Application of DInSAR in mine surface subsidence monitoring and prediction

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Most studies of surface subsidence and its impacts have been done on underground coal mines. There are few studies on the occurrences of surface subsidence in underground metal mines, particularly in India, even though the fundamental subsidence engineering principles are the same for both coal and metal mines. The current ground-based measurement techniques monitor ground subsidence on a particular point and are time-consuming as well as costly. To study hard-rock mine surface deformation due to underground mining, new and effective technologies must be adopted. The spaceborne subsidence monitoring has emerged as a better technique after the development of satellite radar interferometry. The technology is fast improving with enhanced synthetic aperture radar (SAR) sensors on different spaceborne platforms. Differential interferometric SAR techniques are widely used to measure the topographic profile and surface deformations. This article reviews the applications of spaceborne SAR interferometric techniques in the prediction and monitoring of surface subsidence due to underground mining.

Keywords: Interferometric techniques, synthetic aperture radar, surface subsidence, underground mines.

SURFACE subsidence due to underground mining activity is a serious engineering, economic and environmental issue. Subsidence has been defined as an inevitable consequence of underground mining, either small or large, localized or getting extended over large areas; it may be immediate or delayed for many years[1]. Modern hard-rock metal mining, using large-scale methods like block caving, sublevel caving, room and pillar mining, and vertical crater retreat mining creates large areas of subsidence impacts. Even in cases where vein deposit mining methods are employed in competent rock at great depths with low extraction ratios, the surface expression of subsidence is not eliminated, though it may not appear for some time[2]. The amount of subsidence has been observed as a direct function of time[2]. Greater depths of overburden do not prevent subsidence, but may prolong the time period before subsidence effects are observed at the surface[2]. The thickness of the extraction by underground mining and surface subsidence is directly related to each other. A greater thickness results in a greater amount of surface subsidence. Underground mining creates voids inside the mine along with depletion of water table around the area, contributing significantly towards surface deformation. Surface subsidence due to mining activity may affect buildings and other man-made structures.

The common ground-based measurement techniques, using precise levelling, total station and global navigation satellite system (GNSS), monitor ground subsidence at a point. Though these methods are time-consuming and costly, they can measure height information at millimetre to centimetre levels of accuracy. Radar interferometric applications are well explained by Massonnet and Feigl[3]. SAR interferometry was successfully applied by Carnec and Delacourt[4] to study the subsidence caused by underground coal mining. In the last decade, the spaceborne interferometric synthetic aperture radar (InSAR) technique has established its utility for detecting ground deformation. InSAR can measure the ground deformation over a large spatial extent. It is efficient because it involves less manpower, thereby reducing the cost when compared to the conventional ground based survey methods. Moreover, it is not restricted by issues such as site accessibility. Ge *et al.*[5] reported that differential interferometric SAR (DInSAR) can deliver ~1 cm height change resolution. Land subsidence monitoring is an important area of application of DInSAR, in which the mining industry and environmentalists are particularly interested[6]. This article reviews the applications of spaceborne SAR interferometric techniques in the prediction and monitoring of surface subsidence due to underground mining.

Surface subsidence due to mining

Singh[7] defines mine subsidence as 'ground movements that occur due to the collapse of overlying strata into mine voids'. Ground subsidence is the lowering or collapse of the land surface, and is caused by a number of natural and human-induced activities. Most subsidence is either created or accelerated by humans[8]. Subsidence is a natural effect of underground mining and when a void is created nature will eventually seek the most stable geologic configuration, which is collapse of the void and consolidation of the overburden material[9]. Subsidence is a natural and man-made phenomenon associated with a

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variety of processes, including compaction of natural sediments, groundwater dewatering, wetting, melting of permafrost, liquefaction and crustal deformation, withdrawal of petroleum and geothermal fluids, and mining of coal, limestone, salt, sulphur and metallic ores[10]. Surface deformations and slope stability are important issues to the open pit mining industry. They may also disrupt mine scheduling and increase the cost of mining production. In underground mining, inadequate support may lead to collapse of rocks either during or long after mining is completed. The collapse of the overlying strata has always been a safety concern in underground mining.

The formal study of subsidence engineering began in the 19th century and was focused on European coal mines in Belgium, France and Germany. The studies were initiated by damage to overlying mine facilities and railways[11,12]. These early reports established a scientific foundation for future subsidence studies and identified the mechanisms of subsidence[12]. Subsidence and hydrology impacts occur at every underground mining operation bringing about changes to surface landforms, groundwater and surface water[2]. The creation of voids as a consequence of underground mining results in subsidence. Water depletion due to underground mining also causes the formation of cavities. Mining activities that create relatively small voids may create pits or sinkholes, which are commonly associated with historic underground hard-rock mining activities. According to Singh[7], mining at any depth can result in subsidence, and the affected surface area is generally larger than the extraction area.

Subsidence effects of underground coal mines are well documented in comparison to hard-rock underground mines. Blodgett and Kuipers[2] have reported case studies of surface subsidence due to hard-rock underground mining in many mines of the United States, like San Manuel and Miami copper mines in Arizona, Henderson and Climax molybdenum mines in Colorado, Athen iron mine in Michigan, and Montana copper/silver mines in Butte. At present, in India there are only a few hard-rock underground mines which are extracting copper, gold, manganese and uranium. The Singhbhum region of India has a history of many underground mines and in 1994, occurrences of surface subsidence have been reported from Badia copper mine (presently abandoned). Now, there are many abandoned copper mines in the adjoining areas of the abandoned Badia copper mine and there have been occurrences of subsidence causing sinkholes on the surface. Coal mining subsidence has received worldwide attention, but less information is available on subsidence impacts due to hard-rock underground mining, particularly in India. Most studies of surface subsidence using SAR interferometry worldwide have been done on underground coal mines[4,5,13–35]. DInSAR techniques have been demonstrated as an effective tool to monitor the surface subsidence-prone area due to mining activities in Jharia coal field, Jharkhand, India[19–23,29,31]. DInSAR techniques have been applied on surface subsidence in metal mines of Sweden[36], Spain[37] and France[38]. However, SAR interferometric techniques have not been applied to examine the occurrences of surface deformation or subsidence effects in hard-rock underground mines in India.

Analyses on applications of DInSAR in surface subsidence

InSAR, also referred to as SAR interferometry, is the measurement of change in signal phase (interference) between radar images. When a point on the earth's surface moves then there is a change in distance between the sensor and the point, resulting in a corresponding shift of signal phase. This displacement in the phase between two SAR images is measured at each point (pixel) in a phase difference image and is known as an interferogram. The two images are precisely co-registered before the phase difference is computed for each pixel. When InSAR is used to recognize and measure ground deformation, the process is referred to as differential InSAR.

SAR and its interferometric techniques have been widely addressed and reviewed in the literature. DInSAR applications are well explained by Crosetto *et al.*[39]. A slow and local phenomenon of subsidence due to underground coal mining was identified near Gardanne, France by Carnec and Delacourt[4] from images acquired by ERS-1/ERS-2 satellites between 1992 and 1995. Interferometric monitoring has shown that the impact of subsidence on the surface migrated all along the path of advancement of the underground operations establishing a direct relationship between them[4,26,35,37]. The application of SAR interferometry to identify surface displacements through DInSAR has shown its great potential and has developed manifold over the last decade. DInSAR techniques can be used to detect small ground deformation over a large area during a specific period[5]. The basic concept of DInSAR application is to monitor an area at regular intervals of time. An approach to determine the best procedure to connect multi-temporal InSAR datasets was studied by Refice *et al.*[40]. Ge *et al.*[13] used ERS-1/2 (C-band, λ – 5.6 cm), JERS-1 (L-band, λ – 23.5 cm), Radarsat-1 (C-band, λ – 5.6 cm) and Envisat (C-band, λ – 5.6 cm) datasets to monitor mine subsidence in seven active mine collieries near Sydney, Australia and established that shorter wavelength of ERS-1/2 was more sensitive. However, DInSAR with Envisat imagery was found to be complicated due to acquisitions from different passes and imaging modes. Wavelet transform, a mathematical tool for assessing the ability of InSAR to monitor surface deformation induced by mining activities over the Western Australia Goldfields mining region was used by Baran and Stewart[41]. The overall low coherence on the test interferogram was the main constraint. Though it appears to be a promising method for interferogram analysis, it was a preliminary study and not all aspects of wavelet transform were researched. Another technique, the two-pass differential interferometry, was used to monitor land subsidence by DInSAR technique[17,32,42]. The differential interferogram was filtered before unwrapping and due to filtering much better coherence was achieved. ERS and Envisat images were used to investigate the feasibility of DInSAR for coal mine subsidence monitoring in Tang Shan, Hebei Province, China, and the importance of small perpendicular baseline to get good results was highlighted[32]. Colour coding was used to demarcate the mine subsidence regions, indicating the magnitude of subsidence. About six scenes of ERS 1/2 images captured during 1995 and 2000 in a certain place of Jiangsu Province, China, were selected to obtain the land subsidence and velocities in an urban area, in three time segments by two-pass DInSAR method[42]. The results showed that high accuracy could be obtained using this technique to monitor the deformation of a large area. Another DInSAR technique, the coherent pixel technique (CPT) was applied for the study of displacements[37,43,44]. This technique is based on the pixel selection criterion, a coherence threshold and non-restricted generation of the interferometric pairs.

L-band SAR satellites, JERS-1 and ALOS PALSAR (λ – 23.5 cm) has shown great potential in monitoring subsidence[13,14,16,22,24,26,30,33,45]. Subsidence monitoring at Fengfeng coal mining area in China was performed by Guang *et al.*[16] using multi-band SAR data. The L-band was found to maintain coherence despite temporal baseline being larger than six months. L-band SAR data through DInSAR techniques can be used for the long term monitoring of surface subsidence associated with mining activities[16,24]. Bayuaji *et al.*[45] studied urban subsidence in Jakarta during 2007–2008 and found that four northern areas in the city showed clear indications of land subsidence. The location of subsidence centre was anticipated and subsidence volume was evaluated for each area using the unwrapping method. Comparison with ground survey data indicated that the DInSAR analysis could give reliable estimation of the subsidence in an urban environment. By comparing the performance of different bands, L-band SAR images have shown great capabilities in rural and vegetated areas[14,30].

After detailed review of the literature, persistent or permanent scatterer interferometry (PSInSAR or PSI) techniques and approaches[46–53] seem to be more promising, as they give estimates on point targets. PSInSAR technique is the innovation and development of DInSAR technique. This method eliminates the problem of geometrical and temporal de-correlation by considering only point-like scatterers. Many PSI approaches have been developed over the years; their description is beyond the scope of this article. Examples of PSInSAR application in the field of mine surface[14,15,25,26,28,30,34,35,38] and urban[54–64] subsidence have shown the large spectrum of this technique on ground deformation assessment. About 21 TerraSAR X-band (λ – 3.1 cm) images have been used by Liu *et al.*[28] to extract subsidence hazard map (SHM) around Xishan coal mine in China, that suffered from subsidence related to underground mining activities. The results have shown the advantages of DInSAR techniques for large-scale monitoring with high-resolution data. However, applications in mountainous regions led to temporal de-correlation and topographic effects. Using ERS data, Ferretti *et al.*[49] have shown that in urban areas and in rocky terrain, PS exists that allow us to extract useful phase information even after many years. PSInSAR gives point results and enables observation over a longer time-span. It has proved to be extremely effective and more adequate than the classic DInSAR[55]. Recently, Solari *et al.*[57] and Crosetto *et al.*[52] have described PSInSAR as a powerful remote sensing technique. Using 57 ERS 1/2 data and PSI technique Colesanti *et al.*[38] identified precursor signs of collapse 10 months preceding the major collapse event affecting an area of ~300 × 300 m^2, which occurred in February 1999 at the iron mining site of Roncourt, France. They established the relevance of the PSInSAR technique in studying the deformation before the major subsidence, when no levelling data were recorded. Przylucka *et al.*[35] demonstrated that using high-resolution TerraSAR-X data in both conventional and advanced DInSAR approaches was effective for detecting and monitoring fast-evolving mining subsidence in urban areas in the upper Silesian coal basin of Poland. The main design parameters that influence the feasibility and accuracy of PSInSAR are the number of acquisitions (images; N), the temporal baseline (B_T) and spatial/perpendicular baseline ($B_\perp$). The PSI technique was useful for the measurement of ground subsidence in abandoned coal mining areas, even in mountainous regions[14]. The crack levels collected during field survey for the study area located in Gaeun, Korea, when compared with SAR measurements showed good agreement, and despite the low density of persistent scatterers, it was possible to construct a two-dimensional subsidence map[14]. An advantage of high-resolution X-band PSI is its capability to generate dense PS sampling. The X-band time series has shown a remarkable quality improvement with respect to the C-band. The two most important PSI limits are the poor PS spatial sampling capability in vegetated/forested areas, and in measuring fast deformation phenomena[47]. Both limitations need a careful assessment before starting any new PSI analysis. In 2010 a new algorithm – SqueeSAR[35,65,66] – was developed. This is an extension of the PSInSAR algorithm, that exploits both 'point-wise' PS and also provides information in low reflectivity homogeneous areas by identifying 'spatially distributed scatterers' (DS). SqueeSAR incorporates PSInSAR and no information is lost. Przylucka *et al.*[35] have shown the capabilities of SqueeSAR for detecting and monitoring mining subsidence in urban areas of the upper Silesian coal basin of Poland. The complexity of open-pit iron mining in Carajás Mineral Province, Brazil, makes DInSAR a challenging application. However, Paradella *et al.*[66] have demonstrated SqueeSAR as an effective tool for deformation monitoring which showed good agreement with geodetic survey measurements. The validation of PSI results has given valuable inputs for research on PSI and for its development, and has proved to be key for the acceptability of the technique at scientific, technical and commercial level[52].

Assessment of SAR interferometric measurements

SAR interferomety has been extensively used for detecting surface deformations over the past decade. To cover a wide area (several square kilometres) with levelling measurements is time-consuming and expensive. But DInSAR measurements can be carried out in a large area of interest. Tomás *et al.*[67] have studied the cost-effectiveness of DInSAR techniques over traditional ground-based surveys and reported that they are about 4–10 times more expensive even while using archived ERS/Envisat datasets. In ground-based surveys, the density of monitoring points is generally less to understand the mechanisms involved in ground subsidence and they can only be carried out in a small area of interest. In addition, one cannot prevent a natural loss of benchmarks over time, which poses a major limitation in ground surveys. Advanced DInSAR techniques like PSInSAR have greatly increased the density of sampling points, which otherwise is difficult in ground-based surveys. PSInSAR technique unlike conventional interferometric processing is based not on a pair of images but on a stack of images (at least 15 images are needed to perform a C-band PSI analysis).

Many authors have reported that the DInSAR results have shown good agreement when compared with ground-based measurements[4,13,14,16,34,35,37,42,45,58,59,61,66,67] and provide reliable estimates of subsidence, particularly in an urban environment. A comparison of precise levelling and persistent scatterer SAR interferometry has been done[58,59] and PSI results show good agreement with the levelling data. PSInSAR analyses detect ground deformation and help in focusing the attention of geologists[56] and geo-scientists to analyse the results in identifying risk zones.

The maximum subsidence of 11.2 cm over 6 years was measured by Jung *et al.*[14] using JERS-1 and PSI technique while monitoring coal mining area of Gaeun in Korea. More than 50 cm subsidence over 46 days in Westcliff coal mining region of Australia was reported by Ng *et al.*[33], showing the potential of L-band ALOS PALSAR data; the results were also validated with ground survey. Herrera *et al.*[44] using CPT and TerraSAR-X data while monitoring an urban subsidence in Murcia, Spain, have reported an average rate of subsidence from –5 mm/yr to –35 mm/yr. In another study using CPT, Herrera *et al.*[37] while monitoring metal mining area in Murcia, have demonstrated that deformation values with DInSAR (using ERS 1/2 and Envisat images) on comparison with the topographical levelling network measurements of the same period gave an absolute average difference of 0.7 cm with a standard deviation of 0.5 cm. A wide-area study over Tianjin suburbs of China using PSI with TerraSAR-X data by Luo *et al.*[59] has shown a rate of subsidence of –60 mm/yr and a linear deformation trend with a decline in velocity of 36.1 mm/yr. Using PSI technique with 13 ALOS PALSAR, Xing *et al.*[34] have determined subsidence rate of 4 cm/yr in some big collieries in Xixia town of China and also showed that the difference between the mean values of PS targets with the results of levelling was less than 3 mm. Tomás *et al.*[67] have reported that DInSAR measurements of some subsidence areas in Spain on comparison with geodetic or topographical measurements showed about ±2 mm error in levelling and about ≤12 mm in GPS measurements. The PSI techniques offer a high precision in deformation measurements, even down to the sub-millimetre level[62]. Perissin and Rocca[64] have demonstrated the positioning accuracy of a PS within 1 m in all three directions using a large number of SAR scenes. Ground collapse has some special deformation characteristics, which cause SAR images to lose coherence and special measures have to be taken to monitor the subsidence[17].

The enhanced observation capability of the second generation of SAR sensors has reduced revisit time and improved spatial resolution, providing scientists with unprecedented data for mapping and monitoring of natural and human-induced hazards[68–70]. With the constellation of two C-band satellites, Sentinel-1 A (2014) and Sentinel-1 B (2016), each with 12-day repeat orbit cycle, would enable the formation of interferometric pairs with time interval of six-days. The current missions of the SAR satellites like TerraSAR-X (X-band) and TanDEM-X (X-band), COSMO-SkyMed constellation (X-band), Radarsat-2 (C-band), RISAT-1 (C-band), Sentinel-1A/1B (C-band) and ALOS-2 (L-band), spaceborne SAR interferomerty have become more and more significant. Future expected SAR missions like Tandem-L[70] by 2021 and many more, would lead to rapid advancements in research and development of new SAR technologies enhancing applications in geo-science and related fields.

Conclusion

Here we have provided a detailed review on surface subsidence mapping in mining areas using SAR interferometry. SAR interferometric techniques have become an indispensable tool and are widely used for the study of surface subsidence phenomena. Ground deformation data obtained using these techniques help in identifying hazard zones that could potentially threaten lives and damage infrastructure. New algorithms have appreciably improved the density of measurement points, leading to more comprehensive mapping of surface deformation. However, one cannot ignore the importance of conventional DInSAR techniques. PSInSAR, an advanced DInSAR technique, has capability to generate dense PS sampling using high-resolution X-band data. Advanced PSInSAR, the SqueeSAR algorithm has also remarkably increased measurement point densities in non-urban areas. Further, satellites with shorter revisit time and high ground resolution have improved both temporal and spatial resolution of the results. The L-band is capable for measuring rapid subsidence due to its longer wavelength when compared with the C- or X-bands. Time-series analysis of surface subsidence using DInSAR techniques provides reliable estimates and indicates collapse precursor signs. DInSAR techniques can detect any slow or rapid surface deformation to millimetre accuracy, which is otherwise challenging to detect using traditional ground-based techniques. It is quite evident that sufficient number of good quality interferometric pairs are required for land subsidence modelling study to obtain good results. Over the years, DInSAR techniques have been widely used to study surface subsidence due to underground coal mining, but application towards underground hard-rock mining cannot be undermined.

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1. Singh, M. M., Mine subsidence. *SME Mining Engineering Handbook*, 1992, pp. 938–971.
2. Blodgett, S. and Kuipers, J. R., Technical report on underground hard-rock mining: Subsidence and hydrologic environmental impacts. Center for Science in Public Participation, Bozeman, MT, 2002, pp. 2–41.
3. Massonnet, D. and Feigl, K. L., Radar interferometry and its application to changes in the earth's surface. *Rev. Geophys*., 1998, **36**(4), 441–500.
4. Carnec, C. and Delacourt, C., Three years of mining subsidence monitored by SAR interferometry, near Gardanne, France. *J. Appl. Geophys*., 2000, **43**, 43–54.
5. Ge, L., Chang, H. C., Qin, L., Chen, M. H. and Rizos, C., Differential radar interferometry for mine subsidence monitoring. In Proceedings 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.
6. Gupta, R. P., SAR interferometry. In *Remote Sensing Geology*, Springer-Verlag, Berlin 2003, 2nd edn, pp. 367–392.
7. Singh, M. M., *Mine Subsidence*, Society of Mining Engineers, Littleton, Co, AIME, 1986, pp. 73–143.
8. Prokopovich, N. P., Land subsidence and population growth. In *Environmental Geology* (ed. Betz Jr, F.), Reprint from 24th International Geology Congress Proceedings, 1972, vol. 13, pp. 44–54.
9. Marcus, J. J., *Mining Environmental Handbook*, Imperial College Press, London, 1997, p. 184.
10. Soliman, M. M. *et al*., *Environmental Hydrogeology*, CRC Press, LLC, 1998, pp. 81–101.
11. Kratzsch, H., *Mining Subsidence Engineering*, Trans. Springer-Verlag, Fleming RFS, New York, 1983.
12. Whittaker, B. N. and Reddish, D. J., *Subsidence–Occurrence, Prediction and Control*, Elsevier, 1989, p. 528.
13. Ge, L., Chang, H. C. and Chris, R., Mine subsidence monitoring using multi-source satellite SAR images. *Photogramm. Eng. Remote Sensing*, 2007, **73**(3), 259–266.
14. Jung, C., Hahn, Kim, S. W., Jung, H. S., Min, K. D. and Won, J. S., Satellite observation of coal mining subsidence by persistent scatterer analysis. *Eng. Geol.*, 2007, **92**, 1–13.
15. Raucoules, D., Colesanti, C. and Carnec, C., Use of SAR interferometry for detecting and assessing ground subsidence. *C. R. Geoscience*, 2007, **339**, 289–302.
16. Guang, L., Huadong, G., Jinghui, F., Xiaofang, G., Perski, Z. and Huanyin, Y., Mining area subsidence monitoring using multi-band SAR data. In IEEE Urban Remote Sensing Joint Event, Shanghai, China, 2009,
17. Chengsheng, Y., Qin, Z., Chaoying, Z., Lingyun, J. and Wu, Z., Monitoring mine collapse by D-InSAR. *Min. Sci. Technol.*, 2010, **20**, 696–700.
18. Borik, M., 2-Pass differential interferometry in the area of the Slatinice above-level dump, GIS, Ostrava, Czech Republic, 2011.
19. Srivastava, V. K., Sreejith, K. M. and Majumdar, T. J., Utilization of ERS SAR data over the Jharia coalfield (Dhanbad), India for subsidence monitoring. *Space Res. Today*, 2012, **185**, 98–104.
20. Gupta, N. and Syed, T. H., Mapping of potential coal-mine fire zones in Jharia coalfield using differential InSAR (DInSAR). In 9th Biennial International Conference and Exposition Petroleum Geophysics, Hyderabad, 2012, pp. 1–6.
21. Gupta, N., Syed, T. H. and Athiphro, A., Monitoring subsurface coal fires in Jharia coalfield using observations of land subsidence from differential interferomteric synthetic aperture radar (DInSAR). *J. Earth Syst. Sci*., 2013, **122**(5), 1249–1258.
22. Bhaumick, S., Land subsidence modeling by advanced D-InSAR techniques. Thesis submitted to the Andhra University, Visakhapatnam, in partial fulfillment of the requirement for the award of Master of Technology in Remote Sensing and GIS, 2013, pp. 1–35.
23. Kamarajugedda, S. A., Atmospheric correction of DInSAR phase for land subsidence measurements using an integrated approach. Thesis submitted to the faculty of Geo-information science and earth observation of the University of Twente in partial fulfillment of the requirements for the degree of Master of Science in Geo-information and Earth observation, Enschede, The Netherlands, 2013, pp. 1–68.
24. Lazecky, M. and Jirankova, E., Optimization of satellite InSAR techniques for monitoring of subsidence in the surroundings of Karvina Mine: Lazy plant. Geomater. *Acta Geodyn. Geomater.*, 2013, **10**(1), 61–65.
25. Dong, S., Yin, H., Huang, L., Xu, C. and Chen, Y., PS techniques and surface deformation monitoring application. In International Conference on RSETE, Nanjing, China, 2013, pp. 839–842.
26. Engelbrecht, J. and Inggs, M., Differential interferometry techniques on L-Band data employed for monitoring of surface subsidence due to mining. *S. Afr. J. Geomatics*, 2013, **2**(2), 82–93.
27. Zhenguo, L., Zhengfu, B., Fuxiang, L. and Baoquan, D., Monitoring on subsidence due to repeated excavation with DInSAR technology. *Int. J. Min. Sci. Technol.*, 2013, **23**, 173–178.
28. Liu, D., Shao, Y., Liu, Z., Riedel, B., Sowter, A., Niemeier, W. and Bian, Z., Evaluation of InSAR and TomoSAR for monitoring deformations caused by mining in mountainous area with high resolution satellite based SAR. *Remote Sensing*, 2014, **6**, 1476–1495.
29. Gupta, M., Mohanty, K. K., Kumar, D. and Banerjee, R., Monitoring surface elevation changes in Jharia coalfield, India using synthetic aperture radar interferometry. *Environ. Earth Sci*., 2014, **71**, 2875–2883.
30. Qin, Y. and Perissin, D., Monitoring underground mining subsidence in south Indiana with C- and L-band InSAR technique. In Proceedings of IGARSS, Milan, Italy, 2015.
31. Majumdar, R., Environmental monitoring of Jharia coalfield, Jharkhand, India, using multi-polarization SAR and interferometric SAR data. Thesis submitted to Andhra University in partial fulfillment of the requirements for the award of Master of Technology in Remote Sensing and Geographic Information System, 2013, pp. 1–100.

32. Fang, M., Mingxing, Y., Xiaoying, Q., Chengming, Y., Baocun, W., Rui, L. and Jianhua, C., Application of DInSAR and GIS for underground mine subsidence monitoring. *Int. Arch. Photogramm., Remote Sensing Spatial Inf. Sci. Part B1*, 2008, **37**, 251–255.
33. Ng, A. H., Chang, H., Ge, L., Rizos, C. and Omura, M., Radar interferometry for ground subsidence monitoring using ALOS PALSAR data. *Int. Arch. Photogramm., Remote Sensing Spatial Inf. Sci. Part B7*, 2008, **37**, 67–73.
34. Xing, X., Gong, Y. and Zhu, J., Subsidence monitoring in mining area based on PSInSAR. *J. Comput. Inf. Syst.*, 2010, **9**, 2909–2916.
35. Przylucka, M., Herrera, G., Graniczny, M., Colombo, D. and Pizarro, M. B., Combination of conventional and advanced DInSAR to monitor very fast mining subsidence with TerraSAR-X data: Bytom city (Poland). *Remote Sensing*, 2015, **7**, 5300–5328.
36. Wickramanayake, A., Hobbs, S., Henschel, M., Sjoberg, J., Lindgren, T. and Fernando, P., SAR interferometry with seasonally changing snow cover. In Proceedings of Fringe Workshop, Frascati, Italy, 2011.
37. Herrera, G., Thomas, R., Lopez-Sanchez, J. M., Delgado, J., Mallorqui, J. J., Duque, S. and Mulas, J., Advanced DInSAR analysis on mining areas: La Union case study, Murcia, SE Spain. *Eng. Geol.*, 2007, **90**, 148–159.
38. Colesanti, C., Mouelic, S. L., S., Bennani, M., Raucoules, D., Carnec, C. and Ferretti, A., Detection of mining related ground instabilities using the permanent scatterers technique – a case study in the east of France. *Int. J. Remote Sensing*, 2005, **26**(1), 201–207.
39. Crosetto, M., Crippa, B., Biescas, E., Monserrat, O., Agudo, M. and Fernandez, P., State-of-the-art of land deformation monitoring using SAR interferometry. *Photogram. Ferrnerkundung Geoinform.*, 2005, **6**, 497–510.
40. Refice, A., Bovenga, F. and Nutricato, R., Stepwise approach to InSAR processing of multi-temporal datasets. In Proceedings of the Fringe Workshop, Frascati, Italy, 2003.
41. Baran, I., and Stewart, M. P., Small scale surface deformation monitoring in mining regions using differential radar interferometry. In Proceedings of the 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.
42. Hongdong, F., Kazhong, D., Chengyu, J., Chuanguang, Z. and Jiqun, X., Land subsidence monitoring by D-InSAR technique. *Min. Sci. Technol*, 2011, **21**, 869–872.
43. Arjona, A., Monells, D., Fernandez, J., Duque, S. and Mallorqui, J., Deformation analysis employing the coherent pixel technique and ENVISAT and ERS images in Canary Islands. In Proceedings of Fringe Workshop, Frascati, Italy, 2009.
44. Herrera, G. *et al.*, Analysis of subsidence using TerraSAR-X data: Murcia case study. *Eng. Geol.*, 2010, **116**, 284–295.
45. Bayuaji, L., Sumantyo, J. T. S. and Kuze, H., ALOS PALSAR D-InSAR for land subsidence mapping in Jakarta, Indonesia. *Can. J. Remote Sensing*, 2010, **36**(1), 1–8.
46. Hanssen, R. F., Satellite radar interferometry for deformation monitoring: a priori assessment of feasibility and accuracy. *Int. J. Appl. Earth Obs. Geoinf.*, 2005, **6**, 253–260.
47. Crosetto, M., Monserrat, O., Iglesias, R. and Crippa, B., Persistent scatterer inteferometry: potential, limits and initial C- and X-band comparison. *Photogramm. Eng. Remote Sensing*, 2010, **76**(9), 1061–1069.
48. van Leijen, F., Persistent scatterer interferometry based on geodetic estimation theory. Doctoral dissertation, TU Delft, Delft University of Technology, The Netherlands, 2014, pp. 1–220.
49. Ferretti, A., Prati, C. and Rocca, F., Permanent scatterers in SAR interferometry. *IEEE Trans. Geosci. Remote Sensing*, 2001, **39**(1), 8–20.
50. Warren, M., Sowter, A. and Bingley, R., PSInSAR without a DEM: a 3-pass approach. Proceedings of the Envisat Symposium, Montreux, Switzerland, April 2007.
51. Devanthery, N., Crosetto, M., Monserrat, O., Cuevas-Gonzalez, M. C. and Crippa, B., An approach to persistent scatterer interferometry. *Remote Sensing*, 2014, **6**, 6662–6679.
52. Crosetto, M., Monserrat, O., Gonzalez, M. C., Devanthéry, N. and Crippa, B., Persistent scatterer interferometry: a review. *ISPRS J. Photogramm. Remote Sensing*, 2016, **115**, 78–79.
53. Kampes, B. M., Radar interferometry, persistent scatterer technique. In *Remote Sensing and Digital Image Processing*, Springer, 2006, vol. 12, pp. 1–211.
54. Guoqing, Y. and Jingqin, M., D-InSAR technique for land subsidence monitoring. *Earth Sci. Front.*, 2008, **15**(4), 239–243.
55. Ostir, K. and Komac, M., PSInSAR and DInSAR methodology comparison and their applicability in the field of surface deformations – a case of NW Slovenia. *Geologija*, *Ljubljana*, 2007, **50**/1, 77–96.
56. Meisina, C. *et al.*, Geological interpretation of PSInSAR data at regional scale. *Sensors*, 2008, **8**, 7469–7492.
57. Solari, L., Ciampalini, A., Raspini, F., Bianchini, S. and Moretti, S., PSInSAR analysis in the Pisa urban area (Italy): a case study of subsidence related to stratigraphical factors and urbanization. *Remote Sensing*, 2016, **8**, 120.
58. Karila, K., Karjalainen, M., Hyyppa, J., Koskinen, J., Veikko, S. and Rouhiainen, P., A comparison of precise leveling and persistent scatterer SAR interferometry for building subsidence rate measurement. ISPRS. *Int. J. Geoinf.*, 2013, **2**, 797–816.
59. Luo, Q., Perissin, D., Lin, H., Zhang, Y. and Wang, W., Subsidence monitoring of Tianjin suburbs by TerraSAR-X persistent scatterers interferometry. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sensing*, 2014, **7**(5), 1642–1650.
60. Perissin, D. and Ferretti, A., Urban target recognition by means of repeated spaceborne SAR images. *IEEE Trans. Geosci. Remote Sensing*, 2007, **12**(45), 4043–4058.
61. Li, R., Zhao, Z., Duan, M., Wang, Z. and Wang, P., An analysis of surface subsidence in Chiba using PSInSAR technique. *Int. Arch. Photogramm. Remote Sensing Spatial Inf. Sci.*, 2015, **XL-7/W4**, 81–85.
62. Ferretti, A. *et al.*, Submillimeter accuracy of InSAR time series: Experimental validation. *IEEE Trans. Geosci. Remote Sensing*, 2007, **45**, 1142–1153.
63. Bamler, R., Kampes, B., Adam, N. and Suchandt, S., Assessment of slow deformations and rapid motions by radar interferometry. *Photogram. Week*, Wichmann Verlag, Heidelberg, 2005, pp. 111–122.
64. Perissin, D. and Rocca, F., High accuracy urban DEM using permanent scatterers. *IEEE Trans. Geosci. Remote Sensing*, 2006, **44**, 3338–3347.
65. Ferretti, A., Fumagalli, A., Novali, F., Prati, C., Rocca, F. and Rucci, A., A new algorithm for processing interferometric datastacks: SqueeSAR. *IEEE Trans. Geosci. Remote Sensing*, 2011, **44**, 3338–3347.
66. Paradella, W. R. *et al.*, Mapping surface deformation in open pit iron mines of Carajás Province (Amazon Region) using and integrated SAR analysis. *Eng. Geol.*, 2015, **193**, 61–78.
67. Tomás, R. *et al.*, Radar interferometry techniques for the study of ground subsidence phenomena: a review of practical issues through cases in Spain. *Environ. Earth Sci.*, 2014, **71**, 163–181.
68. Herrmann, J. and Bottero, A. G., TerraSAR-X mission: The new generation in high resolution satellites. Anais XIII simposio Brasileiro de sensoriamento remoto, Florianopolis, Brasil, INPE, 2007, pp. 7063–7070.
69. Sansosti, E. *et al.*, How second generation SAR systems are impacting the analysis of ground deformation. *Int. J. Appl. Earth Obs. and Geoinf.*, 2014, **28**, 1–11.
70. Moreira, A., A golden age for spaceborne SAR systems. In IEEE, 20th International Conference on Microwaves, Radar and Wireless Communication (MIKON), 2014, pp. 1–4.

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