Several cold sectors mapped in the masonry thermograms are due to evapotranspiration of the vegetation cover, as evident by comparing thermograms and the corresponding photos (i.e., see Figure 9b–g). The absence of cold thermal anomalies on the masonry structures during both the first and the second survey indicated the absence of moisture. Following this rapid and qualitative approach, during both the performed IRT surveys, dry conditions were assessed in correspondence with almost all of the analyzed structure; nevertheless, during the first survey some thermal anomalies were detected (Figures 10 and 11). Figure 10 shows the case of the city wall's northwestern sector along *Viale Francesco Ferrucci* (label 1 in Figure 9a), in which a cold thermal anomaly was detected on the masonry top portion (Figure 9a); no evidence of wet areas is visible in the corresponding optical image (Figure 10b). During the second performed survey, the detected thermal anomaly was no longer present (Figure 10c,d). Field inspections targeted on the back of the investigated wall portion revealed a bad masonry state of maintenance, with the presence of uncontrolled vegetation growing on the structure, which is probably the cause of rainfall infiltration in that sector portion (Figure 10e,f). Figure 10g shows a single thermogram acquired during the first survey along *Viale Trento e Trieste* (label 1 in Figure 9a), revealing a cold wet portion of the masonry structure, this time clearly visible also in the correspondent optical image (Figure 10h). In the thermogram of the same scenario acquired during the second survey (Figure 10i), the detected cold thermal anomaly is no longer present, even though a coat of weathering is still visible (Figure 10j).

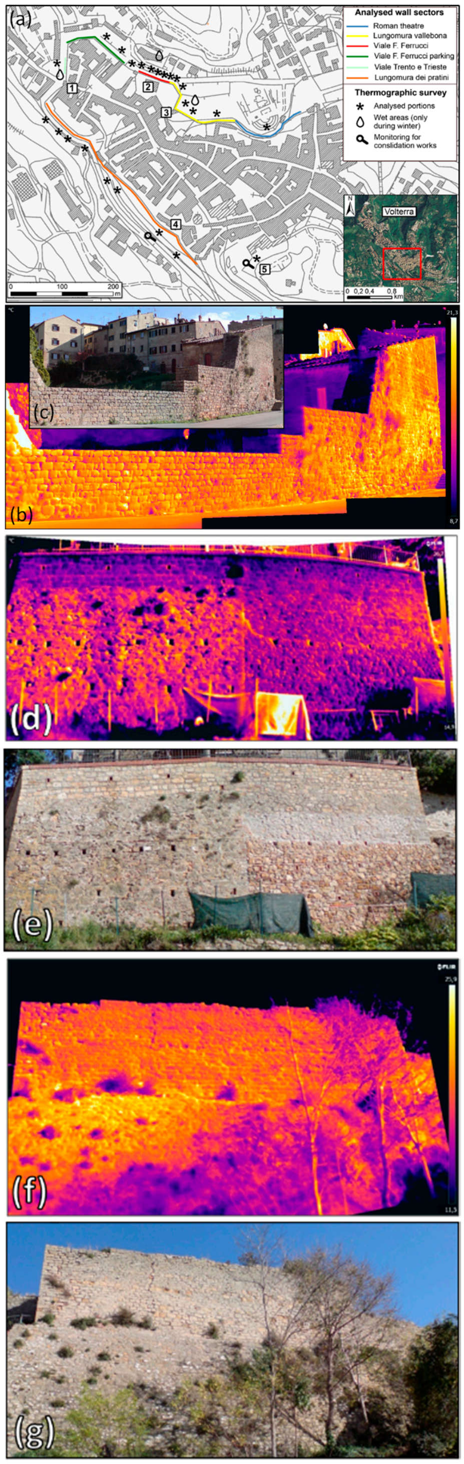

Figure 9. (**a**) Thermographic conservation criticality map of the Volterra city wall enclosure; labels from 1 to 5 represent the thermograms shown in the text. Examples of mosaicked thermograms acquired during the first IRT survey and correspondent photos: wall portion along *Lungomura dei Pratini* (**b**,**c**), from NW to SE along *Viale Trento e Trieste* (**d**–**g**).

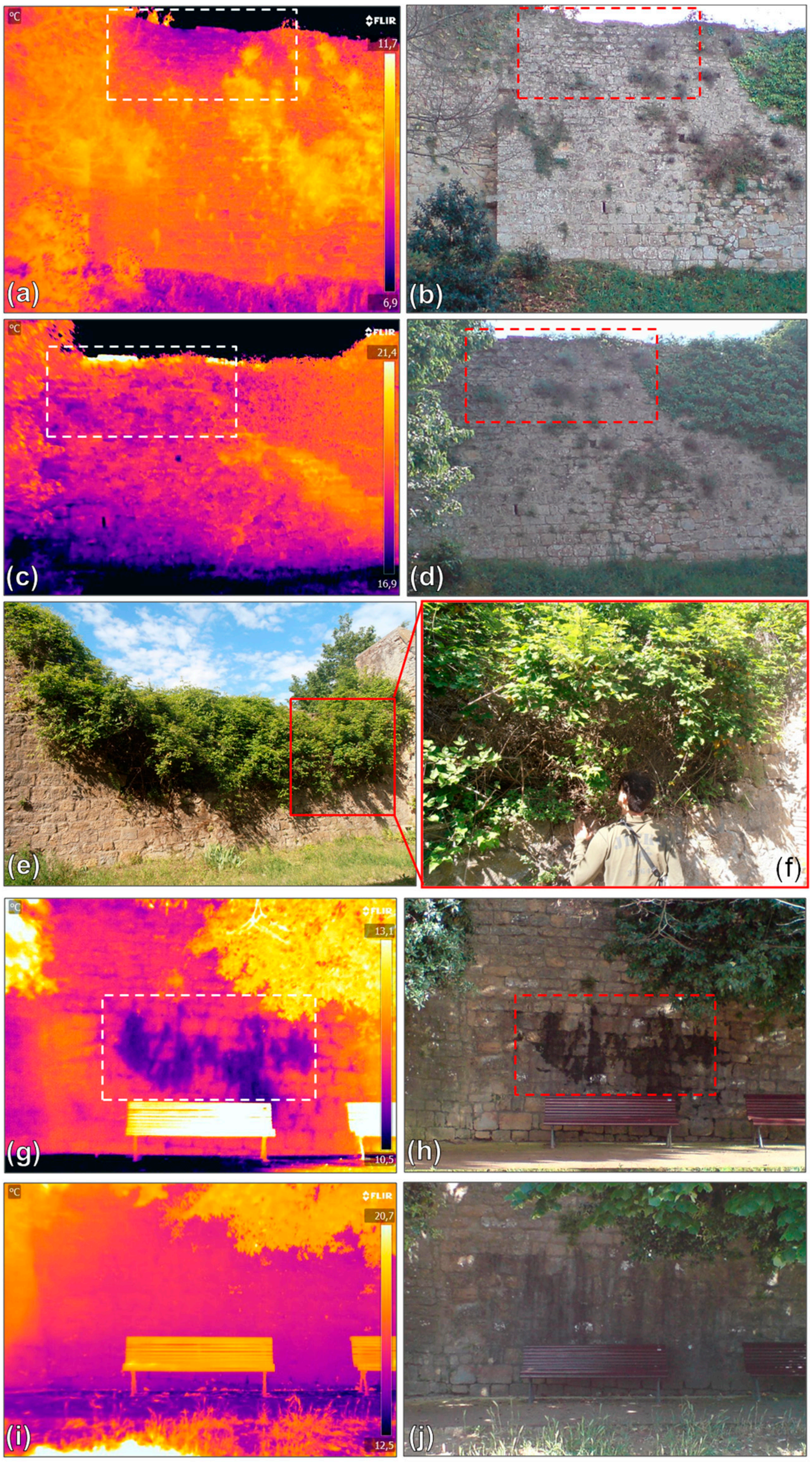

Figure 10. (**a**) Mosaicked thermogram of the northern wall sector (*Viale Francesco Ferrucci*, label 2 in Figure 9a), acquired on 2 December 2014 and correspondent photo (**b**) (dashed white and red squares enhance the sectors where a cold thermal anomaly was detected); (**c**) Mosaicked thermogram acquired in the same sector during the 25 May 2015 survey and correspondent photo (**d**); (**e**,**f**) Views of the back portion of the investigated wall shown in Figure 10a–d; (**g**) single thermogram of western city wall sector (*Viale Trento e Trieste*, label 1 in Figure 9a) acquired on 2 December 2015 and correspondent photo (**h**) (dashed squares enhance the detected cold thermal anomalies); (**i**) single thermogram acquired in the same sector on 25 May 2015 and correspondent photo (**j**).

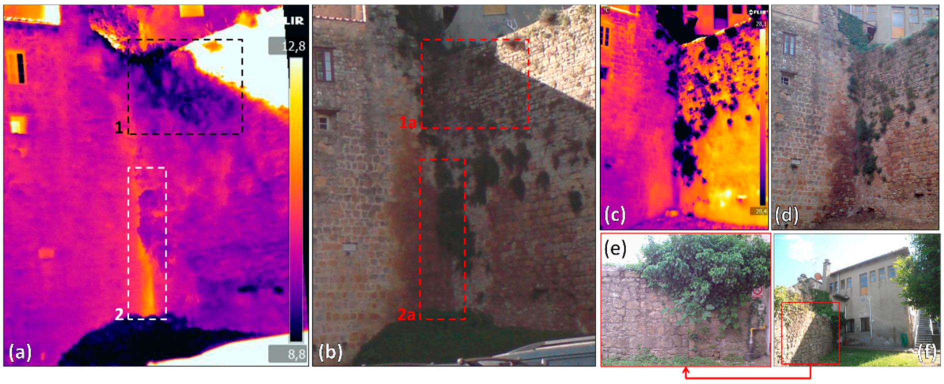

Figure 11. (**a**) Mosaicked thermograms of the northwestern wall sector along Lungomura Vallebona (label 3 in Figure 9a), acquired on 2 December 2015 and correspondent photo; (**b**) Dashed squares 1 and 2 respectively highlight the detected cold and warm thermal anomalies, while dashed squares 1a and 2a enhance the correspondent sectors on the photo; (**c**) Mosaicked thermograms acquired during the 25 May 2015 survey and correspondent photo (**d**); (**e**,**f**) Back portion of the investigated wall sector were the cold thermal anomaly was detected (red square highlights the location of a primary school building water plant).

Interaction between the wall enclosure and recent structural additions is part of the city building history, but at the same time it can be a potential cause of vulnerability. The results of the IRT survey in correspondence of a wall sector facing a parking lot along *Lungomura Vallebona* (label 3 in Figure 9a) are shown in Figure 11. Mosaicked thermograms acquired during the first survey (Figure 11a) show the presence of both a cold and warm thermal anomalies (Figure 11, dashed squares 1 and 2, respectively). Inspections performed on the back of the wall structure revealed that the warm thermal anomaly was located in accordance with the thermal plant of a primary school, while the cold thermal anomaly was related to a water leak caused by a damaged water pipe (Figure 11e,f).

5. Discussion

The use of appropriate technologies and data accuracy are important issues to take into account for deriving useful information for risk prevention and management. The choice is conditioned by several factors, such as the investigation target, the time available, the size of studied area and its accessibility, the exposure to further hazardous conditions, the investigation and representation scale. In this paper, a multi-platform remote sensing system was applied for a multi-scale monitoring/surveying activity of cultural and environmental heritage elements in the Volterra area. During the winter of 2014, after a period of intense rainfall, the pressure of undrained water caused the massive collapses of two wall sectors (Figure 3b,c), while slope instability phenomena occurred also in the spring of 2014, in an uninhabited area west of the urban center (*Le Balze* geosite, Figure 3d). In particular, PS-InSAR technique was applied in order to perform the detection of unstable areas at an urban scale. This analysis was performed as back-monitoring by acquiring pre-and post-event SAR images, after the wall collapses occurred in winter 2014.

GB-InSAR systems allowed for the carrying out of a near-real time monitoring of the urban instability phenomena at slope scale; structural and ground displacements were detected continuously, supporting the local authorities in emergency management. IRT was applied at a building-scale during two surveying days after the wall collapse events, allowing for a rapid surveying of the city wall masonry enclosure seasonal surface temperature variation.

PS-InSAR results permitted to derive the more potentially hazardous sectors with respect to instability phenomena, namely “active clusters,” according to procedures already tested in the scientific literature [62,63]. The PS-InSAR analysis revealed a general stability of the historical city center, while active clusters are located in the southwestern sectors, outside the historic urban area, where shallow translational landslides and soil erosion phenomena occur due to geological and geomorphological conditions (Figure 5). Only three active clusters are located near the city center (Figure 6); field surveys and photo-interpretation allowed verification that one active cluster placed on Filosofi Avenue (close-up 1), is affected by slow-moving ground deformation, while the other two active clusters are related to temporary land cover changes due to anthropgenic activity.

GB-InSAR technique was implemented by means of two radar systems: GB-InSAR 1 system allowed to detect an acceleration in the velocity-recorded values representing the March 2014 failure precursor, providing an effective early warning for the local authorities, which interdicted the access to the area almost 12 h before the cathastrofic fall of a 30 m long portion of the bastion wall (Figure 7) [9]. On *Le Balze* geosite, GB-InSAR 2 system ensured the detection of potential failure precursors, such as displacements of the sandy cliffs and shallow landsliding in correspondence with the underlying clayey badlands (Figure 8). The monitored scenario showed a general stability, with special regards to the historical buildings and sub-vertical sandy crags, with the exception of some clayey badlands sectors, which are affected by noise factors related to vegetation cover and to decorrelation effects due to their rapid morphodynamic evolution and acting rapid erosion processes.

The application of IRT allowed to collect during two surveying days surface temperature maps along a 2.6 km-long sector of the Volterra city walls, for a rapid qualitative assessment of moisture areas. The results were synthesized in a "thermographic conservation criticality map", a product thought to support local authorities, technicians and conservators involved in emergency management in the planning of future restoration works. Given the emergency context and the Volterra walls' length and height, IRT allowed for rapidly inspecting the entire city wall enclosure providing remote data acquisition over large areas with high device portability, logistic versatility, fast and easy data-processing time, and safety of the operator. Given these advantages IRT was considered a suitable technique with respect to other time-consuming, expensive and destructive methods, such as gravimetric direct measures, ground-penetrating radar [67] and ultrasonic velocity measurements [68], which on the contrary can provide data necessarily limited to a small number of control points/areas. Following the first thermographic survey (performed on 2 December 2014 after a rainy period; Figure 3), dry conditions were assessed along the entire wall enclosure, with the exception of some sectors where thermal anomalies were detected. In the latter sectors, the second survey and the related field inspections (performed on 25 May 2015, following a drier period; Figure 3) confirmed that the presence of cold thermal anomalies was related to rainfall (Figure 3) and to structural criticalities within the masonry wall enclosure. The research is now focusing on the thermographic monitoring activity of the collapsed wall portions and is providing additional information for the design and the management of restoration works, with the aim of detecting: (i) possible reactivation of water infiltrations during and after the work; (ii) wet portions to be properly drained; (iii) possible water infiltrations related to the presence of cisterns (dating back to the Roman age) located on the backside of the collapsed bastion.

The presented multi-platform approach allowed for the monitoring of the Volterra area, its cultural heritage and landscape, in both near-real time and back-analysis and at different scales of investigation. The collected data will be the basis for future activities to be completed in collaboration with local authorities, for a complete hazard risk characterization of the Volterra site, with the final aim of allowing the safety of touristic activities and for historical site preservation. The use of the employed remote sensing techniques may also lead to the use of a network sensors and probes connected to data-logging systems (i.e., crackmeters, tilt-meters, moisture sensors), to be placed to correspond with the detected hotspot unstable areas and thermal anomalies, for a real-time and remote-controlled monitoring system of possible displacements and moisture seasonal variations. Furthermore, the rapid evolution of IRT technology opens up future scenarios of automated inspections, which could be quickened by using IRT sensors mounted on remotely controlled aerial platforms (drones) [68–70].

The outcomes of this paper reveal the usefulness and scalability of a multi-platform remote sensing system, which includes different technologies to be employed during a monitoring campaign in both near-real time and back-analysis, for risk management strategies in natural and cultural heritage environments.

6. Conclusions

This work shows the outcomes of the monitoring activities performed on the historic town of Volterra (Italy) and surrounding environment, after hazardous events occurred in 2014, related to wall collapses and slope failures.

The investigation was carried out at different scales of investigation, i.e., from slope to single-building scale, in both near-real time and back-monitoring modes, by means of space-borne (PS-InSAR) and ground-based (GB-InSAR) radar remote sensing techniques. These monitoring systems permitted the analysis of the displacements occurring in the urban built-up area and in the surrounding slopes, and the detection of possible critical sectors with respect to instability phenomena. PS-InSAR data revealed 19 hotspot areas with ground velocity higher than 10 mm/year within the whole urban area. GB-InSAR systems locally monitored two slopes, allowing to detect a wall failure precursor, represented by an acceleration in velocity, up to 1.7 mm/h, and acting as an effective early warning system. Furthermore infrared thermography (IRT) was also applied in order to survey the wall-enclosure surface temperature with the aim of detecting possible criticalities, with special regards to moisture and seepage areas. During field IRT inspections, 65 thermograms were acquired, covering 23 different sectors of the town wall and highlighting four thermal anomalies.

The presented multi-platform approach provided a comprehensive overview of the Volterra site and its cultural heritage and landscape, in near-real time and back-analysis. The results of this work demonstrate the importance of monitoring strategies in risk preparedness and recovery phases that can be suitably supported by multiple remote sensing techniques, for both short- and long-term actions, especially in the case of natural and cultural heritage sites.

Acknowledgments: This work was conducted in the framework of the collaboration between Florence University, Department of Earth Sciences, and the National Civil Protection Department together with Tuscany Region Administration. Authors are grateful to Fosco Pasquinuzzi (Office of Environmental Service and Civil Protection Activities of the Volterra municipality) for his support, comments and valuable suggestions, and to Fabio Pratesi for his efforts in the monitoring activity. The GB-InSAR apparatus used was designed and produced by Ellegi s.r.l., and based on the proprietary technology GB-InSAR LiSALAB provided through the improvement of LiSA technology licensed to the Ispra Joint Research Centre of the European Commission. The available COSMO-SkyMed data were processed by Tele-Rilevamento Europa (TRE).

Author Contributions: T.N. conceived the article structure, processed and analysed the GB-InSAR data; W.F. performed the IRT survey, processed and analysed the related data; S.B. processed and analyzed the Ps-InSAR data; T.N., W.F. and S.B. contributed to the field inspection and equally to the paper writing process; N.C. coordinated the project work, the paper's writing with special regards to the reviewing process.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Frodella, W.; Ciampalini, A.; Gigli, G.; Lombardi, L.; Raspini, F.; Nocentini, M.; Scardigli, C.; Casagli, N. Synergic use of satellite and ground based remote sensing methods for monitoring the San Leo rock cliff (Northern Italy). *Geomorphology* **2016**, *264*, 80–94. [CrossRef]
2. Riveiro, B.; Jauregui, D.V.; Arias, P.; Armesto, J.; Jiang, R. An innovative method for remote measurement of minimum vertical underclearance in routine bridge inspection. *Autom. Constr.* **2012**, *25*, 34–40. [CrossRef]
3. Tapete, D.; Morelli, S.; Fanti, R.; Casagli, N. Localising deformation along the elevation of linear structures: An experiment with space-borne InSAR and RTK GPS on the Roman Aqueducts in Rome, Italy. *Appl. Geogr.* **2015**, *58*, 65–83. [CrossRef]
4. Taubenbock, H.; Esch, T.; Felbier, A.; Roth, A.; Dech, S. Pattern-based accuracy assessment of an urban footprint classification using TerraSAR-X data. *IEEE Geosci. Remote Sens. Lett.* **2011**, *8*, 278–282. [CrossRef]
5. Tapete, D.; Gigli, G.; Mugnai, F.; Vannocci, P.; Pecchioni, E.; Morelli, S.; Fanti, R.; Casagli, N. Correlation between Erosion Patterns and Rockfall Hazard Susceptibility in Hilltop Fortifications by Terrestrial Laser Scanning and Diagnostic Investigations. In Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium, Munich, Germany, 22–27 July 2012; pp. 4809–4812.

6. Bianchini, S.; Pratesi, F.; Nolesini, T.; Casagli, N. Building deformation assessment by means of persistent scatterer interferometry analysis on a landslide-affected area: The Volterra (Italy) case study. *Remote Sens.* **2015**, *7*, 4678–4701. [CrossRef]
7. Delmonaco, G.; Leoni, G.; Margottini, C.; Spizichino, D. Implementation of advanced monitoring system network in the Siq of Petra (Jordan). In *Engineering Geology for Society and Territory 8*; Lollino, G., Jordan, D., Maruneanu, C., Christaras, B., Yoshinori, I., Margottini, C., Eds.; Springer International Publishing: Lausanne, Switzerland, 2015; pp. 299–303.
8. Broussolle, J.; Kyovtorov, V.; Basso, M.; Castiglione, G.F.D.S.E.; Morgado, J.F.; Giuliani, R.; Oliveri, F.; Sammartino, P.F.; Tarchi, D. MELISSA, a new class of ground based InSAR system. An example of application in support to the Costa Concordia. *ISPRS J. Photogramm. Remote Sens.* **2014**, *91*, 50–58. [CrossRef]
9. Pratesi, F.; Nolesini, T.; Bianchini, S.; Leva, D.; Lombardi, L.; Fanti, R.; Casagli, N. Early warning GBInSAR-based method for monitoring Volterra (Tuscany, Italy) city walls. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2015**, *8*, 1753–1762. [CrossRef]
10. Tarchi, D.; Ohlmer, E.; Sieber, A.J. Monitoring of structural changes by radar interferometry. *Res. Nondestruct. Eval.* **1997**, *9*, 213–225. [CrossRef]
11. Tarchi, D.; Rudolf, H.; Pieraccini, M.; Atzeni, C. Remote monitoring of buildings using a ground-based SAR: Application to cultural heritage survey. *Int. J. Remote Sens.* **2000**, *21*, 3545–3551. [CrossRef]
12. Tarchi, D.; Casagli, N.; Fanti, R.; Leva, D.; Luzi, G.; Pasuto, A.; Pieraccini, M.; Silvano, S. Landslide monitoring by using ground-based SAR interferometry: An example of application to the Tessina landslide in Italy. *Eng. Geol.* **2002**, *68*, 15–30. [CrossRef]
13. Luzi, G.; Pieraccini, M.; Mecatti, D.; Noferini, L.; Guidi, G.; Moia, F.; Atzeni, C. Ground-based radar interferometry for landslides monitoring: Atmospheric and instrumental decorrelation sources on experimental data. *IEEE Trans. Geosci. Remote Sens.* **2004**, *42*, 2454–2466. [CrossRef]
14. Luzi, G.; Monserrat, O.; Crosetto, M.; Copons, R.; Altimir, J. Ground-Based SAR Interferometry Applied to Landslide Monitoring in Mountainous Areas. In Proceedings of the Mountain Risks Conference: Bringing Science to Society, Firenze, Italy, 24–26 November 2010; pp. 24–26.
15. Gigli, G.; Intrieri, E.; Lombardi, L.; Nocentini, M.; Frodella, W.; Balducci, M.; Venanti, L.D.; Casagli, N. Event scenario analysis for the design of rockslide countermeasures. *J. Mount. Sci.* **2014**, *11*, 1521–1530. [CrossRef]
16. Grinzato, E.; Vavilov, V.; Kauppinen, T. Quantitative infrared thermography in buildings. *Energy Build.* **1998**, *29*, 1–9. [CrossRef]
17. Avdelidis, N.P.; Moropoulou, A. Applications of infrared thermography for the investigation of historic structures. *J. Cult. Herit.* **2004**, *5*, 119–127. [CrossRef]
18. Teza, G.; Marcato, G.; Castelli, E.; Galgaro, A. IRTROCK: A matlab toolbox for contactless recognition of surface and shallow weakness traces of a rock mass by infrared thermography. *Comput. Geosci.* **2012**, *45*, 109–118. [CrossRef]
19. Gigli, G.; Frodella, W.; Garfagnoli, F.; Morelli, S.; Mugnai, F.; Menna, F.; Casagli, N. 3-D geomechanical rock mass characterization for the evaluation of rockslide susceptibility scenarios. *Landslides* **2014**, *11*, 131–140. [CrossRef]
20. Frodella, W.; Morelli, S.; Fidolini, F.; Pazzi, V.; Fanti, R. Geomorphology of the Rotolon landslide (Veneto Region, Italy). *J. Maps* **2014**, *10*, 394–401. [CrossRef]
21. Sabelli, R.; Cecchi, G.; Esposito, A.M. *Mura Etrusche di Volterra, Conservazione e Valorizzazione*; La Grafica Pisana: Bientina, Italy, 2012. (In Italian)
22. Bianchini, S.; del Soldato, M.; Solari, L.; Nolesini, T.; Pratesi, F.; Moretti, S. Badland susceptibility assessment in Volterra municipality (Tuscany, Italy) by means of GIS and statistical analysis. *Environ. Earth Sci.* **2016**, *75*. [CrossRef]
23. Terrenato, N. The romanization of Volaterrae (Volterra). *J. Rom. Stud.* **1998**, *88*, 94–114. [CrossRef]
24. Cateni, G.; Furiesi, A. *La Città di Pietra. Mura Etrusche e Medievali di Volterra*; Pacini: Pisa, Italy, 2006. (In Italian)
25. Esposito, A.; Malesani, M.; Sabelli, R. Attività della Soprintendenza per i Beni Archeologici della Toscana nel Territorio Comunale di Volterra dal 1999 al 2003. In Proceedings of the VI Convegno Beni Ambientali e Culturali nella Città Storica, Volterra, Italy, 13–14 June 2003; pp. 16–171. (In Italian)
26. Bonamici, M. Contributo alla Cinta Muraria Arcaica di Volterra. In Proceedings of the la Città Murata in Etruria 25th Convegno di Studi Italici, Chianciano Terme, Italy, 30 March–3 April 2005; pp. 337–352. (In Italian)

27. Ferretti, A.; Prati, C.; Rocca, F. Nonlinear subsidence rate estimation using Permanent Scatterers in differential SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* **2000**, *38*, 2202–2212. [CrossRef]
28. Ferretti, A.; Prati, C.; Rocca, F. Permanent scatterers InSAR interferometry. *IEEE Trans. Geosci. Remote Sens.* **2001**, *39*, 8–20. [CrossRef]
29. Hooper, A.; Zebker, H.; Segall, P.; Kampes, B. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. *Geophys. Res. Lett.* **2004**, *31*. [CrossRef]
30. Massironi, M.; Zampieri, D.; Bianchi, M.; Schiavo, A.; Franceschini, A. Use of PS™ data to infer active tectonics: Clues on the differential uplift across the Giudicarie belt (Central-Eastern Alps, Italy). *Tectonophysics* **2009**, *476*, 297–303. [CrossRef]
31. Costantini, M.; Iodice, A.; Magnapane, L.; Pietranera, L. Monitoring Terrainmovements by Means of Sparse SAR Differential Interferometric Measurements. In Proceedings of the IEEE 2000 International Geoscience and Remote Sensing Symposium, Honolulu, HI, USA, 24–28 July 2000; pp. 3225–3227.
32. Ferretti, A.; Fumagalli, A.; Novali, F.; Prati, C.; Rocca, F.; Rucci, A. Higher-order permanent scatterers analysis. *Eurasip J. Appl. Signal Process.* **2005**, *20*, 3231–3242. [CrossRef]
33. Hanssen, R.S. Satellite radar interferometry for deformation monitoring: A priori assessment of feasibility and accuracy. *Int. J. Appl. Earth Obs. Geoinform.* **2005**, *6*, 253–260. [CrossRef]
34. Raucoules, D.; Colesanti, C.; Carnec, C. Use of SAR interferometry for detecting and assessing ground subsidence. *Comptes Rendus Geosci.* **2009**, *339*, 289–302. [CrossRef]
35. Crosetto, M.; Monserrat, O.; Iglesias, R.; Crippa, B. Persistent scatterer interferometry: Potential, limits and initial C- and X-band comparison. *Photogramm. Eng. Remote Sens.* **2010**, *76*, 1061–1069. [CrossRef]
36. Ferretti, A.; Fumagalli, A.; Novali, F.; Prati, C.; Rocca, F.; Rucci, A. A new algorithm for processing interferometric data-stacks: SqueeSAR. *IEEE Trans. Geosci. Remote Sens.* **2011**, *49*, 3460–3470. [CrossRef]
37. Tofani, V.; Raspini, F.; Catani, F.; Casagli, N. Persistent scatterer interferometry (PSI) technique for landslide characterization and monitoring. *Remote Sens.* **2013**, *5*, 1045–1065. [CrossRef]
38. Bellotti, M.; Bianchi, D.; Colombo, A.; Ferretti, A. Tamburini, A. Advanced InSAR techniques to support landslide monitoring. In *Mathematics of Planet Earth Lecture Notes in Earth System Sciences*; Pardo-Igúzquiza, E., Guardiola-Albert, C., Heredia, J., Moreno-Merino, L., Durán, J.J., Vargas-Guzmán, J.A., Eds.; Springer: Berlin, Germany, 2014; pp. 287–290.
39. Notti, D.; Herrera, G.; Bianchini, S.; Meisina, C.; García-Davalillo, J.C.; Zucca, F. A methodology for improving landslide PSI data analysis. *Int. J. Remote Sens.* **2014**, *35*, 2186–2214.
40. Zebker, H.A.; Goldstein, R.M. Topographic mapping from interferometric synthetic aperture radar observations. *J. Geophys. Res.* **1986**, *91*, 4993–4999. [CrossRef]
41. Curlander, J.C.; McDonough, R.N. *Synthetic Aperture Radar: Systems and Signal Processing*; Wiley: New York, NY, USA, 1991; p. 672.
42. Bamler, R.; Hartl, P. Synthetic aperture radar interferometry. *Inverse Probl.* **1998**, *14*, R1. [CrossRef]
43. Rudolf, H.; Leva, D.; Tarchi, D.; Sieber, A.J. A Mobile and Versatile SAR System. In Proceedings of the IEEE 1999 International Geoscience and Remote Sensing Symposium, Hamburg, Germany, 28 June–2 July 1999; pp. 592–594.
44. Pieraccini, M.; Tarchi, D.; Rudolf, H.; Leva, D.; Luzi, G.; Bartoli, G.; Atzeni, C. Structural static testing by interferometric synthetic radar. *NDT E Int.* **2000**, *33*, 565–570. [CrossRef]
45. Pieraccini, M.; Casagli, N.; Luzi, G.; Tarchi, D.; Mecatti, D.; Noferini, L.; Atzeni, C. Landslide monitoring by ground-based radar interferometry: A field test in Valdarno (Italy). *Int. J. Remote Sens.* **2002**, *24*, 1385–1391. [CrossRef]
46. Monserrat, O.; Crosetto, M.; Luzi, G. A review of ground-based SAR interferometry for deformation measurement. *ISPRS J. Photogramm. Remote Sens.* **2014**, *93*, 40–48. [CrossRef]
47. Maldague, X. *Theory and Practice of Infrared Technology for Non Destructive Testing*; John-Wiley & Sons: New York, NY, USA, 2001; p. 684.
48. Laguela, S.; González-Jorge, H.; Armesto, J.; Arias, P. Calibration and verification of thermographic cameras for geometric measurements. *Infrared Phys. Technol.* **2011**, *54*, 92–99. [CrossRef]
49. Aggelis, D.G.; Kordatos, E.Z.; Soulioti, D.V.; Matikas, T.E. Combined use of thermography and ultrasound for the characterization of subsurface cracks in concrete. *Constr. Build. Mater.* **2010**, *24*, 1888–1897. [CrossRef]
50. Avdelidis, N.P.; Moropoulou, A.; Theoulakis, P. Detection of water deposits and movement in porous materials by infrared imaging. *Infrared Phys. Technol.* **2003**, *44*, 183–190. [CrossRef]

51. Tavukçuoğlu, A.; Dügünes, E.N.; Caner-Saltık, E.N.; Demirci, Ş. Use of IR thermography for the assessment of surface-water drainage problems in a historical building, Ağzıkarahan (Aksaray). Turkey. *NDT E Int.* **2005**, *38*, 402–410. [CrossRef]
52. Meola, C. Infrared thermography of masonry structures. *Infrared Phys. Technol.* **2006**, *49*, 228–233. [CrossRef]
53. Grinzato, E.; Rosina, E. Infrared and thermal testing for conservation of historic building. In *Non Destructive Testing Handbook, Infrared and Thermal Testing*, 3rd ed.; American Society For Nondestructive Testing (ASNT): Columbus, OH, USA, 2001; pp. 942–954.
54. Grinzato, E.; Bressan, C.; Marinetti, S.; Bison, P.G.; Bonacina, C. Monitoring of the Scrovegni Chapel by IR thermography: Giotto at infrared. *Infrared Phys. Technol.* **2002**, *43*, 165–169. [CrossRef]
55. Paoletti, D.; Ambrosini, D.; Sfarra, S.; Bisegna, F. Preventive thermographic diagnosis of historical buildings for consolidation. *J. Cult. Herit.* **2003**, *14*, 116–121. [CrossRef]
56. Cabrelles, M.; Galcerá, S.; Navarro, S.; Lerma, J.L.; Akasheh, T.; Haddad, N. Integration of 3D Laser Scanning, Photogrammetry and Thermography to Record Architectural Monuments. In Proceedings of the 22nd International CIPA Symposium, Kyoto, Japan, 11–15 October 2009.
57. De Freitas, S.S.; de Freitas, V.P.; Barreira, E. Detection of façade plaster detachments using infrared thermography, a nondestructive technique. *Constr. Build. Mater.* **2014**, *70*, 80–87. [CrossRef]
58. Alba, M.I.; Barazzetti, L.; Scaioni, M.; Rosina, E.; Previtali, M. Mapping infrared data on terrestrial laser scanning 3D models of buildings. *Remote Sens.* **2011**, *3*, 1847–1870. [CrossRef]
59. Ludwig, N.; Redaelli, V.; Rosina, E.; Augelli, F. Moisture detection in wood and plaster by IR thermography. *Infrared Phys. Technol.* **2004**, *46*, 161–166. [CrossRef]
60. FLIR, 2012, FLIR Reporter Professional 9. Available online: http://www.flir.com/cs/emea/en/view/?id=42405 (accessed on 30 June 2015).
61. FLIR, 2014, FLIR ResearchIR 3.4. sp3. Available online: http://support.flir.com/DsDownload/Assets/T198206en_40.pdf (accessed on 30 June 2015).
62. Bianchini, S.; Herrera, G.; Mateos, R.M.; Notti, D.; Garcia, I.; Mora, O.; Moretti, S. Landslide activity maps generation by means of persistent scatterer interferometry. *Remote Sens.* **2013**, *5*, 6198–6222. [CrossRef]
63. Mansour, M.F.; Morgenstern, N.R.; Derek Martin, C. Expected damage from displacement of slow-moving slides. *Landslides* **2011**, *8*, 117–131. [CrossRef]
64. Meisina, C.; Zucca, F.; Notti, D.; Colombo, A.; Cucchi, A.; Savio, G.; Bianchi, M. Geological interpretation of PSInSAR data at regional scale. *Sensors* **2008**, *8*, 7469–7492. [CrossRef]
65. Cigna, F.; Bianchini, S.; Righini, G.; Proietti, C.; Casagli, N. Updating landslide inventory maps in mountain areas by means of Persistent Scatterer Interferometry (PSI) and photo-interpretation: Central Calabria (Italy) case study. In *Mountain Risks: Bringing Science to Society*; CERG Editions: Strasbourg, France, 2010; pp. 24–26.
66. Maierhofer, C.; Leipold, S. Radar investigation of masonry structures. *NDT E Int.* **2001**, *34*, 139–147. [CrossRef]
67. Kandemir-Yucel, A.; Tavukcuoglu, A.; Caner-Saltik, E.N. In situ assessment of structural timber elements of a historic building by infrared thermography and ultrasonic velocity. *Infrared Phys. Technol.* **2007**, *49*, 243–248. [CrossRef]
68. Eschmann, C.; Kuo, C.M.; Kuo, C.H.; Boller, C. Unmanned Aircraft Systems for Remote Building Inspection and Monitoring. In Proceedings of the 6th European Workshop on Structural Health Monitoring, Dresden, Germany, 3–6 June 2012.
69. Pavlidis, I.; Symosek, P.; Fritz, B.; Bazakos, M.; Papanikolopoulos, N. Automatic detection of vehicle occupants—The imaging problem and its solution. *Mach. Vis. Appl.* **2000**, *11*, 313–320. [CrossRef]
70. Pavlidis, I.; Morellas, V.; Papanikolopoulos, N. A vehicle occupant counting system based on near-infrared phenomenology and fuzzy neural classification. *IEEE Trans. Int. Transp. Syst.* **2000**, *1*, 72–85. [CrossRef]