GEOSTATISTICAL AND SPACE GEODETIC
METHODS APPLIED TO A 3D COSEISMIC
DISPLACEMENT FIELD: MAPPING
EARTHQUAKES FROM SPACE

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Summary

Coseismic displacements at the Earth's surface arise due to the release of energy by earthquakes. The energy, and hence the amount of displacement, depends mainly on the magnitude, depth and the movement mechanism of an earthquake. Coseismic displacements play a vital role in the characterization of geological faults and understanding of earthquake dynamics. This understanding is based in turn on the accurate measurement of coseismic displacements and creation of a continuous-field displacement map. The main objective of this research was to measure the coseismic displacements and to construct a 3D coseismic displacement field for an earthquake.

Displacements are typically measured by comparing pre- and post-earthquake radar images. In this study InSAR is used that measures phase (time) differences between pre- and post-earthquake SAR images resulting in displacements into line-of-sight (LOS) direction. The LOS is mainly sensitive in the vertical direction, moderately in the across flight direction and insensitive in the along flight direction. To measure the along-flight displacement component pixel tracking was used, providing azimuth offsets (AZO). Pixel tracking correlates the coregistered pre- and post-earthquake optical or SAR images. In this study pixel tracking was used for both SAR and optical data, whereas InSAR is used for SAR data only. Using the obtained displacement results, a 3D displacement field was generated from both descending and ascending image pairs bracketing the earthquake event.

The study considered the 2003 Bam earthquake. The city is located on a geological fault that caused occurrence of the earthquake. From the measured displacements it appeared that the major part of the fault is located south of the city. It has a length of 13 km and the fault strike equals 170° , close to the along flight direction. The major vertical displacement occurred on east of the fault, showing a uplift in the south-eastern part of displacement map and subsidence in its north-eastern part. Horizontal displacements showed a relative movement along the fault in the along flight direction. The displacement was greater in horizontal direction than the LOS, revealing that the earthquake causative fault is a strike-slip fault.

A displacement map commonly contains missing coseismic values due to lack of coherence between SAR images. In this study, missing displacement values were caused by non-coherence of pre- and post-earthquake SAR images for the area affected by the earthquake. These missing displacement values may be important for fault characterization, in particular if they occur along the earthquake-causative geological fault. Missing values were interpolated to evaluate the continuity of the earthquake causative fault underneath the city of Bam.

To assess the accuracy of the interpolated coseismic values, subsets of missing co-seismic values were selected and translated towards locations where displacement values exist. Here, missing values were generated artificially. These values were interpolated and the accuracy was quantified by comparing the interpolated values with the actual values. The accuracy was found to be satisfactory with a low mean error and low RMSE values. This procedure was applied to each LOS and AZO displacement map, for both descending and ascending orbits.

For interpolation kriging was used taking into account the spatial dependence of the measurements by means of the variogram and ensuring preservation of local characteristics of the coseismic displacements. It also tackled potential anisotropic behaviour of coseismic values along the geological fault. The thesis demonstrates that kriging served as a powerful tool for interpolating missing values for displacement maps derived from InSAR and pixel tracking. The use of kriging for interpolation of missing coseismic values is a novel component of this research.

The displacement map using an anisotropic variogram showed a clear indication for the continuity of the geological fault below the city of Bam. Therefore, coseismic displacements may be used to calculate the fault parameters at the subsurface. This, in turn, may help to understand the fault behaviour during the earthquake. Additional geologic observations, however, are needed to determine up to which distance beyond the city the fault extends.

Finally, the four input displacement results obtained with LOS and AZO from descending and ascending orbit image pairs were combined to construct the 3D displacement field. A computationally efficient Markov Random Field (MRF)-based discontinuity adaptive method was developed that could construct the 3D displacement field. The ability of MRFs to exploit the spatial dependence of the measurements and constructing the 3D displacement field is another novelty of this research. The MRF solution provided a smoothly varying displacement field. Smoothness, however, is undesirable along the geological fault. Therefore a discontinuity-adaptive MRF (DA-MRF) procedure was adopted to preserve the discontinuity along the fault. Its application showed a well preserved geological fault and smooth displacement variation on either side of the fault. The displacements have a natural pattern as produced by an earthquake mechanism of the strike-slip movement.

Samenvatting

Coseismische verplaatsingen op het aardoppervlak ontstaan als gevolg van het vrijkomen van energie door aardbevingen. De hoeveelheid energie die vrijkomt en de mate van verschuiving als gevolg daarvan hangen voornamelijk af van de omvang, diepte en het mechanisme van de beweging van een individuele aardbeving. Coseismische verplaatsingen spelen een centrale rol in de karakterisatie van geologische plooien en het begrip van de dynamiek van aardbevingen. Dit begrip is op zijn beurt gebaseerd op de nauwkeurige meting van de coseismische verplaatsingen en het maken van een afbeelding van een continue veld verplaatsing. De belangrijkste doelstelling van dit onderzoek was om de coseismische verplaatsingen nauwkeurig te meten om een 3D veld van een coseismische verplaatsing als gevolg van een aardbeving te construeren.

Verplaatsingen worden meestal gemeten door het vergelijken van radarbeelden voor en na een aardbeving. In deze studie worden InSAR beelden gebruikt. Deze meten de fase (tijd) verschillen tussen pre- en postaardbeving SAR-beelden die verplaatsingen laten zien in de line-of-sight (LOS) richting. De LOS is vooral gevoelig in de verticale richting, matig in de richting loodrecht op de vlucht en ongevoelig in de vluchtrichting zelf. Voor het meten van de verplaatsing in de vluchtrichting is pixelvolgen gebruikt, dat Azimut offsets (AZO) registreert. Pixelvolgen correleert de geregistreerde pre en post aardbeving beelden met optische of SAR-beelden. In deze studie werd pixelvolgen gebruikt voor zowel SAR als optische gegevens, terwijl InSAR alleen is gebruikt voor SAR gegevens. Met behulp van de resultaten die voor de verplaatsing verkregen zijn is een 3D verplaatsing veld gegenereerd op basis van zowel dalende als stijgende afbeeldingsparen rond de aardbeving.

De studie richt zich op de 2003 Bam aardbeving. De stad Bam is gelegen op een geologische plooi die het ontstaan van de aardbeving heeft veroorzaakt. Uit de gemeten verplaatsingen bleek dat het grootste deel van de plooi ten zuiden van de stad ligt. Het heeft een lengte van 13 km en de ploorichting is gelijk aan 170°, dus vrijwel in de richting van de vlucht. De grote verticale verplaatsing vond plaats ten oosten van de plooi, die een verhoging in de Zuidoostelijke deel van verplaatsingsafbeelding en een verzakking in het Noordoostelijke deel tonen. Horizontale verschuivingen laten een relatieve beweging zien langs de breuk in de vluchtrichting. De verplaatsing was groter in de horizontale richting dan in de LOS richting; dit toont aan dat de plooi die de aardbeving veroorzaakte een horizontale beweging is strike-slip

Een afbeelding van de verplaatsing bevat vaak ontbrekende coseismische waarden vanwege gebrek aan samenhang tussen de SAR-beelden. In deze studie werden deze ontbrekende waarnemingen veroorzaakt door gebrek aan

coherentie tussen pre- en post aardbeving SAR-beelden voor het gebied dat door de aardbeving werd getroffen. Deze ontbrekende waarden kunnen van belang zijn voor de karakterisering van de plooï, in het bijzonder wanneer zij zich langs de geologische breuk bevinden die de aardbeving heeft veroorzaakt. Om de continuïteit van de aardbeving te evalueren zijn de ontbrekende waarden voor de plooï die de oorzaak is van de aardbeving geïnterpoleerd onder de stad Bam.

Om de juistheid te beoordelen van de geïnterpoleerde coseismische waarden, zijn deelgebieden geselecteerd waar co-seismische waarden ontbreken en verplaatst naar locaties waar wel verplaatsingswaarden zijn. Hier zijn de ontbrekende waarden kunstmatig gegenereerd. Deze waarden zijn geïnterpoleerd en de nauwkeurigheid is gekwantificeerd door de geïnterpoleerde waarden met de werkelijke waarden te vergelijken. De nauwkeurigheid bleek bevredigend te zijn met een lage gemiddelde fout en lage RMSE waarden. Deze procedure werd toegepast op iedere LOS en AZO verplaatsingsafbeelding, voor zowel dalende als stijgende afbeeldingsparen.

Voor interpolatie is kriging gebruikt. Door middel van het variogram houdt deze methode rekening met de ruimtelijke afhankelijkheid van de metingen, en zorgt het voor behoud van de lokale kenmerken van de coseismische verplaatsingen. Potentiëel anisotroop gedrag van coseismische waarden langs de geologische breuk is hiermee geanalyseerd. Het proefschrift laat zien dat kriging een krachtig hulpmiddel is voor het interpoleren van ontbrekende waarden voor verplaatsingsafbeeldingen die zijn verkregen via InSAR en pixelvolgen. Het gebruik van kriging voor interpolatie van ontbrekende coseismische waarden is een nieuw onderdeel van dit onderzoek.

De verplaatsingsafbeelding die verkregen is met behulp van een anisotroop variogram toont een duidelijke aanwijzing voor de continuïteit van de geologische fout onder de stad Bam. Coseismische verplaatsingen mogen daarom worden gebruikt voor het berekenen van de parameters voor een plooï op de ondergrond. Dit, op zijn beurt, kan helpen om het gedrag van de plooï tijdens de aardbeving te begrijpen. Aanvullende geologische waarnemingen, zijn echter nodig om te bepalen tot welke afstand buiten de stad de plooï zich uitstrekt.

Ten slotte zijn de vier verplaatsings resultaten die verkregen zijn met LOS en AZO voor de stijgende en dalende baan gecombineerd om een 3D verplaatsingsveld te vrijen. Een efficiënte, discontinuïteit adaptieve methode is ontwikkeld gebaseerd op een Markov toevalsveld (MRF), die dit 3D verplaatsing veld kon construeren. Het vermogen van MRFs om de ruimtelijke afhankelijkheid van de metingen te exploiteren en het construeren van het veld 3D verplaatsing mogelijk te maken is een ander nieuw onderdeel van dit onderzoek. Deze MRF oplossing biedt een licht variërend verplaatsing veld. Lichte variatie is echter ongewenst langs de geologische breuk. Daarom is

een discontinuïteit-adaptieve MRF (DA-MRF) procedure toegepast dat de discontinuïteit langs de breuk in stand houdt. De toepassing ervan bleek een goed bewaard gebleven geologische plooï en variatie over een korte afstand aan weerszijden van de plooï. De verplaatsingen hebben een natuurlijk patroon als geproduceerd door een aardbeving mechanisme van de strike-slip-beweging.

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. . . the loving memory of my father

. . . my lovely mother

. . . wife and children

. . . brothers and sisters

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Chapter 1: Introduction

1.1 Earthquake monitoring

Earthquakes and their effects have a large impact on buildings and roads, the infrastructure and hence on the lives and well-beings of people around the globe. Due to these effects, causes of earthquakes and predictions of the effects have been studied extensively in the past. Understanding the physical processes that generate earthquakes is a prerequisite to better understand the causes. This, however, is not a simple task due to physical limitations, including the complexity of transmission of waves through the earth crust that result in earthquake occurrences. Moreover, tectonic processes that generate earthquakes have their origin deep below the earth's surface and hence do not allow direct observation. These limitations prohibit a proper understanding of earthquakes and their consequences at the earth surface.

Therefore, locating and observing the effects of individual earthquake events on the earth surface is important. Earthquakes manifest themselves by shaking ground and by ground displacements. This study considers displacements. By definition, a co-seismic displacement or deformation i.e. the permanent deformation of the Earth's surface associated with the earthquake, is the difference between the initial position of a reference point and any position taken in later on the earth surface. It is thus the distance that any point that was affected by an earthquake has moved from where it was before the earthquake. It represents an active deformation of the earth crust as a result of an earthquake. Coseismic displacements constitute an important fraction of all the deformations; they take place by frictional sliding on faults, giving rise to earthquakes as a release of built-up interseismic strain.

Measurements of ground displacements are widely used to obtain insight into the deformation of the earth and to increase the understanding of tectonic processes deep inside the earth's crust that result in earthquakes. Obtaining this knowledge is crucial to assess the tectonic processes and their potential effects. Ultimately earthquake hazard maps can be made to define precautionary measures to mitigate the destructiveness of future earthquakes. Such information is of great economic importance as well, on regional as well as on global scales, since recommendations for infrastructure construction are based on those studies. In fact, they place our understanding of earthquake rupture mechanics at the center of seismic hazard assessment. The settlement of major cities and construction of critical facilities such as nuclear reactors in earthquake prone areas highlight the importance of securing the human populations against the earthquake hazards, disaster mitigation and prevention. Surface deformation measurements are therefore critical for the study and detailed understanding of tectonics.

Several methods are currently used for monitoring the geometry of the earth surface, including levelling, total station surveys, and GPS measurements. Field surveys are of particular importance because until recently they have provided the only data to reliably constrain the geometry and the slip distribution of fault ruptures. Field survey methods, however, require a considerable time and effort to acquire enough information to make an earthquake hazards map of a sufficient quality. As an alternative, urban authorities and foresters have considered remote sensing solutions to provide timely, cost effective and periodic information on the urban state. The main advantage of remotely sensed images is their synoptic view to provide information over large areas. Finally, global positioning systems (GPS) as a satellite radio positioning system designed to provide global all-weather, 24-hour instantaneous position, velocity, and time information, generally cover in a sparse way, if at all, the near fault zone of seismic ruptures. These technologies can measure height information at the mm to cm level of accuracy. They also have their limitations, however, primarily because they measure subsidence on a point-by-point basis and hence are too costly if a very large area needs to be monitored.

Recently, a promising alternative area-based technique interferometric synthetic aperture radar (InSAR) has been explored (Massonnet and Feigl, 1998; Burgmann et al., 2000; Hanssen, 2001). InSAR makes it possible to measure dense points in a study area accurately, economically, conveniently and efficiently, hence demonstrating its effectiveness for detecting ground deformation. It can measure the ground movement (or deformation) over a large spatial extent of up to hundreds of square kilometers as compared to the conventional ground-based survey methods. InSAR has a unique ability to measure deformation of cm accuracy over large contiguous areas (typically a few hundred kilometers). InSAR provides rich details on ground displacements induced by earthquakes and is not limited by issues such as site accessibility. This is particularly important because earthquakes regularly occur in areas where no conventional geodetic measurement networks exist. Therefore, InSAR observations are often the only measurements available of the coseismic deformation field.

Every technique has its limitations, and for SAR Interferometry the major limitations include: it measures displacements only in line-of-sight (LOS) and it is affected by decorrelation (Zebker and Villasenor, 1992; Pritchard and Simons, 2002; Ryder and Burgmann, 2008). LOS mainly provides the vertical component of a displacement. For horizontal displacements, pixel tracking can be used as another remote sensing technique. Pixel tracking measures displacements by cross-correlating the pre- and post-earthquake images at the sub-pixel scale (Michel et al., 1999; Bechor and Zebker, 2006; Hyung et al., 2009). Both InSAR and pixel tracking are affected by decorrelation. Pixel tracking, however, suffers smaller decorrelation effects than InSAR.

Decorrelation can be defined as the loss of information due to differences in the backscattered signal between the two considered SAR images. Major causes of decorrelation may be changes in imaging geometry, vegetation, or surface scattering properties. Measuring reliable displacements is not possible at decorrelation places and hence displacement maps have missing coseismic displacement values at such places. These missing coseismic displacements, particularly along the earthquake causative geological fault, may be of crucial importance for characterization of the fault. Different geostatistical methods such as kriging may help us to interpolate the missing displacement values (Addink and Stein, 1999; Stein et al., 1999).

Kriging is a geostatistical technique which interpolate at unsampled locations using a linear combination of the values at sampled locations (Curran and Atkinson, 1998; Webster and Oliver, 2008). Kriging assigns weights to the sample values and interpolates in such a way that the variance of the interpolation errors is minimized. The variance of interpolation errors depends upon the configuration of the sample points and the degree of spatial variation. The weights sum to unity, and are calculated based on a variogram model. A variogram provides the spatial structure of variability of the observations by relating their squared dissimilarity to the distance between their locations (Curran, 1988). Kriging is considered superior to other interpolation methods e.g. Inverse Distance Weighting (IDW) because it gives least prediction error variance among all linear unbiased predictor.

After getting the missing coseismic values, complete displacement results are available in LOS and horizontal displacement maps for both ascending and descending orbit data. These four maps can be combined to retrieve the three orthogonal displacement components of a 3D displacement field. In the past they were combined using weighted least squares (Funning et al., 2005; Pathier et al., 2006; Erten et al., 2010; Hu et al., 2010). The weights were selected by taking the inverse of variance for each displacement map and considering the spatial independence among measurements. For earthquakes, however, displacements are spatially dependent. Markov random fields can be used to exploit the contextual and spatial dependence information of the displacements for constructing the 3D coseismic displacement field (Gudmundsson et al., 2002; Samsonov et al., 2008).

In most natural spatial phenomena, physical properties show homogeneity over space and do not usually establish abrupt changes. Thus the observations may depend upon their neighbours and should not be treated in isolation. The MRF model exploits the spatial dependence of observations through the contextual information (Geman and Geman, 1984; Li, 2009). The contextual information is used to build prior probabilities. MRFs based on spatial dependence of observations provide spatially smooth results which may be widely required. In earthquake studies, however, an earthquake

causative fault relates to a relative ground movement and shows a discontinuity, therefore such smoothness is not desirable along the fault. In order to preserve the discontinuity, the MRF should be expanded to discontinuity adaptive models (Li, 1995).

1.2 Study area

Bam is an ancient city that lies in Kerman province, south-east Iran. Large parts of Iran are located in a tectonically active area. Central Iran accommodates approximately 14 mm yr^{-1} motion due to the northward convergence of Arabian plate into relatively stable Eurasia plate (Peyret et al., 2007; Gonzalez et al., 2009). Tectonically the study area (Figure 1.1) is a part of a rigid Lut block bounded by two fault systems (Funning et al., 2005).

The study area is flat with a partially cemented alluvial fan system from the southern Jebel Barez Mountains. The cities of Bam and Baravat are separated by a ridge, 1520 m above mean sea level, which is actually a scarp of the Bam fault. It starts 9 km southeast of the Bam city and is oriented into the north-south direction.

On 26 December 2003, a devastating earthquake of magnitude 6.5 at the Richter scale struck the area, killing more than 30,000 people and causing severe damage to the city of Bam infrastructure. A preliminary study suggested that this earthquake was along the Bam fault (Fu et al., 2004). Subsequent field investigations and preliminary interferometric studies (Talebian et al., 2004), however, showed that the earthquake occurred along a previously unknown fault (Jonsson et al., 2004; Perski and Hanssen, 2006). The InSAR studies revealed that the major part of this fault is south of the city and that it may have extended towards the north, passing under the city (Stramondo et al., 2005; Peyret et al., 2006).

Figure 1.1: The study area, Bam, is located in south eastern Iran. Regional tectonic settings are shown with respect to the 2003 Bam earthquake area (Peyret et al., 2007). The blue box is the footprint of the ENVISAT ASAR images from the descending orbit. The lower left inset shows the existing Bam fault (red) and earthquake causative fault (yellow) derived from InSAR results.

The study area is an important and well suited area for the study: it is dry, sparsely vegetated and flat having very stable meteorological conditions (Fielding et al., 2005; Funning et al., 2005). All these conditions provide excellent environment for the application of InSAR technique and hence it could produce a very good quality interferogram. Moreover, the study involved interpolation of the missing coseismic values which are produced due to decorrelation of SAR images. Because of Bam's arid situation, such decorrelation would occur the least and hence fewer missing coseismic values exist. The earthquake causative fault also lies close to Bam city, and according to some researchers (Stramondo et al., 2005; Peyret et al., 2006) it is passing under the Bam city. Location of the study area makes it attractive for research.

1.3 Research Motivation

The sparse and point-based measurements of coseismic displacements from conventional methods motivate the use of InSAR and pixel tracking remote sensing techniques for obtaining dense coseismic displacements. InSAR provides displacement vector in line-of-sight (LOS) direction only. The sub-

pixel correlation (pixel tracking technique) of SAR images was therefore carried out in this study to provide spatially continuous displacement field over wider areas. InSAR and sub-pixel correlation techniques do not require field work and hence are very helpful for remote and inaccessible areas.

In the use of InSAR and pixel tracking techniques, a limitation is given by decorrelation of SAR images due to lack of coherence in pre- and post-earthquake imagery. Major sources of decorrelation include temporal change between the two SAR images, earthquake damages and intensive ground shaking around the fault. Decorrelation hinders the calculation of coseismic values which are of vital importance for earthquake causative fault characterization. The retrieval of missing coseismic displacement values is acutely needed in the case of Bam earthquake because of their important location, as the earthquake causative fault is identified just south of Bam city and, according to researchers (Stramondo et al., 2005; Peyret et al., 2006), it is extending underneath Bam city. Moreover Bam city is a flat area and have arid environment with stable meteorological conditions, hence other types of decorrelation (e.g. due to changes in vegetation cover and water bodies etc. with time) will be limited causing fewer missing values and we can obtain purely the coseismic displacements. This provides an additional motivation for selecting the Bam study area and makes the 2003 Bam earthquake an excellent case for interferometric studies.

The missing coseismic values can be obtained by interpolation. The missing coseismic displacements are calculated in this research with the use of interpolation technique named kriging. The use of kriging for interpolation of missing coseismic values is a novel work in this research. As it interpolates using spatial structure of the measurements through variogram model, it ensured the preservation of local characteristics of the coseismic measurements. It also investigated the anisotropic behaviour of the coseismic values along the geological fault.

Until recently, mostly 2D displacements have been calculated by researchers. Only few attempts are made in past to build 3D field using least squares (LSQ) method (Funning et al., 2005; Hu et al., 2010). In this research we used SAR pre- and post-earthquake image pairs from both ascending and descending orbits to construct 3D coseismic displacement field using results from InSAR and pixel tracking techniques. The LSQ method was not utilized in this work because it assumes that measurements are spatially independent and therefore it can magnify inherent errors of displacements from the two techniques. Instead, we applied the Markov random fields (MRF) for exploiting the spatial dependence and configuration of observations, and simulated annealing (SA) as optimizing tool to improve accuracies of 3D displacement field. Another novelty of our research thus is exploiting the

spatial dependence of the measurements through MRF and SA for constructing the 3D displacement field.

The research is motivated by the need to ultimately provide a methodology for constructing the 3D displacement field from SAR images that can be used for characterizing and understanding the earthquake dynamics. The 3D field provides quantitative description for studying the details of fault rupture process. It gives comprehensive understanding of source geometry associated with earthquake and characteristics of the local active fault which will allow us more knowledge about the regional geology of the area.

1.4 Problem statement

The current research aims to construct 3D coseismic displacement field for the 2003 Bam earthquake using SAR data.

Coseismic displacements can be measured with conventional geodetic methods, leveling, total station field surveys or GPS. Although these methods can provide accurate measurements, they are restricted to point-based sparse information. Remotely sensed images, however, are capable of providing accurate information with synoptic coverage of large area. They can allow dense and accurate measurements in a study area accurately, efficiently, conveniently and economically.

InSAR measures surface displacements in line-of-sight (LOS) direction only, and hence reflects mainly the vertical component of the displacement. It has only medium sensitivity for the across track displacement component. LOS sensitivities depend upon the incidence angles of the SAR images, orientation of the earthquake causative fault and the study area location (Funning et al., 2005). InSAR is insensitive in measuring surface displacement in the along-track direction (Michel et al., 1999). Vertical and horizontal components of coseismic displacements can be retrieved using SAR image pairs from ascending and descending orbits.

The 2003 Bam earthquake occurred along a strike-slip geological fault whose existence was not known before the earthquake (Talebian et al., 2004). It produced major displacements along a right-lateral strike-slip geological fault that is oriented in the north-south direction. The vertical and east-west components of the coseismic displacement are small as compared to north-south component. Therefore InSAR is not helpful to detect and measure the displacements caused by the Bam earthquake.

For measuring the north-south (along track) component of the coseismic displacements, pixel tracking, can be applied. Pixel tracking produces horizontal displacement components in both the north-south and east-west directions by cross-correlating the pre- and post-earthquake SAR images. Accuracy of the measurements from pixel tracking is less than that of InSAR.

InSAR produces measurements of a cm accuracy whereas pixel tracking gives a $< 1\text{m}$ accuracy. Pixel tracking is, however, less affected by decorrelation than InSAR in quantifying coseismic displacements.

Another issue to consider in coseismic displacements measurement is the decorrelation of SAR pre- and post-earthquake images. Decorrelation hinders coseismic displacements in an earthquake hit area. Decorrelation may occur due to earthquake damages in urban area or intensive ground shaking particularly around earthquake causative fault. As a consequence of decorrelation, the coseismic displacement results by InSAR or pixel tracking will have gaps of missing coseismic values. The gaps of missing coseismic values may be present at places of prime importance, e.g. near the geological fault. In such a case, calculation of missing values can improve characterization of the fault and can help in understanding earthquake dynamics. Pixel tracking is less affected by decorrelation than InSAR.

In measuring coseismic displacements of the Bam earthquake, InSAR and pixel tracking can complement each other. Their results can be combined to construct a 3D displacement field for the earthquake by using data from ascending and descending orbits (Fialko et al., 2001; Wright et al., 2004; Fialko et al., 2005). In the present study four coseismic displacement results were obtained using ASAR-ENVISAT image pairs from ascending and descending orbits by applying InSAR and pixel tracking techniques. Thus we have two LOS and two horizontal (north-south) displacement results. Conventionally, least squares or weighted least squares are used to combine these results. In previous studies (Funning et al., 2005; Hu et al., 2010) weights were calculated by taking inverse of variance of the measurements. There was not any explicit way adopted to account for different accuracies of the measurements. These studies considered the measurements as spatially independent. In reality, however, the coseismic displacements have correlation and dependencies over space. Use of their correlation and spatial dependence information can improve accuracy of three orthogonal components of coseismic displacements (Kasetkasem et al., 2005). This can be achieved by exploiting the contextual information of the measurements. In the present research this is done by applying Markov Random Fields (MRFs). MRFs, however, provide smooth variation of displacements for 3 components, whereas the magnitude of coseismic displacements is greater along the earthquake causative geological fault. The fault represents a discontinuity among the displacement field. In order to preserve the discontinuity an MRF should be constrained. A discontinuity adaptive MRF can then provide a smoothly varying 3D displacement field with a well-preserved geological fault.

1.5 Research objectives

The main objective of the research was to construct a 3D coseismic displacement field by exploiting the geostatistical and space geodetic methods, for 2003 Bam earthquake using ASAR-ENVISAT radar images pairs from ascending and descending orbits. This main objective is divided into sub-objectives as below:

1. To accurately measure LOS (line-of-sight) coseismic displacements through InSAR using ASAR images from ascending and descending orbits
2. To estimate coseismic displacement values, in LOS displacement maps, that were missing due to decorrelation of ASAR images through interpolation by means of kriging
3. To measure horizontal coseismic values through pixel tracking and to interpolate its missing coseismic values after investigating and correcting for the anisotropy in the measurements
4. To develop a discontinuity adaptive MRF-based method for constructing the 3D displacement field by means of combining different sources of coseismic displacement data

This PhD research thus aimed at applying a new method to efficiently generate three orthogonal coseismic displacement components by combining InSAR and pixel tracking techniques' derived LOS and horizontal displacement maps. There are three focuses in this dissertation. First, to measure LOS and horizontal displacement maps accurately. Second, to interpolate the missing coseismic displacement values produced due to decorrelation of SAR images through the use of kriging in order to have complete displacement information. Third, to combine the input displacement maps, after interpolating their missing coseismic values, by applying MRFs.

A few challenges are addressed in this research. First, during interpolation, exploring and investigating the nature of coseismic displacements to understand the physical phenomenon and spatial dependence using variogram analysis. Furthermore while interpolating, to investigate the anisotropy of measurements and preserve their local characteristics. Second, combining the displacements results of different accuracies and uncertainties by exploiting their contextual information based on MRFs. In addition, estimating the optimal MRF parameters and applying simulated annealing for optimization to have three orthogonal displacement components including their accuracy, smooth variation and smaller details. Finally to preserve the earthquake causative geological fault which shows as a discontinuity in a smoothly varying displacement map.

In reaching the above mentioned objectives, our proposed methodology was investigated for its applicability by considering two different earthquakes occurring in regions of widely different topological and metrological characteristics: 2005 Kashmir earthquake in Northern Pakistan and 2003 Bam earthquake in south-east Iran.

Kashmir is a mountainous area with narrow valleys and significant vegetation cover. For measuring horizontal component of displacement, optical remote sensing data was availed and focus was restricted mainly to measuring horizontal displacements using COSI-Corr, a new technique developed for only optical data, and then testing the sensitivity of the technique for its various parameters. For vertical displacement component, interferogram could not be generated for this earthquake due to decorrelation at large scale in the study area. In addition, there were also issues like remote sensing data availability and field verification survey reports. This study highlights the issues restricting the applicability of our methodology.

The 2003 Bam earthquake-hit area was considered next as it provided an ideal environment for a complete application of our proposed methodology. Bam area is dry, sparsely vegetated and flat having very stable metrological conditions (Fielding et al., 2005; Funning et al., 2005) thus it provided an excellent environment for the application of InSAR technique for measuring vertical component of the displacement.

1.6 Thesis roadmap

The dissertation comprises 6 chapters including 4 technical chapters which are published or submitted to peer-review ISI journals. Each of the technical chapters is written as an independent study. Therefore, the reader can read the chapters of interest without looking at other chapters. In general format, each chapter is arranged as abstract, introduction, methodology, results, discussion and conclusion sections.

Chapter 1 gives detailed overview and scope of the dissertation. It includes general introduction, motivation for the research work, problem statement research objectives and thesis roadmap.

Chapter 2 provides horizontal displacement map using optical remote sensing ASTER image pair bracketing the 2005 Kashmir earthquake in Pakistan. It investigates a newly developed technique "COSI-Corr" for measuring horizontal displacements by cross-correlating the optical images at sub-pixel level (Leprince et al., 2007). In this chapter, a sensitivity analysis is performed in order to evaluate the technique for its potential and accuracy in measuring the coseismic displacements.

Chapter 2 is published in the Journal of Asian Earth Sciences:

Yaseen, M., Anwar, S., 2013. "Sensitivity analysis of sub-pixel correlation technique for measuring coseismic displacements using a pair of ASTER images" *Journal of Asian Earth Sciences* 62 (0), 349-362."

Chapter 3 presents LOS (line-of-sight) coseismic displacement results calculated by InSAR technique. This chapter is divided in two parts: part-A provides LOS results for descending orbit ASAR images, whereas part-B is for ascending orbit ASAR image pair. The missing coseismic displacements due to decorrelation in both maps were interpolated using kriging geostatistical technique. The results of part-A are published in the journal:

Yaseen, M., Hamm, N.A.S., Woldai, T., Tolpekin, V.A., Stein, A., 2013. "Local interpolation of coseismic displacements measured by InSAR" *International Journal of Applied Earth Observation and Geoinformation* 23, 1-17."

Chapter 4 is concerned with the application of pixel tracking technique for producing horizontal coseismic displacements for both ascending and descending orbit ASAR images. The missing coseismic values produced due to decorrelation were interpolated using kriging after correcting the anisotropy effect of the measurements. This chapter is also divided in two parts: Part-A gives displacements from descending orbit image pair and its results are published in the journal given below. While part-B produces the displacement results for ascending orbit image pairs following the same methodology adopted for part A.

Yaseen, M., Hamm, N.A.S., Tolpekin, V., Stein, A., 2013. "Anisotropic kriging to derive missing coseismic displacement values obtained from synthetic aperture radar images" *Journal of Applied Remote Sensing* 7".

Chapter 5 presents the three displacement maps describing the orthogonal displacement components of the 3D coseismic field for 2003 Bam earthquake. The three displacement maps were obtained by combining the four displacement results derived from InSAR and pixel tracking techniques through applying the Markov random field (MRF) theory. MRF exploits the contextual information of the measurements for combining displacement maps of different uncertainties. The results of this chapter are under review in *ISPRS journal of remote sensing and photogrammetry*.

Chapter 6 presents a synthesis of the results produced during the research work, and their discussion. It also provides the main conclusion of the research and its significant contribution in scientific knowledge. Finally future research directions and recommendation are provided.

Chapter 2: Measuring horizontal coseismic displacements from optical remotely sensed images

This chapter is based on:

Yaseen, M., Anwar, S., 2013. "Sensitivity analysis of sub-pixel correlation technique for measuring coseismic displacements using a pair of ASTER images" Journal of Asian Earth Sciences 62 (0), 349-362.

Abstract

Coseismic displacements play a key role in understanding earthquake dynamics. To derive displacement fields from optical and microwave remote sensing datasets, various methods are available. This study evaluated in detail the offset tracking technique on optical ASTER data for 2005 Kashmir earthquake. This technique required input parameters like resampling methods, correlator types, window sizes and step sizes. For accurate displacement field calculation, careful selection of these parameters is imperative which depends on the study area and dataset characteristics. In the study, we made relative comparisons of coseismic displacement fields calculated by using different combinations of input parameters. The results were validated by field based displacement data of vertical separation. Validation was based on the hypothesis that horizontal displacement component may also have vertical component contribution depending upon local characteristics of the fault. Validation results showed that general trend of the measured displacements was in agreement with the field data. Field measurements were bounded within the uncertainty limits of the technique however at some locations significant deviations were also observed. All the coseismic displacement results obtained by using different input parameter were within the uncertainty limit $\pm 1/10$ of the pixel size, except for window size 4×4 and 8×8 . The measured component of the fault rupture for northwest of Muzaffarabad is irregular. It may be due to rugged topography as compared to southeast part. The measured fault rupture also coincided to surface rupture mapped in the field. Analysis of the results showed that in comparison to standard parameter set, defined in the literature (Sinc resampling method, Frequential correlator with window size 32×32 and Step size 8), selection of resampling method and correlator type had no significant effect on the calculated displacement field. However, window size and step size were found to be the most important parameters of the technique. This study showed that changing the window size does not affect the detection limit of the technique but induces bias in the calculations. Step size is used in relation to window size, however relatively larger step size is found to provide better sensitivity and accuracy of the technique.

Keywords: coseismic displacements, earthquake, sensitivity analysis, remote sensing

2.1 Introduction

Coseismic displacements play a key role in understanding earthquake dynamics such as seismic fault geometry and fault rupture modelling (van Puymbroeck et al., 2000; Leprince et al., 2008; Taylor et al., 2008). The coseismic displacements can give insight into earthquake source, earthquake dynamics (i.e. fault mechanics and geometry), future earthquake recurrence and seismic hazard assessment (Leprince et al., 2007; Kaneda et al., 2008). Moreover, these measurements also assist in interpretation of morpho-tectonic features in other earthquake prone areas for preparing seismic hazard maps (Binet and Bollinger, 2005; Kaneda et al., 2008).

In situ coseismic displacements are usually measured using GPS (global positioning system), geodetic techniques, and field based measurements and observations. These methods have some limitations like lack of clear visible offset piercing points and localization. More importantly the horizontal displacement component perpendicular to the fault is not directly measureable in the field (Avouac et al., 2006; Ayoub et al., 2009). These limitations hinder capturing of complete coseismic displacement field; as displacements are distributed to a wider deformation zone. Although field methods are capable to provide accurate measurements, they cannot provide a holistic view of the displacement field.

Remote sensing data, due to its synoptic view, is capable to detect spatially distributed coseismic displacement measurements. It provides images of the ground regularly with good radiometric and geometric quality (van Puymbroeck et al., 2000; Michel and Avouac, 2006). There are two major sources of remote sensing data, microwave and optical, for measuring coseismic displacements. Using remote sensing data, displacement field can be measured by comparison of pre- and post-earthquake images. These displacements can be calculated either by using Synthetic Aperture Radar (SAR) Interferometry (Massonnet et al., 1993; Taylor et al., 2008) or by offsets tracking with sub-pixel correlation of SAR amplitude (Simons et al., 2002; Fialko et al., 2005; Pathier et al., 2006) or optical images (Crippen, 1992; van Puymbroeck et al., 2000; Dominguez et al., 2003; Binet and Bollinger, 2005; Leprince et al., 2007).

Synthetic Aperture Radar Interferometry (InSAR) gives accuracy at centimeter level, however is incapable to measure near fault measurements due to large gradient of deformation (Leprince et al., 2007). Besides, it gives mainly near vertical component of the displacements (Michel et al., 1999; Simons et al., 2002; Dominguez et al., 2003). Offset tracking technique applied on SAR amplitude data does not provide horizontal displacement components directly. Because it measures track-parallel (azimuth-offsets) and track-perpendicular (range-offsets) displacement components (Fialko et al., 2005). East-west and north-south components of displacement can be

inferred using azimuth and range offsets (Elliott et al., 2007). The accuracy of the displacement field, calculated by SAR offset technique, may also be affected by topography of the area and ionospheric distortions (Leprince et al., 2007; Scherler et al., 2008).

Optical data has advantages over SAR and InSAR, because optical data is capable to provide horizontal coseismic displacement components directly. Sub-pixel correlation technique relates the coordinates of both optical images from spatial domain to frequency domain reciprocally and measures phase shifts of both images' Fourier Transforms (Leprince et al., 2007; Gonzalez et al., 2009). Optical data may provide more robust displacements as it is less affected by atmospheric distortions and topographical effects as compared to SAR data (Avouac et al., 2006; Arikan et al., 2007). Sub-pixel correlation of optical images has also been used efficiently to study glacier movements, landslides and sand dunes migration (Klinger et al., 2005; Leprince et al., 2007; Scherler et al., 2008; Vermeesch and Drake, 2008; Barisin et al., 2009).

The optical images offset tracking technique for measuring coseismic displacements comprises two main steps; coregistration and correlation of pre- and post-earthquake images accurately. Coregistration between paired optical images is a critical step to accurately measure coseismic displacements. Correlation process is significantly dependent on accurate coregistration of both the images for determining the coseismic displacements. Topographic errors can be corrected exclusively during the orthorectification in order to remove artefacts due to the topography. In coregistration process, orthorectification of both pre- and post-earthquake images is accomplished by resampling to a common reference frame. To account for attitude variations and parallax effects, ancillary information (positions, velocities, attitudes variations and pointing directions for spacecrafts) and Digital Elevation Model (DEM), are required (Leprince et al., 2007).

Following the coregistration, correlation of two images is the next step in the process. For a precise correlation of the images, type of correlator, window size (number of pixels on both images) and step size (shift between two sliding windows) need to be cautiously selected. Selection of these parameters requires careful analysis of data (sensor, spatial resolution, quality etc.) and study area characteristics (topography and land cover). Uncertainties due to topography on the displacements can be removed by modelling topographic errors in the coregistration process, whereas decorrelation due to landcover changes can be minimized by selecting the images of similar seasons.

In the present study, effects of these parameters on displacement measurements caused by the 2005 Kashmir earthquake were investigated.

The main objective of the study was to investigate the relative comparison of coseismic displacements using different resampling methods, correlator types, window sizes and step sizes with reference to default values defined by Leprince et al. (2007) and Avouac et al. (2006). This analysis would help to enhance the performance of the technique by selecting optimal combination of parameter for a given study area. The effects of these parameters were assessed on a pair of ASTER images bracketing the 2005 Kashmir earthquake.

2.2 Study area

The study area is located in the state of Azad Jammu and Kashmir in the Lesser Himalaya of northern Pakistan (Figure 2.1). Most of the terrain is mountainous with the highest peaks exceeding 4572 m above sea level, particularly the epicenter is located in rugged mountainous area with deep narrow valleys and relief of 1524 m or more and slopes of 45-50 degrees. The region is drained by the Jhelum River and its two tributaries Neelum and Kunhar. Due to Rapid discharge flow of rivers, erosion rate is high, which produces steep lower valley slopes. Muzaffarabad, about 10 km south west of the epicenter, is the largest city in the region, with a population of about 200,000 and was severely damaged during the 2005 Kashmir earthquake (Naeem et al., 2005; Kaneda et al., 2008; Hussain et al., 2009).

Figure 2.1: Study area in the Northern Pakistan

2.3 Data and methods

2.3.1 Datasets

A pair of ASTER Images along with their respective ASTER DEMs bracketing the October 8, 2005 Kashmir earthquake were used in the present study. Therefore pre-earthquake image dating November 14, 2000 and post-earthquake image dating October 27, 2005 were used. There was 5-years' time span in both pre- and post-earthquake images because no other cloud free image was available close at pre-earthquake event. Incidence angle of both images was 8.6° with 1A processing level.

The ASTER uses a push broom sensor containing a linear array of detectors oriented normal to the satellite flight path for image acquisition. Three subsystems are integrated in ASTER instrument with spatial resolutions as 15 m in visible and near-infrared (VNIR), 30 m in shortwave infrared (SWIR) and 90 m in thermal infrared (TIR) (Abrams et al., 2002). The bands 3N and 3B of VNIR subsystem are nadir-looking and backward-looking; respectively.

Both bands provide stereo capability for extracting DEM with ground resolution of 30 m and vertical accuracy of 13 m (Cuartero et al., 2005).

2.3.2 Methods

The technique of sub-pixel correlation of optical images, used to measure coseismic displacements, was implemented in software package COSI-Corr (Co-Registration of Optically Sensed Images and Correlation) (Leprince et al., 2007). COSI-Corr is an IDL-based module embedded in ENVI® software. The COSI-Corr comprises two main steps (Figure 2.2), coregistration and correlation of pre- and post-earthquake images. As coseismic displacements are usually at centimeters to meters scale, all calculations should measure at sub-pixel level. Shaded relief image were prepared using the available ASTER DEM resampled to 15 m pixel size. We used band 3N for both images in order to retrieve sub-pixel coseismic displacements. The pre-earthquake imagery was orthorectified by taking shaded relief images as master. The process did not require any external information, like GPS points. It used only ancillary information (attitude variations, velocity and position of remote sensing platform) provided with satellite data of both images to account for biases in the images. The parallax effects due to incidence angle difference and topography were compensated by using DEM.

Figure 2.2: Basic steps of COSI-Corr technique for estimating co-seismic ground displacements

A set of Ground Control Points (GCPs) were generated automatically by using initially defined 3 tie points between master and pre-earthquake images. GCPs on the areas of expected coseismic displacements and with higher RMSE (Root Mean Square Error) were excluded. GCPs were optimized by minimizing their miss-registration on both images through correlation process iteratively. Orthorectification was performed using these optimized GCPs, DEM and ancillary information by resampling the pre-earthquake image into master image's geometry and onto a common reference system (datum WGS

84 and projection UTM). Similarly the post-earthquake imagery was orthorectified by taking the already orthorectified pre-earthquake imagery as master. Both images were coregistered within the accuracy of $1/50$ – $1/20$ of the pixel size. Then both orthorectified and coregistered images were correlated by calculating their phase shifts in the Fourier domain. This process produced two images- line shifts that was E-W displacement component and column shifts N-S displacement component with $1/20$ – $1/10$ pixel accuracy (Leprince et al., 2007; Scherler et al., 2008).

During the process of coregistration, images were resampled using one of the resampling methods. Resampling methods reconstruct an image using different mathematical models. There are three resampling methods available which are Sinc (Sinus Cardinal), Bilinear and Bicubic corresponding to use of zeroth-, first- and second-order polynomials respectively. A careful selection of resampling method is required in order to preserve sub-pixel information from raw image. Bilinear and Bicubic methods are usually used for fast and visual results but their use may require specific area or data characteristics. Sinc resampling method is recommended for better resampling accuracy for sub-pixel correlation method (Leprince et al., 2007).

For correlation of orthorectified images, there are two correlation engines Frequential and Statistical. Frequential correlator is recommended for images of good quality whereas Statistical correlator provides better results for noisy images (Leprince et al., 2007). The correlation process also requires the selection of window size and step size. Window size is the area on both images for which correlation is determined in order to know the relative shift. Step size is the shift (number of pixels) between two sliding windows. The COSI-Corr accepts window size in power of 2 only. The larger the window size, the more average the results are. Moreover, if window size is too small it will not work in FFT calculations according to time-frequency uncertainty principle. Window size 32×32 is recommended for improved correlation results. Step size is used in relation to the window size. A step size not greater than half of the window size is recommended. A too small step size oversamples the image without adding additional information whereas large step size produces coarser results and missing details (Leprince et al., 2007).

Different input parameters such as Sinc resampling method, Frequential correlator with window size 32×32 and step size 8 are recommended by Leprince et al. (2007). Various studies on different applications (Avouac et al., 2006; Scherler et al., 2008; Vermeesch and Drake, 2008; Barisin et al., 2009; Quincey and Glasser, 2009) also used these recommended parameters. In the present study these parameters were taken as standard.

The present study compared the effects of different parameters of the technique with the standard parameters defined above, and presented the comparative analysis for each parameter. A set of input parameters used to

get coseismic displacements in this study are given in Table 2.1. These parameters were applied to a pair of ASTER images bracketing the 2005 Kashmir earthquake.

Table 2.1: COSI-Corr technique's parameters used for measuring coseismic displacements

Resampling Methods	Sinc	Bilinear	Bicubic
Correlators	Frequential	Statistical	Standard parameters
Window Sizes	Win-Sizes: 4, 8, 16, 32 and 64	Standard parameters (win-32 and step 8)	Standard parameters (Frequential Correlator with win-32 and step 8)
Step Sizes	Step-Size: 4, 8 and 16	Correlator with win-32 and step 8)	

From application of different parameters (Table 2.1) such as resampling methods, correlators, window sizes and step size, 10 correlation results were obtained from a pair of pre- and post-earthquake ASTER images. The images were correlated by taking any one of these parameters as variable and keeping other parameters (standard ones) constant. For example to compare the results of resampling methods, for each resampling method a correlation process was carried out keeping Frequential correlator with window size 32×32 and step size 8 as constants. In the same way, correlation results were obtained for correlator type, window sizes and step sizes.

Post processing was applied on the correlated images in order to minimize the residual errors due to attitude variations and to filter outliers due to temporal changes. The attitude variations found in the images in the form of a long wavy pattern. These were due to not accounting for attitude variations as a result of under-sampling the ancillary information (Teshima and Iwasaki, 2008) during the process of orthorectification. To remove these wavy patterns, a patch of relatively stable ground (with no coseismic displacements) was taken and effect of wavy pattern on it is calculated. The effect was then subtracted from the whole image. The larger the area of stable ground, the better is the correction. However effect of wavy patterns can still remain in the images particularly when noise due to other sources like DEM inaccuracy are also present in the images (Scherler et al., 2008). After correction, the images were filtered keeping coseismic displacement values with in ± 10 (the expected coseismic displacement range).

The correlated images were then used to measure displacement for each E-W and N-S displacement component and for all input parameters. The fault rupture due to the earthquake was digitized from the correlated image as it showed clear discontinuity where coseismic displacements occurred. The displacements were measured by drawing profile of 18×6 km across the

digitized fault line and applying least square adjustment method for each E-W and N-S displacement components.

Using correlated image obtained by applying technique's standard parameters, displacement values were measured at 100 locations with average interval of 700 m for E-W and N-S offset images separately. A graph of horizontal displacements at these 100 locations along the fault was prepared with technique's error margin curves. This process was repeated to calculate horizontal displacement at selected 15 locations where field data was available for different input parameters (Table 2.1). The comparative graphs for each investigated parameter were prepared separately. No field data of the horizontal displacements were available to validate our results. Therefore data for validation purpose were prepared (detail given below) from the field measured vertical displacements as it may give the comparison of displacement distribution trend along the fault (qualitative analysis) based on the hypothesis that the amount of horizontal displacement component is relative to vertical component. A set of 16 field values (detail given in subsection 3.3) of vertical displacements were overlaid to the graph of horizontal displacement. Comparison graphs of horizontal displacements measured at selected 15 locations (for each input parameter such as resampling method, correlator, window size and step size) were also validated by the defined dataset of 15 field values (detail given subsection 3.3). These graphs were used to evaluate the sensitivity of the technique by having relative comparison of above mentioned input parameters.

2.3.3 Validation data set

A Pakistani-Japanese collaborative team mapped the fault's surface rupture in detail and measured coseismic offsets (mostly vertical displacement) at various locations along earthquake causative fault. This field survey was conducted 5 months after the earthquake on 8-19 march 2006. The results were published in (Kaneda et al., 2008). The supplementary data for this article is available at website: <http://www.bssaonline.org/content/98/2/521/suppl/DC1>.

The vertical displacement across the fault was measured from topographic profile at 63 locations. Field expressions of the earthquake causative fault include a monoclinical scarp. It formed a pressure ridge with northeast-side up and having surface shortening feature like rolled-up with flat surface at its base. Due to lack of infrastructure or other anthropogenic features, the field values of vertical displacement were mostly measured on streams and high terraces crossing the fault. The values at top of terraces are smaller than the others, showing the effect of energy-absorbed by thick gravel fill (Kaneda et al., 2008).

Two sets of validation data were prepared; one was selecting values at valley bottom with maximum value of 2 km interval. These are 16 points which were overlaid to the graph of horizontal displacement at 100 locations. Second dataset was prepared by selecting vertical displacement value at valley bottom and displacement values of 2 m and greater. Values less than 2 m were dropped because they were below the detection limits of the technique with using ASTER images. These were 14 values, by including one more at which the horizontal shortening was measured in the field so it finally build 15 values of validation data set.

In the absence of horizontal field measurements the coseismic displacement were compared with the vertical field measured displacements for qualitative analysis. This validation is hypothesized that horizontal displacement component may also have vertical component contribution depending upon local characteristics of the fault (Avouac et al., 2006; Kaneda et al., 2008).

2.4 Results

Sub-pixel correlation of ASTER images performed using the described methodology (Table 2.1). Despite 5 years temporal gap between the two images, the correlation images clearly revealed surface rupture of the fault. It provided clear discontinuity of the positive and negative coseismic displacement values (Figure 2.3). A correlation image gave horizontal displacement values in two bands; band 1 is East-West (E-W) displacements and band 2 North-South (N-S) displacements.

Both E-W and N-S images showed a wavy pattern running top to bottom along the scene. It was due to the residuals of attitude variations which were not removed during the process of orthorectification as the ancillary information, available to compensate these effects was not enough. The wavy pattern was removed in the post-processing (de-striping, filtering, masking) and results are shown in Figure 2.3a and 2.3b. This effect is more prominent in E-W displacement component. The N-S displacement component showed clear discontinuity in center of the image running NW-SE. It gives clear indication that major movement was along N-S direction as E-W displacement image did not provide such sharp discontinuity although there was also E-W movement.

Figure 2.3: Sub-pixel correlation of ASTER images, measured in meters, shows (a) De-striped, filtered and masked (post processed) East-West displacement component, (b) De-striped, filtered and masked (post processed) North-South displacement component.

The results indicated (Figure 2.4) that there was no wavy pattern anymore and filtering procedure removed the outlier due to different noises. The masking was applied to focus on area of interest in order to minimize the residual errors. After applying these post-processing steps the N-S displacement component showed discontinuity more clearly and E-W displacement also manifested some indication of the fault movement.

Figure 2.4a shows North-South component of horizontal displacement; positive values show displacement towards the North, while negative values give displacement in the South direction. The white areas in the image are decorrelation patches due to landslides, shadows, seasonal variations or snow cover changes. Most of the landslides reside in upper part which is hanging wall of the fault. The density of landslides is high around and north of Muzaffrabad city. However one of the big landslides can be seen at lower right corner of the Figure 2.4a. Here fault rupture makes a 'V-shape' due to a topographic ridge in the way of fault rupture. The traced line (Figure 2.5) is the fault rupture due to the 2005 Kashmir earthquake. The discontinuity was traced up to a distance of 75 km by following the fault rupture shown in the N-S displacement component (Figure 2.4a). This digitized fault trace was compared with the field mapped surface rupture (Figure 2.5).

Figure 2.4: Displacement results. (a) A north-south displacement component with exemplifying of measuring co-seismic displacement at a specified location across the fault. (b) Displacement measured for one stack profile at specified location. (c) Total 15 stack profiles at selected locations for measuring displacements across the fault.

The coseismic displacement was measured by drawing a profile of 18×6 km across the fault (Figure 2.4b). Coseismic displacements, using technique's standard parameters, were measured at 100 locations by drawing profiles across the fault with an average interval of 700 m (Figure 2.6 and subsection 4.2). For sensitivity analysis of technique's parameters (Table 2.1) 15 locations were selected to measure coseismic displacements, where the field data was available (Figure 2.4c).

2.5 Fault rupture

The fault rupture was traced up to 75 km length from the correlation image discontinuity (Figure 2.5). It is mostly along the pre-existing fault segments of Muzaffarabad and Tanda faults called collectively Balakot-Bagh Fault (BBF).

Figure 2.5: Comparison of fault ruptures measured by the technique and mapped in the field. Field mapped fault rupture is from (Kaneda et al., 2008) given in the supplementary information at website: <http://www.bssaonline.org/content/98/2/521/suppl/DC1>

The field mapped rupture (Figure 2.5) almost exactly coincide to the one traced by the technique. For analysis, the fault rupture may be divided into two segments; one along Muzaffarabad and the other along Tanda fault (Figure 2.5). Northwest of Muzaffarabad city the fault rupture along Muzaffarabad fault was irregular along the Kunhar river valley showing its complex nature. The rupture suddenly diminished just north of Balakot city, it

might be due to structural control of existing Main Boundary Thrust (MBT), where it takes sharp hairpin-like turn and also it is near to a zone called IKSZ (Indus Kohistan Seismic Zone) where most of the aftershocks occurred (Avouac et al., 2006; Kaneda et al., 2008). North of Muzaffarabad city fault turns sharply to left, making a step over. At center of the fault where fault rupture turns sharply, actually a segment connects two previously mapped Muzaffarabad and Tanda fault segments, now collectively called Balakot-Bagh Fault (BBF). The connected part is called a tear fault and this place is near the epicenter where earthquake was nucleated at the depth of 26 km and propagated bilaterally (Avouac et al., 2006; Kaneda et al., 2008). Southeast of Muzaffarabad city the fault trace was remarkably linear and rupture the northeast flank of upper-Jhelum river valley. Near the end of fault rupture it turns its way and resulting a 'V-shaped' due to topographic ridge in its way. It is the place where the biggest landslide occurred in the area (Figures 2.4 and 2.5).

2.6 Fault displacement results

Sub-pixel correlation of pre- and post- Kashmir earthquake provided horizontal coseismic displacements. Horizontal displacement, calculated from E-W and N-S displacement components, measured at 100 locations using the defined standard input parameters of the technique are shown in Figure 2.6. The error of $\pm 1/10$ of the pixel size of image may exist in measurements using the technique, based on it error margin curves are also drawn in the figure.

Figure 2.6: Horizontal displacement measured by sub-pixel correlation technique at 100 locations separated by an average distance of 700 m, showing a continuous line of displacements. Dotted red and green lines show error margins and black triangles are field measured vertical displacements with $\pm$ error bars. Field measurements are from (Kaneda et al., 2008) given in the supplementary information at website: <http://www.bssaonline.org/content/98/2/521/suppl/DC1>

The average coseismic horizontal displacement was measured about 3.9 m along the entire earthquake causative fault. Displacements along the Muzafarabad fault were higher peaking about 7.26 m in northwest of Muzafarabad city. It showed unimodal pattern of displacement distribution with peak value at its center. Just north of Balakot city the displacement varied quite significantly and terminated with high gradient. This northern part of the fault rupture was parallel to western flank of the existing inactive MBT but both faults have opposite fault planes. The average displacement along the Muzaffarabad fault segment was 5.25 m with maximum and minimum values of 7.26 m, 2.29 m respectively. At the southern end of Muzaffarabad fault a local minima of displacement values existed at the location where two faults join each other.

The coseismic displacements showed multimodal behaviour such as plateau like distribution in southeast of Muzaffarabad city. The fault rupture in southeast of Muzafarabad was linear and followed north-eastern bank of the river Jehlum in upper Jehlum valley. At the southern-most end of the fault after crossing the Jehlum River it showed irregular pattern again. The displacement distribution along the Tanda fault segment was relatively simple; with mean displacement of 2.9 m and maximum and minimum values of 4.3 m and 1.4 m respectively.

The Figure 2.6 also shows a comparison of field measured vertical displacement values with the displacement measured by the technique. The 16 points out of 63 field measurements were selected (detail is given in Methodology section). The field measurements were discrete points but here the selected 16 values were joined just to show trend of the displacement distribution. The figure shows trend of these field values follows the coseismic displacements measured by the technique, although there are variations at many locations. All field values are within error margin curves of the technique except at three locations showed underestimation near to center of Muzaffarabad fault. One field point showed underestimation on Tanda fault but it has value 0.85 m which was below the technique's detection limits.

2.7 Sensitivity analysis

Sensitivity analysis of the technique for measuring coseismic displacements using a pair of ASTER images gave an overview of how the change in different parameters (Table 2.1) affects the results. All results for different input parameters were within error margin curves of the technique except the window size 4×4 and 8×8. The error margin curves were drawn in all comparison graphs (Figure 2.7) calculated from the results obtained using defined standard parameters.

The field data of vertical displacement at 15 selected locations were in agreement with these error margin curves except at four locations (at 5, 6, 9

and 15, labelled in Figure 2.7a). Three out of four points were at margin of these curves while at location 5 showed highest deviation (underestimate) of 4.1 m from the measured displacement. The other two locations 6 & 9 also showed under estimation of 1.3 m and 1.9 m from the measured value respectively. The value at location 15 was overestimated (2.2 m) above the measured value. Field measured horizontal displacement at location 7 was in good agreement (1 m overestimation from the field measured value). The average displacement of field measure value was 3.4 m in comparison of the technique measured value 3.6 m.

Resampling methods

The comparison of three resampling methods i.e. Sinc, Bilinear and Bicubic, of the technique is given in Figure 2.7a. All three resampling method showed small variation with respect to each other in measuring smaller values. The average differences of Bilinear and Bicubic methods with respect to standard Sinc method were 0.15 m and 0.13 m respectively. So Bicubic method gave relatively similar results than Bilinear result. For three resampling methods, relatively larger variations were observable along Muzaffarabad fault segment and less variations on Tanda fault segment. However results were inconsistency for three resampling methods along the Tanda fault.

The average differences of Sinc, Bilinear and Bicubic methods with respect to field measurements were 0.16 m, 0.01 m, 0.02 m respectively. Field measured horizontal displacement value was close to the Bilinear method result with difference of 0.4 m overestimation, while 1.1 m and 1.4 m overestimation for Sinc and Bicubic methods respectively. These measurements' differences revealed that Bilinear method varies less with reference to field measured horizontal displacement value.

Correlators

Both correlator results were similar in general (Figure 2.7b). The average difference of Statistical correlator with respect to Frequential was 0.33 m. Statistical correlator varies of 1 m approximate at locations 4, 6, 7 and 11 with respect to Frequential correlator. The Statistical correlator underestimates measurements in comparison with Frequential correlator.

The average difference of Frequential and Statistical correlators with respect to field data were 2.1 m and 1.3 m respectively. The field measured horizontal displacement at location 7 differs with Frequential and Statistical by 1 m and 2.1 m of overestimation respectively.

Figure 2.7: Comparison of results for sensitivity analysis; resampling methods (a), Correlators (b), window sizes (c) and step sizes (d), used in the COSI-Corr technique to derive the horizontal coseismic displacements at 15 selected locations. Field mapped fault rupture is from (Kaneda et al., 2008) given in the supplementary information at website: <http://www.bssaonline.org/content/98/2/521/suppl/DC1>

Window sizes

Figure 2.7c shows comparison of different window sizes. It suggests that window size 4×4 and 8×8 were very low displacements compared to other window sizes and having average difference of 2.7 m with respect to the standard. So their results were not comparable to other three window size. They were also out of the error margin curves of the technique (Figure 2.7c). The average differences of window sizes 16×16 and 64×64 with respect to the standard (window size 32×32) were 0.76 m and 1.1 m respectively. So window size 16×16 was more similar to the standard window than the window size 64×64 . Window size 64×64 results were also relatively inconsistent than the window size 16×16 results with respect to standard. Window size 64×64 overestimated the measurements while window size 16×16 underestimated and it can also be verified from Figure 2.8.

The average differences of window sizes 16×16 , 32×32 and 64×64 with respect to field measurements of vertical displacement were 0.63 m, 0.16 m, and 1.3 m respectively. Therefore the standard window size 32×32 was in good agreement with the field data. The field measured horizontal displacement at location 7 showed differences of 0.95 m, 1 m and 0.53 m with respect to window sizes 16×16 , 32×32 and 64×64 respectively. So the results of window size 64×64 varied less on average with respect to this field point.

Step sizes

In the comparison of three step sizes (Figure 2.7d), step size 16 gives similar result with respect to standard (step size 8) result. The average difference of step 4 and step 16 with respect to standard were 0.5 m and 0.7 m. Generally both step sizes 4 and 16 overestimated measurements with respect to standard. Step size 16 overestimated measurements at Tanda fault segment while it underestimated at Muzaffarabad fault except at 2 locations at the northern end. Step size 4 results were relatively inconsistent with respect to standard compared to step 16.

The average difference for three step sizes (4, 8 and 16) with respect to field measurements were 0.16 m, 0.63 m and 0.87 m respectively. It means that the field-measurements were in agreement with step size 8 (standard parameter) results. The field measured horizontal value at location 7 varied as 0.4 m, 1 m and 0.5 m with respect to step 4, 8, and 16 respectively. So step 4 and 16 vary less than step 8 with respect to this particular field measurement.

Figure 2.8: Scatter plot comparison for finding Correlation of Window size 32×32 to others.

2.8 Discussions

2.8.1 Coseismic displacements and fault rupture

The correlation images showed that the rupture reached the surface and followed the previously mapped Muzaffarabad and Tanada faults up to 75 km. It was oriented in NW-SE direction, starting in north of Balakot city to Bagh city in south (Figure 2.5). The distribution of coseismic displacement was also visible from the correlation images (Figure 2.3), it has a large number of landslides to the hanging wall side of the fault and hence the devastation also. The pattern of fault movement was mainly in N-S direction indicating Thrust fault mechanism while E-W displacement was small showing it has also small strike-slip component. This agrees to the fault plane solution by Harvard CMT focal mechanism model (Avouac et al., 2006).

The correlation images showed wave pattern on both E-W and N-S displacement components. These waves showed attitude behaviour of the satellite movement in the orbit. E-W displacement component showed roll movement of the remote sensing platform while N-S showed pitch effects. These patterns can be removed, if the satellite movement data is recorded during the operation of image acquisition. Unfortunately in the case of ASTER it is not recorded enough with sufficient accuracy. Therefore due to the under-sampling of attitude information of satellite, the correlation images

showed wavy patterns. However these wave-patterns can be removed in a post processing step, but still its effect can bias the coseismic measurements.

Despite the five years gap between the images' acquisition dates, the correlation images result showed clear discontinuity marking the fault rupture due to the earthquake. Due to the cloud coverage and snow differencing the pre- and post-earthquake, ASTER images could not be made available for the shorter period of interval. The pre- and post-earthquake images used in this study were of similar season, therefore land cover changes may have little effects on the correlation results. The correlation images showed that the technique is capable to map the fault rupture from ASTER data. For measuring coseismic displacements, band 3N of ASTER images which is nadir looking were used and therefore it assuring small topographic distortions. The fault rupture was linear along the Tanda fault in south of Muzaffarabad city while in north it was irregular along the Muzaffarabad fault (Figure 2.5). The irregularity may be due to high topography as in the areas of steep topography, orthorectification and coregistration of both images is less accurate due to DEM accuracy. DEMs (e.g. SRTM) particularly the ASTER DEMs show inaccuracies in steep mountainous areas. This irregularity may be explained due to local characteristics of the fault like strike, dip and rake. The fault dip angle ranges from 300 to 100, higher the dip angle more is the irregularity of the fault rupture (Kaneda et al., 2008). Another reason of fault rupture irregularity may be due to the tear fault that connects the Muzaffarabad fault to the Tanda fault (Avouac et al., 2006). Fault rupture along Muzaffarabad fault segment was parallel to western flank of inactive Main Boundary Thrust (MBT). Fault rupture stopped suddenly near the hairpin-like turn of MBT showing a strong structural control over it.

Decorrelation due to landslides affected the coseismic displacement measurements. The earthquake triggered a large number of landslides. Most of the landslides were rock and debris fall triggered by the main shock. These were concentrated on hanging wall side of the fault in the epicentral region as well as in the close vicinity of the earthquake causative fault. The occurrence of these landslides were based on terrain parameters like surface geology, slope gradients, slope aspects, curvature and relief classes and human activities like road construction (Owen et al., 2008). Most of slides were corresponding to 30°-40° slope having south, south-eastern and south-western aspects on the convex curvatures (Sato et al., 2007; Owen et al., 2008). The density of landslide was higher along the geologic boundary between Precambrian dolomite of the Muzaffarabad formation and Miocene sandstone of the Murree formation. The coseismic displacement measurements were affected by decorrelation due to the landslides along the north-west oriented Muzaffarabad fault. It was due to high topography with steep slopes. Most of the landslides in the area were of smaller size, only 3 or 4 landslides were huge. One extremely large landslide (the Hattian Bala

landslide) was occurred near the south-eastern end of the Tanda fault. This landslide was structurally controlled and occurred in a plunging syncline (Owen et al., 2008). It produced a major decorrelation patch in the correlation image (Figure 2.4a). The most of the landslides were smaller than the optimal window size (32×32) and did not affect the displacement measurements; however the big landslides may have affected the coseismic displacement measurements.

The coseismic displacements on both part of the fault segment show contrasting distributions (Figure 2.6). It may be due to complexity of fault geometry or may be due to different bedrock geology. Muzaffarabad fault separates, two geological formations, the Precambrian rocks of Lesser Himalaya from the Miocene rocks of the Sub-Himalaya. While the Tanda fault rupture is within same geological formation, Miocene molasses of the Sub-Himalaya. The frictional characteristics of both fault segments due to different geology may have control on surface displacement distribution and on maximum displacement value (Kaneda et al., 2008). Most of the thrust faults mark mountain fronts whereas Balakot-Bagh Fault (BBF) runs through mountainous area. Therefore it may have effect on slip distribution due to topography and complex geometry of the fault. The field data of selected 16 vertical displacement measurements showed almost similar trend as of measured coseismic displacements except at four places (details given in subsection 5.2).

2.8.2 Sensitivity analysis

Sensitivity analysis of sub-pixel correlation technique's input parameters (Table 2.1) showed effects in measuring coseismic displacements by changing the parameters. The analysis of change of parameters was limited to only one pair of ASTER images bracketing the 2005 Kashmir earthquake. According to the analysis, the importance of resampling method and correlator selection was less than the window size and step size selection for measuring the displacements. The comparison results were validated by the field data of vertical displacements. The field data at selected 15 locations (14 vertical displacements and one horizontal) along the earthquake causative fault was in agreement generally. All field data were within technique's error margin curves except at 4 locations (labelled as number 5, 6, 9 and 15 in Figure 2.7a). Points 5, 6 and 9 around Muzaffarabad city show underestimation while point 15 has overestimation at the end of the fault rupture in south.

Point 5 (Figure 2.9) shows largest deviation, underestimating the coseismic displacement. The reason is that it was not measured at valley bottom, a number of landslides were also present in the surrounding (Figure 2.9, point 5) and deformation may be present over a wider zone which may not be

measureable in the field. The point 6 (Figure 2.9) was located in the main residential area and on the fault segment that joins Muzaffarabad and Tanda fault. This point also showed underestimation, it might be due to lot of landslides present around it, effects of urban infrastructure change and/or complex nature of the fault geometry. Similarly for point 9, justification may be made that the deformation is on wider zone not represented by the field value. The last point showed overestimation, it is due to the accumulative effect of repeated surface faulting (Kumahara and Nakata, 2006). At location 7, which is 30 m away from the location 6, horizontal displacement was measured in the field. This field measured value was in good agreement with the technique measured values for all parameters generally.

Figure 2.9: Four field data locations marked on Google Earth imagery, which have considerable deviations from the measured displacements by the technique. Red line shows fault rupture measure by the technique whereas yellow shows field mapped fault rupture.

Most of the landslides were around and north of Muzaffarabad city, it might affect the displacement measurement by the technique. Landslides produce decorrelation patches because correlation fails due to low SNR value. An 18×6 km profile was taken across the fault so that decorrelation effect is minimum on coseismic displacement measurement. In this box (profile) the least square adjustment method will find enough values in order to provide accurate measurement. Similarly the fault complexity would also affect measurement locally; its effect on 18×6 size profile may be averaged. The residual of attitude variations may also effect the coseismic displacement measurements. These were present in form of wave on the images; the

displacement value may be affected, depends on its location on wave pattern (wave crest or trough). These wavy pattern repeat at 4.5 km with 1.5 m amplitude on the ground (Leprince et al., 2007). So the effect of these wavy pattern after applying the de-stripping of image would be even less (< 1 m) and also its effect would be averaged within profile size of 18×6 km. Figure 2.10 shows comparison of displacements measured with and without applying de-stripping and filtering steps. The figure shows displacement measured, without applying de-stripping and filtering options, follow wave like pattern in graphs.

Effects of resampling methods

Orthorectification of pre- and post-earthquake image involves the application one of the resampling methods of the COSI-Corr technique. According to Leprince et al. (2007), the implementation of Bilinear and Bicubic resampling methods in the technique is only for quick visual assessments. They should not be used for quantitative results. For improved accuracy of coregistration and hence correlation Sinc resampling method should be used.

Figure 2.10: Sensitivity analysis results by comparison of resampling methods (a), window sizes (b) and step sizes (c) for deriving horizontal coseismic displacements with and without applying de-stripping and filtering post-processing steps

Anyhow all three methods were tried during the orthorectification and coregistration process. The correlation results were then used for relative comparison of these methods in measuring coseismic displacements. The effect of resampling methods in the process coseismic displacement can be seen in Figure 2.10a. The variations were relatively higher where the fault rupture geometry is irregular showing its control on displacement distribution. While displacement values trend on Tanda fault were inconsistent for the results of three resampling methods. The attitude variation effect can also be seen from Figure 2.10a when displacements were measured without applying de-stripping and filtering steps. These showed wave like pattern in measured displacement values. Sinc resampling method was more sensitive to variation while Bilinear and Bicubic method showed exactly overlapped results. If the measured value was at crest of attitude wave pattern, its value may be overestimated and under estimated when it was at trough. So at center near Muzaffarabad city displacement values were overestimated that is why field measured values have large deviation at these locations.

From the above discussion we can conclude that the effect of resampling methods in measuring coseismic displacements was not strongly based on displacement measurements obtained by one pair of ASTER images.

Effects of correlators

Frequential correlator is recommended (Leprince et al., 2007) for accurate results but it is sensitive to noises in correlated images. Therefore Statistical correlator is used for noisy images, it is less accurate but more robust (Leprince et al., 2007). The results (Figure 2.7b) showed almost similar behaviour in measuring coseismic displacements. The figure shows that Statistical correlator underestimates the displacements. The attitude variation effect analysis showed, Statistical correlator produced similar trend as that of Frequential correlator. However these effects were higher in using the Statistical correlator.

Effects of window sizes

COSI-Corr accept window sizes as a power of 2 and defines a square area on both the images and calculate correlation locally. Larger the window size more average is the result and lower the correlation uncertainty. Figure 2.10b also shows that varying window size does not affect on sensitivity of the technique, it will only change level of noise in the correlation images. So it is a trade of between spatial smoothness and spatial resolution. The selection of window size also depend on data type (aerial or satellite), spatial resolution, study area characteristics and the expected displacement values. High spatial resolution imagery may require bigger window size for measuring relative shifts in images.

Window size 16×16 was more similar to standard 32×32 than the window size 64×64 . Window size 64×64 provided inconsistent results than the standard result. It may be due to averaging effect, as it produced large decorrelation patches in the correlation images. If window size is too small the Fast Fourier Transform (FFT) will not work according to time-frequency uncertainty principle (Leprince et al., 2007), this was the case which can be seen with window size 4×4 and 8×8 .

The attitude variation effects can be seen in Figure 2.10b for the use of different window sizes. The Figure 2.10b gives comparison of different window size used to measure displacement from images with and without post processing steps (de-striping, filtering). Window size 32×32 and 64×64 behaved similar in giving results from without de-striped and filtered images. However window size 16×16 was more sensitive to these attitude variations. Window sizes 4×4 and 8×8 which produced unreliable results due Fast Fourier Transformation (FFT) limitations so attitude variation effects were not clear for them. In comparison to window size 16×16 , 32×32 and 64×64 it may be infer that larger the window size more is the residual bias due to attitude variations. it may be justified that larger window size will take more wavy pattern while correlating two patches so it has more chance of increasing bias in the results.

Therefore, from the above discussion we can conclude that the selection of window size has critical effect in measuring coseismic displacements so more attention should be made in its careful selection.

Effects of step size

Step size is the shift (number pixels) between two sliding windows. Its selection is in relation to the selected window size and its size should not be greater than half of the window size. If step size is larger than the window size then all measurements will be independent. Its selection also depends on type of application and the amount of expected displacement to be measured. It defines pixel size in output correlation image. Larger the step size, lower the spatial resolution of output correlated image.

Figure 2.10c describes the effect of step size in measuring displacements from images with and without de-striping and filtering steps. Step 8 and 16 produced similar results, however step 4 showed uneven results as it may be sensitive toward noise. Step 8 and 16 were exactly overlapping in measuring displacement from images without post-processing steps, whereas step 4 showed irregular behaviours in dealing attitude variations.

At the end it may be concluded that the selection of step size in relation to window size is also critical parameter which may have effects on the displacement results.

2.9 Conclusions

Following conclusions may be drawn from the study of "Sensitivity analysis of sub-pixel correlation of pre- and post-earthquake ASTER images in measuring coseismic displacements for 2005 Kashmir earthquake".

- The COSI-Corr technique worked overall accurately for measuring coseismic displacements when using the technique's default parameters.
- The outcomes of resampling methods and correlators showed less variations in measuring coseismic displacements. Therefore the choice of resampling and correlation methods is less important than the selection of other parameters.
- The sensitivity analysis showed that window size and step size were more critical parameters and need a more careful selection. Their selection may require the analysis of area and data characteristics, type of application and accuracy of measurements.
- The horizontal displacement measured by sub-pixel correlation using optical images may be validated from field measured values of vertical displacements. The finding of this study showed reasonable agreement, the values lies within the confidence limit of the used technique.

Chapter 3: A complete set of LOS coseismic displacements for 2003 Bam earthquake using SAR Interferometry and kriging

This chapter has two parts, A and B; each of which has been written as an independent case study. Part-A describes all the theory and methodology for descending orbit image pair. This part has been published in a peer-reviewed ISI journal*. Part-B is mainly a replication of the work in part-A but applies to the ascending orbit image pair. There is some repetition of text in part-B so that the reader does not have to look back and forth to part-A for reference.

* **Yaseen, M.**, Hamm, N.A.S., Woldai, T., Tolpekin, V.A., Stein, A., 2013. "Local interpolation of coseismic displacements measured by InSAR" International Journal of Applied Earth Observation and Geoinformation 23, 1-17.

Part A: LOS Displacements from ASAR images from the Descending orbit

Abstract

Coseismic displacements play a significant role in characterizing earthquake causative faults and understanding earthquake dynamics. They are typically measured from InSAR using pre- and post-earthquake images. The displacement map produced by InSAR may contain missing coseismic values due to the decorrelation of ASAR images. This study focused on interpolating missing values in the coseismic displacement map of the 2003 Bam earthquake using geostatistics with the aim of running a slip distribution model. The gaps were grouped into 23 patches. Variograms of the patches showed that the displacement data were spatially correlated. The variogram prepared for ordinary kriging (OK) indicated the presence of a trend and thus justified the use of universal kriging (UK). Accuracy assessment was performed in 3 ways. First, 11 patches of equal size and with an equal number of missing values generated artificially, were kriged and validated. Second, the four selected patches results were validated after shifting them to new locations without missing values and comparing them with the observed values. Finally, cross validation was performed for both types of patch at the original and shifted locations. UK results were better than OK in terms of kriging variance, mean error (ME) and root mean square error (RMSE). For both OK and UK, only 4 out of 23 patches (1, 5, 11 and 21) showed ME and RMSE values that were substantially larger than for the other patches. The accuracy assessment results were found to be satisfactory with ME and RMSE values close to zero. InSAR data inversion demonstrated the usefulness of interpolation of the missing coseismic values by improving a slip distribution model. It is therefore concluded that kriging serves as an effective tool for interpolating the missing values on a coseismic displacement map.

Keywords: Earthquakes; Coseismic displacements; InSAR; Kriging; Geostatistics

3A.1 Introduction

Coseismic displacements at the Earth's surface arise due to the energy released by earthquakes. Coseismic displacements play a key role in understanding their source mechanism (van Puymbroeck et al., 2000; Leprince et al., 2007). For example earthquake causative fault characterization and modelling depends on accurate measurement of them. Conventionally they are measured in the field using a total station or a GPS. Field methods provide accurate measurements but allow only sparse sampling. They are sometimes not feasible due to problems in accessing the area. Moreover, they may be time consuming and laborious (Kaneda et al., 2008).

Remote sensing can be used as an alternative, as both optical and radar data from space and aerial platforms allow the detection and measurement of coseismic displacements in earthquake hit areas (Avouac et al., 2006). Pre- and post-earthquake images are compared by using specialized remote sensing techniques (Taylor et al., 2008). A comprehensive database of images is available almost worldwide. Coseismic displacements can be measured from remotely sensed data as soon as a post-earthquake image of the area is available (Pathier et al., 2006).

Synthetic aperture radar interferometry (InSAR) is an often used technique for detecting and measuring coseismic displacements. InSAR exploits the phase difference of pre- and post-earthquake data and yields the displacement vector, which is sensitive mainly in the vertical direction. This technique has centimeter precision. InSAR, however, fails if the gradient of change is high. For generating an interferogram, the gradient of displacements should not exceed half a fringe per pixel size of the images (Michel et al., 1999). The gradient of change more than half a fringe per pixel would cause a loss of coherence between the images (Sarti et al., 2006). Such a loss of coherence may also be caused by several other factors, such as topography, vegetation, water bodies, agricultural practices and man-made changes. This factor is a major obstacle to estimate coseismic displacement measurements near the earthquake causative fault (Fialko et al., 2005; Funning et al., 2005). As a consequence, an InSAR derived displacement map has missing values (gaps), mainly due to temporal changes, topography and earthquake induced damages. Keeping in view the importance of coseismic displacements for fault characterization, there is a need to calculate these missing values.

This study addresses the displacement map of the 2003 Bam earthquake. The study area details are provided in chapter 1, section 1.2. The produced displacement map has major gaps in the urban areas of Bam and Baravat, the river passing near Bam and the surrounding streams and vegetation. For this earthquake missing values also occur along the earthquake causative

fault. Interpolation of the missing values is, therefore, useful for its characterization.

The Bam earthquake area was selected due to the following reasons. To our knowledge, interpolation of missing coseismic displacement values has not previously been applied to such data. Bam was severely damaged and the earthquake causative fault is directly passing under the city (Stramondo et al., 2005). In order to obtain the coseismic displacements at Bam city, interpolation is needed. The Bam area is dry and flat with little vegetation and topography, hence the number of missing values in the displacement map, is expected to be limited. Finally, there is an extensive literature and interest in the area.

Typical interpolation techniques available in a geographical information system (GIS) are inverse distance weighting (IDW) and trend surface analysis (Burrough and McDonnell, 1998). A trend surface is based on regression of measurements on the coordinates, whereas IDW interpolation is based on a weighted combination of the surrounding measurements with weights depending upon the distance to observations. Geostatistical methods are preferred over trend surfaces and IDW because they build an explicit model of the spatial dependence and use it to interpolate at un-sampled locations and minimize the interpolation error variance (Addink and Stein, 1999).

Inversion of coseismic displacements is a commonly applied procedure to calculate the earthquake source parameters, in particular the slip magnitude and its distribution on the fault plane in the subsurface. This slip model can give a spatial insight into dislocation properties like the depth of the locked fault segment and the location of major asperities. The accuracy of a slip model depends upon the near-field (near the fault) spatially dense coseismic displacements. If a slip model is prepared using only the far-field displacements then details may be lost as compared to using near-field displacements (Elliott et al., 2007). As InSAR does not provide the near fault displacements, interpolation can help in obtaining these near fault displacements. The present study aims to compare the inversion models for both the original and the interpolated datasets in order to appraise the usefulness of the kriging.

The objective of the study is to interpolate the missing coseismic displacements by applying kriging. The accuracy of interpolation was evaluated by validation and cross-validation. The results from the geophysical modelling, obtained through inversion of the displacements, were compared for the original and the interpolated datasets. This was necessary in order to assess the utility of the interpolation.

3A.2 Data and pre-processing

The pre- and post-earthquake SAR images (ENVISAT ASAR) are dated 3 December, 2003 and 11 February, 2004 respectively, with a difference of 70 days. The perpendicular distance between orbits of the two scenes (the baseline) is 4 m. The images are in IS2 mode and have an incident angle of 23°, VV polarization and single look complex format. The generation of displacement map was carried out using SARscape 4.2 utility in the ENVI® 4.7 software. The image was multilooked using the software's default value that was 5 looks in azimuth direction while 1 in range. A post-earthquake ASTER image dated 2 January, 2004 was used for the visual classification of landcover of the study area.

3A.2.1 Modelling displacements using InSAR

An interferogram shows the phase-difference of two co-registered SAR images of pre- and post-earthquake. Each fringe in the interferogram represents a 2π change whereas 'k' is finite number of wavelength that is unknown. The phase-difference measurements (φ) are the summation of several effects; namely, ground deformation (φ_{def}), topography (φ_{topo}), atmospheric delay (φ_{atmp}), flat earth (φ_{flat}), temporal changes (φ_{temp}) and other unknown sources of noise (φ_{noise}) (Wang, et al., 2009):

$$\varphi = 2\pi k + \varphi_{def} + \varphi_{topo} + \varphi_{atmp} + \varphi_{flat} + \varphi_{temp} + \varphi_{noise} \quad (1)$$

In order to measure φ_{def} , the other effects of phase contribution have to be removed. To remove φ_{topo} , an SRTM DEM of 3 arc seconds was used. It was assumed that φ_{atmp} is negligible for this study, because of the dry and stable meteorological conditions in the area. The flat Earth phase (φ_{flat}) is compensated by using orbital information. Also, φ_{temp} , which represents temporal environmental changes, is negligible due to the arid environment of the study area. Finally, φ_{noise} is assumed to be small. A Goldstein filter was applied (Goldstein and Werner, 1998) to improve the quality of the interferogram. It is an adaptive filter that reduces the phase noises and preserves the local fringe rate in the interferogram. The filter significantly improves the fringe visibility in the decorrelated areas (Baran et al., 2003).

Phase unwrapping of the interferogram converts the 2π cyclic fringes into a continuous signal using a region growing algorithm (Costantini, 1998; Fornaro and Sansosti, 1999; Baldi, 2003). Phase unwrapping provided the surface displacements projected onto the radar LOS (line of sight). A coherence image, giving the measure of the stability of the phase, was produced as well. The unwrapped interferogram was geocoded using GCPs and SRTM DEM to have the map coordinates projected to UTM zone 40-North and datum WGS-84.

3A.2.2 Coseismic displacement map

The interferogram is of good quality (Figure 3A.2(a)) due to very dry conditions on the ground, relatively flat area and short baseline (Gonzalez et al., 2009). The cities of Bam and Baravat show major incoherent areas (Figure 3A.2(b)) in the main deformation site due to vegetation and the collapse of buildings.

The interferogram shows an asymmetric, 4-lobed pattern; the eastern lobes are larger in magnitude than those in the west (Figure 3A.2(a)). Fringes of the interferogram extend up to 28 km in the north-south and 16 km in east-west direction. Each colour cycle corresponds to 2.8 cm (half of the wavelength of C band of ASAR) along the LOS direction. Colour cycles of fringes are opposite (Figure 3A.2(a)) within the lobes of the interferogram. The south-eastern lobe shows maximum LOS positive displacement (i.e. towards the satellite sensor, indicating uplift) of about 30 cm (~ 11 fringes) whereas the north-eastern lobe shows a negative displacement (i.e. away from the satellite sensor, indicating subsidence) of 18.8 cm (~ 7 fringes). The two western lobes show smaller displacements, with ~ 7 cm negative displacement of the NW lobe and ~ 4 cm of positive displacement of the SW lobe. The opposite motion of lobes may be due to the strike variations in the seismogenic fault and the low angle between the fault strike and satellite orbital direction (Stramondo et al., 2005).

The location of the fault is marked where fringes of the interferogram are very close (Figure 3A.2 (a)). Closest fringes show the maximum gradient of the deformation. The fault location also shows low values on the coherence image (Figure 3A.2(b)). This fault lies 4 to 5 km west of the existing Bam fault and south of Bam city. The length of the fault is approximately 13 km and a fault strike is 170° ($\sim$ N-S trending) respectively.

The coherence of the interferogram is high (coherence value ≥ 0.7) for almost the entire area, except for the urban and vegetated areas (Figure 3A.2(a)). The fault rupture can also be marked on this coherence image although it is not visible on the ASTER image of post-earthquake (black rectangle in Figure 3A.3(a)), whereas Figure 3A.3(b) shows clearly the trace of surface rupture with left stepping south of the city of Bam.

A geocoded unwrapped interferogram produced the displacement map (Figure 3A.4). A coherence value of 0.25 was selected as a threshold to unwrap the interferogram. The low coherence areas are the cities of Bam and Baravat, vegetated areas and locations near the fault.

Figure 3A. 1: Results from InSAR; (a) The wrapped interferogram. (b) The coherence image gives coherence between two ASAR images ranging from high (1) to low (0) values. The location of the surface rupture of the fault is marked by the black rectangle. The red line shows the previously known Bam fault and the blue line is the earthquake causative fault with a possible fault extension (yellow line) inferred by InSAR measurements.

3A.2.3 Formation and description of the patches

The displacement map contained missing values. There were 290 polygons of missing values (Table 3A.1). Small neighbouring polygons of sizes up to 15 pixels were combined to form larger polygons in order to keep the number of polygons to a minimum. The groups of polygons were combined into patches. A criterion for a patch was defined as: (1) a group of missing values in a patch should either be contiguous or (2) the missing values within a patch should be within 1000 m. The boundaries of the patches were delineated manually in order to interpolate the missing values locally, while the size of the patch was kept small for the sake of convenience in the processing. Figure 3A.4(a) shows that gaps of these missing values are of different sizes. Some are large, e.g. those around the locations of Bam and Baravat.

Figure 3A. 2: Fault rupture; (a) Post earthquake ASTER image of Band 3, 1, 2 given RGB colour codes respectively, green shows vegetation which is concentrated mostly in the cities of Bam and the Baravat. (b) corresponds to black rectangle on the coherence image (Figure3A.2b). The fault rupture is clearly visible on the coherence image and it marked the location of earthquake causative fault. The ASTER image does not show (black rectangle) any indication of the fault rupture.

Table 3A. 1: Missing coseismic displacements gaps in the displacement map.

No. of polygons	No. of pixels	Area (m ²) range
175	1-15	625-9375
45	16-32	20000
29	33-75	46875
21	84-147	91875
17	177-956	597500
3	3243-57655	36034375
290	98520	61575000

3A.3 Methodology

Coseismic displacements are distributed spatially and represent continuous stochastic (random) phenomena and thus can be represented by a regionalized variable. The variogram is used to explore and model the spatial

structure of values of such a regionalized variable relating the dissimilarity of measurements as a function of spatial distance between them (Woodcock et al., 1988; Curran and Atkinson, 1998). Kriging uses the variogram to interpolate values at unobserved locations as a weighted sum of the observed neighbouring values, in such a way that the variance of the interpolation error is minimized.

Before actual interpolation of the missing values, kriging performance was evaluated by generating patches of artificial missing values at locations with known coseismic values. To demonstrate the superiority of kriging, the kriged interpolation results were compared with those obtained by inverse distance weighting (IDW). An accuracy assessment of interpolation results of actual missing coseismic values was carried out using validation and cross-validation.

3A.3.1 Geostatistical implementation

Geostatistical techniques are used widely and well explained in the literature. Hence, an extensive description is not provided here. The reader is referred to the books of Journel and Huijbregts (1978) and Cressie (1993) for details. Discussions of geostatistics in a remote sensing context are given by Woodcock et al. (1988), Curran and Atkinson (1998), Addink and Stein (1999) and van der Meer (2012).

To illustrate the assessment of interpolation accuracy, a small patch (the central part of patch 2) was selected first and repositioned at 11 different locations on the displacement map (Figure 3A.4(b)). For one of those, patch 2a, configurations of sample and validation points are shown in Figure 3A.5. Missing values were generated artificially in each patch identical to the original patch. The patches were investigated by their histograms, postplots and empirical variograms. Both ordinary kriging (OK) and universal kriging (UK) were used for interpolation of the missing values. For universal kriging a first order trend on location was modelled.

Next, patches 1, 5, 11 and 21 are investigated. Patch 5 and patch 21 are the largest patches with the highest number of missing values and fewest sampled points, whereas patch 1 and patch 11 lie at the gradients of fault lines. From the perspective of fault identification, these are the most important patches.

These four patches were shifted to new locations without missing values (Figure 3A.6). For each patch the same patterns of missing values were generated as of the respective original patch. OK and UK were compared for interpolating the missing values by validating their interpolations with the original values at each of these patches. All 23 patches with actual missing gaps were interpolated in a similar way.

Finally, for both OK and UK, a full image was produced by integrating the interpolated results with the known values of the displacement map.

Figure 3A. 3: Bam earthquake displacements (m) from the descending orbit images and missing values are shown in white colour. Displacement measurements (ranging - 0.18 to 0.3 m) are classified into 32 classes with class interval of 0.015 m. (a) The missing values were grouped to 23 patches for interpolation. (b) For accuracy assessment, the central part of patch 2 was shifted at 11 different locations.

Accuracy assessment

Error, e , is the difference between measured and interpolated values. Validation calculates these errors by evaluating the model using a separate dataset. In cross validation (CV) one sample point is removed and the model is estimated using the remaining data points. The removed sample point is

then interpolated using the estimated variogram model. Such differences between the actual and interpolated are calculated repeatedly for all sample points. This is called leave-one-out cross-validation (LOOCV). The validation and cross-validation results are summarized in the form of mean error ($ME = \frac{1}{n} \sum e_i$) and root mean square error ($RMSE = (\sum e_i^2 / n)^{1/2}$). ME is a measure of bias and should be close to zero. RMSE is a measure of accuracy and low values are preferred. CV was performed for each of the 23 patches (except for patch 5, 16 and 21), using both OK and UK. This process was computationally demanding and not feasible for the large patches (5, 16 and 21). The approach is discussed by Webster and Oliver (2008) and by Zhang et al. (2012).

In short, validation and cross-validation provide suitable ways to evaluate interpolation. The validation was performed for each of the 11 shifted patches (patch 2a, 2b,..., 2k), and the four selected patches (patch 1, 5, 11 and 21) at shifted locations on the displacement map. Cross-validation was carried out for both shifted as well as for actual patches.

3A.3.3 Coseismic displacements inversion modelling

Inversion of the coseismic displacements, based on the Okada model (Okada, 1985), was performed for the Bam earthquake. According to Okada, the fault plane exhibits shear dislocation in a uniform elastic Earth model. The InSAR data were inverted to derive the source parameters of the Bam earthquake and its slip distribution pattern on the fault plane (Atzori et al., 2009). The InSAR dataset has to be subsampled for performing the inversion. Both the original data and interpolated surface displacement data were subjected to inversion modelling, resulting in a modelled surface displacement map along with residuals for the both datasets. Based on these residuals the root mean square error (RMSE) was calculated to assess accuracy of the inversion modelling.

In order to calculate slip distribution on the fault plane, the earthquake causative fault was considered with its three fault segments. Each segment was subdivided in turn into 1 km × 1 km fault patches along the strike and dip directions. A least square linear inversion was applied to the surface coseismic displacements with and without interpolated values. The slip distribution models were developed using surface displacements from both datasets. The source seismic moment and source moment magnitude were calculated using the inversion results. For comparison, an image highlighting the differences between the slip distribution models of the two datasets was plotted. To compare the inversion results, the slip values at various depths were plotted along with their respective sigma values.

Figure 3A. 4: Samples and validation points of patch 2a (one of the 11 patches shifted to new locations). Displacement measurements (m) are grouped into three levels for calibration and validation points separately.

3A.4 Results

The results for the 11 shifted patches are given in section 3.5.1; for the 23 patches of actual missing values in section 3.5.2 and for the four selected patches in section 3.5.3. Interpolation results for both OK and UK of 23 patches were integrated and the full displacement map was generated for OK and UK. Results for the data inversion model are given in section 3.5.5.

Figure 3A. 5: Bam earthquake displacements (m) from the descending orbit images. Missing values are shown in white. Displacement measurements (ranging -0.18 to 0.3 m) are classified into 32 classes with class interval of 0.015 m. The four patches that were shifted to new locations having known values are shown.

3A.4.1 Eleven shifted patches

The variograms for the 11 patches are given in Table 3A.2 and Figure 3A.7 for both ordinary (OK) and universal kriging (UK). For OK, the structure of spatial dependency of the measurements was modelled by two variograms: Gaussian and power. For OK, the variogram shapes of all patches were similar and did not reach a finite sill, except for patch 2b. It indicates that the study area was smaller than the range of spatial dependency, or that the stationary mean assumption is not valid.

For UK, after removing the regional trend, the fitted residual variograms were Gaussian for 8 patches while the remaining 2 patches were spherical and one

(patch 2i) was exponential (Table 3A.2 and Figure 3A.7). They are all bounded variograms with a finite range and maximum variance (sill). In contrast to OK, the fitted variograms for all patches show a range below 500 m. All fitted variograms had a nugget approaching zero showing that variability is strongly correlated in space.

Missing values of the 11 patches were interpolated using OK and UK. The validation results (mean error (ME), root mean square error (RMSE) and correlation coefficient (R^2)) of the interpolated values are shown in Table 3A.3 for both OK and UK. IDW results for 5 selected patches (2a, 2c, 2d, 2g and 2i) are also shown in Table 3A.3. Both OK and UK are more accurate than IDW with lower ME and RMSE values for all 5 patches. The ME values of the 11 patches were approximately zero for both OK and UK. Patches 2a and 2d showed larger ME and RMSE values indicating less accurate interpolations than for the other patches. They lie on the geological fault where the values are heterogeneous.

RMSE values were smaller for UK than for OK except for patches 2b, 2c, 2j and 2k. The patches 2b and 2c do not show a clear trend and the RMSE values for OK and UK are similar. For 2j and 2k the RMSE for UK is clearly larger. This is because these patches show a complex pattern that is not modelled well by the linear trend. Because UK did not remove the trend properly for these latter patches, OK results are more accurate. The ME of all patches for both OK and UK was close to zero confirming the un-biasedness of kriging. The correlation between the interpolated and measured values was high (99%) for both OK and UK except for patches 2h and 2k.

Table 3A. 2: Variograms for OK and residual variograms for UK for Patch 2 at its original and shifted locations. The fitted variograms are shown graphically in Figure 3A.7.

Patches	Fitted Variogram (OK)					Fitted Residual Variogram (UK)				
	Model	Range	Sill	Nugget	SSE	Model	Range	Sill	Nugget	SSE
Patch 2 (original)	Power	1.9	7.8×10^{-11}	3.5×10^{-7}	8.1×10^{-5}	Exponential	322.18	1.4×10^{-6}	9.0×10^{-8}	1.2×10^{-5}
Patch 2a	Gaussian	4067.8	8.8×10^{-2}	1.2×10^{-5}	2.96	Gaussian	427.47	1.67×10^{-4}	4.17×10^{-7}	3.07×10^{-3}
Patch 2b	Gaussian	365.02	4.1×10^{-5}	2.8×10^{-7}	1×10^{-4}	Gaussian	326.24	3.6×10^{-5}	1.15×10^{-7}	1.63×10^{-3}
Patch 2c	Gaussian	958.91	4.25×10^{-4}	6.1×10^{-7}	1.9×10^{-3}	Gaussian	387.32	4.8×10^{-5}	2.1×10^{-7}	3.4×10^{-3}
Patch 2d	Gaussian	2733.81	1.28×10^{-2}	2.3×10^{-6}	2.7×10^{-1}	Gaussian	277.88	3.6×10^{-5}	1.2×10^{-6}	4.5×10^{-3}
Patch 2e	Gaussian	3403.19	3.7×10^{-3}	7.3×10^{-7}	4.8×10^{-3}	Gaussian	446.00	1.8×10^{-6}	1.7×10^{-7}	3.7×10^{-6}
Patch 2f	Gaussian	2798.1	2.9×10^{-3}	6.0×10^{-7}	1.8×10^{-3}	Gaussian	429.43	4.1×10^{-6}	1.9×10^{-7}	5.3×10^{-6}
Patch 2g	Gaussian	3931.39	1.7×10^{-3}	3.3×10^{-7}	1.2×10^{-3}	Spherical	385.76	5.7×10^{-7}	0	1.99×10^{-7}
Patch 2h	Power	1.5994	1.1×10^{-9}	1.4×10^{-7}	9.1×10^{-4}	Spherical	458.82	3.7×10^{-6}	0	2.3×10^{-5}
Patch 2i	Power	1.8960	1.3×10^{-10}	1.6×10^{-7}	6.9×10^{-5}	Exponential	374.72	8.1×10^{-7}	3.2×10^{-8}	6.7×10^{-7}
Patch 2j	Power	1.5322	2.6×10^{-9}	0	3.4×10^{-4}	Gaussian	252.48	1.4×10^{-5}	1.7×10^{-7}	9.2×10^{-4}
Patch 2k	Power	1.16	2.4×10^{-9}	1.1×10^{-7}	3.2×10^{-5}	Gaussian	142	1.5×10^{-6}	1.1×10^{-7}	6.7×10^{-6}

Table 3A. 3: Interpolation results of 11 patches using OK and UK. The variogram models were power (Pow), Gaussian (Gau), pentaspherical (Pen), circular (Cir) and exponential (Exp). Inverse distance weighting squared (IDW) was applied to 5 selected patches for comparison.

Patches	OK Prediction					UK Prediction					IDW Prediction				
	Vario gram	ME	RMSE	R ²	Vario gram	ME	RMSE	R ²	ME	RMSE	ME	RMSE	R ²	ME	R ²
P2a	Pow	-1.336×10 ⁻³	0.00311152	0.9955	Gau	-9.334×10 ⁻⁵	0.0007352	0.9996	-2.691×10 ⁻³	0.0054276			0.9807		
P2b	Gau	-7.869×10 ⁻⁵	0.0003626	0.9943	Gau	-2.905×10 ⁻⁵	0.0003681	0.9938							
P2c	Gau	-6.674×10 ⁻⁵	0.0004894	0.9970	Gau	-1.718×10 ⁻⁴	0.0005058	0.9971	3.295×10 ⁻⁴	0.0017532			0.9678		
P2d	Gau	2.747×10 ⁻⁴	0.0043582	0.9629	Gau	-7.247×10 ⁻⁵	0.0014790	0.9954	7.546×10 ⁻⁴	0.0054595			0.9530		
P2e	Gau	2.052×10 ⁻⁴	0.0005283	0.9974	Gau	-3.701×10 ⁻⁵	0.0004463	0.9976							
P2f	Gau	-4.922×10 ⁻⁵	0.0005477	0.9968	Gau	-1.477×10 ⁻⁵	0.0005346	0.9969							
P2g	Gau	-8.216×10 ⁻⁵	0.0006266	0.9865	Sph	1.415×10 ⁻⁵	0.0003125	0.9966	-1.159×10 ⁻⁴	0.0008458			0.9781		
P2h	Pow	-6.833×10 ⁻⁵	0.0008537	0.9687	Sph	3.726×10 ⁻⁶	0.0008505	0.9687							
P2i	Pow	-9.831×10 ⁻⁵	0.0004083	0.9908	Exp	-8.351×10 ⁻⁵	0.0003843	0.9918	-7.643×10 ⁻⁴	0.0006822			0.9755		
P2j	Pow	2.301×10 ⁻⁴	0.0006069	0.9909	Gau	9.057×10 ⁻⁵	0.0009635	0.9736							
P2k	Pow	2.272×10 ⁻⁴	0.0005491	0.9547	Gau	2.659×10 ⁻⁴	0.0006126	0.9467

Figure 3A. 6: Fitted variograms for OK and residual variograms for UK for patch 2 at its original and shifted locations. Variogram names and their parameters are given in Table 3A.2.

Cross-validation (CV) results for all patches for OK and UK are given in Table 3A.4. The mean error (ME) is approximately zero for both OK and UK cross-validation for each patch. RMSE values are also low, showing a maximum value of 2.7 mm in case of OK and 1.1 mm for UK. The results for UK cross validation are more accurate than those for OK with a lower RMSE value for all patches. The ME and RMSE values for CV results are lower than the validation results.

Table 3A. 4: Mean error (ME) and root mean square error (RMSE) from cross validation by ordinary kriging (OK) and universal kriging (UK) for original patch and eleven shifted patches. The unit of measurement for these statistics is meter (m).

Patches	CV (OK)		CV (UK)	
	ME	RMSE	ME	RMSE
P2_Original	1.23×10^{-7}	0.000500	3.59×10^{-8}	0.000279
P2a	-8.84×10^{-7}	0.002679	1.57×10^{-7}	0.000621
P2b	-1.99×10^{-7}	0.000402	-2.19×10^{-7}	0.000401
P2c	-9.21×10^{-8}	0.000481	-2.53×10^{-7}	0.000447
P2d	6.19×10^{-7}	0.002718	3.15×10^{-7}	0.001167
P2e	9.07×10^{-9}	0.000479	-8.26×10^{-8}	0.000317
P2f	8.34×10^{-8}	0.000551	7.49×10^{-8}	0.000503
P2g	3.28×10^{-8}	0.000543	3.24×10^{-7}	0.000145
P2h	2.67×10^{-8}	0.001150	-1.29×10^{-7}	0.000269
P2i	-2.37×10^{-8}	0.000481	-1.72×10^{-7}	0.000212
P2j	-2.72×10^{-8}	0.000822	2.26×10^{-7}	0.000535
P2k	-3.32×10^{-7}	0.000255	-4.00×10^{-7}	0.000178

3A.4.2 Twenty-three actual patches

The variograms for both OK and UK for all 23 patches are shown in Table 3A.5. All patches, except two, showed spatial dependence modelled by the Gaussian or power variograms for OK. The shape of the sample variograms indicates the presence of a trend. UK variograms, after removing the trend, were fitted by Gaussian models for 11 patches, exponential models for 6 patches, spherical models for 3 patches and 1 patch (patch 14) was best-fitted by a power model. Patch 1 and 11 lie on the geological fault, whereas patches 5 and 21 have a high percentage of missing values and a small sample size (Table 3A.5).

Table 3A. 5: Patch information (total points, samples and percentage missing) for each of 23 patches. Variogram models are also provided.

Patches	Total	Sample Size	Missing %	Variogram fitted (OK)	Variogram fitted (UK)
Patch 1	6952	5182	25%	Penta-spherical	Gaussian
Patch 2	3473	2780	20%	Power	Exponential
Patch 3	2024	1021	50%	Power	Exponential
Patch 4	774	665	14%	Power	Exponential
Patch 5	45431	18817	59%	Power	Gaussian
Patch 6	1184	927	22%	Gaussian	Exponential
Patch 7	256	156	39%	Gaussian	Gaussian
Patch 8	63	58	8%	Power	Gaussian
Patch 9	5970	5388	10%	Power	Exponential
Patch 10	601	554	8%	Gaussian	Gaussian
Patch 11	2551	1899	26%	Power	Gaussian
Patch 12	30	26	13%	Gaussian	Spherical
Patch 13	416	296	29%	Gaussian	Spherical
Patch 14	571	470	18%	Power	Power
Patch 15	5009	3852	23%	Power	Spherical
Patch 16	14570	9541	35%	Gaussian	Gaussian
Patch 17	4023	3355	17%	Power	Exponential
Patch 18	1096	947	14%	Power	Gaussian
Patch 19	5118	4938	4%	Power	Gaussian
Patch 20	450	428	5%	Power	Gaussian
Patch 21	81121	22012	73%	Gaussian	Gaussian
Patch 22	793	654	18%	Gaussian	Gaussian
Patch 23	258	248	4%	Exponential	Gaussian

The accuracy of the interpolation results of the actual 23 patches was assessed by cross-validation (except for patch 5, 16 and 21 due to their large size). For accuracy assessment of the kriged values for the 23 patches, cross-validation (using OK and UK) results of all patches are given in Table 3A.6. The ME values, obtained for OK and UK cross-validation, were close to zero for all patches. The RMSE values for OK and UK cross-validation were small, giving more than millimeter accuracy except for patches 1 and 11.

These patches show larger RMSE values as they are located on the geological fault. For these two patches, OK is more accurate than UK. This may be due to improper modelling of their variograms by the linear trend.

3A.4.3 Four selected patches

The variogram models for the four selected patches (1, 5, 11 and 21) are given in Table 3A.7 and Figure 3A.8. All four patches, at both the original and shifted locations, had spatial correlation modelled by Gaussian and power variograms, with the exception of patch 1 at its original location.

The variograms of patch 1 and 11, calculated for both OK and UK, were substantially different at the original and shifted locations, while patch 5 and 21 showed similar variograms (Table 3A.6). This might be due to the heterogeneous nature of the measurements along the geological fault, as shifting patch 1 and 11 changed the variogram models substantially, in contrast to patch 5 and 21. The variograms show that values are spatially correlated and most of the variograms do not reach a finite sill suggesting that the range of spatial dependence was beyond the patch area.

Accuracy assessment results for the four selected patches shifted to new locations (patch 1, 5, 11 and 21) are given in Table 3A.8. The ME values were close to zero and RMSE values showed that the bias and accuracy were at the millimeter scale. The coefficient of correlation of actual and interpolated values was also high for all 4 patches. Patches 1 and 11 UK gave more accurate results than those given at their original location, highlighting the effect of the geological fault. For patch 5, OK and UK results were similar while for patch 21 UK was more accurate.

Table 3A. 6: Cross validation of 23 patches by OK and UK using their samples. Cross-validation could not be performed for patch 5, 16 and 21 due to the large sample size. Patches 5, 16 and 21 were too large for cross-validation to be feasible.

Patches	Cross-Validation (OK)		Cross-Validation (UK)	
	Mean Error	RMSE	Mean Error	RMSE
Patch 1	1.23×10^{-6}	0.00163	-1.14×10^{-6}	0.00209
Patch 2	2.24×10^{-7}	0.00072	-3.21×10^{-7}	0.00031
Patch 3	-2.07×10^{-6}	0.00049	-4.00×10^{-6}	0.00036
Patch 4	4.32×10^{-7}	0.00081	-1.67×10^{-6}	0.00037
Patch 5	NA	NA	NA	NA
Patch 6	-1.98×10^{-7}	0.00058	-1.14×10^{-8}	0.00022
Patch 7	-7.77×10^{-6}	0.00050	-3.57×10^{-6}	0.00037
Patch 8	-1.10×10^{-5}	0.00030	-1.70×10^{-6}	0.00027
Patch 9	-2.38×10^{-8}	0.00316	-1.05×10^{-6}	0.00061
Patch 10	2.31×10^{-6}	0.00038	-1.63×10^{-6}	0.00031
Patch 11	3.92×10^{-8}	0.00063	4.68×10^{-7}	0.00113
Patch 12	2.52×10^{-5}	0.00092	-3.00×10^{-6}	0.00089
Patch 13	-9.72×10^{-7}	0.00084	-1.11×10^{-7}	0.00041
Patch 14	2.15×10^{-6}	0.00059	9.86×10^{-7}	0.00031
Patch 15	5.11×10^{-7}	0.00135	3.09×10^{-7}	0.00031
Patch 16	NA	NA	NA	NA
Patch 17	-7.66×10^{-8}	0.00153	-4.06×10^{-7}	0.00035
Patch 18	-9.20×10^{-7}	0.00050	-2.22×10^{-6}	0.00049
Patch 19	3.50×10^{-7}	0.00039	-2.76×10^{-8}	0.00036
Patch 20	-5.31×10^{-7}	0.00026	2.18×10^{-6}	0.00026
Patch 21	NA	NA	NA	NA
Patch 22	4.44×10^{-6}	0.00050	-2.42×10^{-6}	0.00049
Patch 23	-1.84×10^{-6}	0.00028	-1.63×10^{-7}	0.00027

Table 3A. 7: Variograms for OK and residual variograms for UK for four patches at key locations. The fitted variograms are shown graphically in Figure 3A.8.

Patches	Fitted Variogram (OK)					Fitted Residual Variogram (UK)				
	Model	Range	Sill	Nugget	SSE	Model	Range	Sill	Nugget	SSE
Patch 1 (Original)	Penta-spherical	1308	1.3×10^6	0	29	Gaussian	302	6.3×10^4	1.9×10^6	12.5
Patch 1 (Shifted)	Gaussian	11235	1.4×10^6	1.4×10^6	9.61	Power	1.7	2.6×10^9	0	8.2×10^2
Patch 5 (Original)	Power	1.99	3.5×10^{10}	1.8×10^6	1.14	Gaussian	2331	4.72×10^4	2.8×10^6	0.218
Patch 5 (Shifted)	Power	1.191	1×10^7	0	9.1	Gaussian	1341	1.03×10^6	2.5×10^6	15.25
Patch 11 (Original)	Gaussian	564	6.3×10^4	0	3.19	Gaussian	234	9×10^5	2.0×10^6	0.16
Patch 11 (Shifted)	Power	1.3	9.2×10^9	0	7×10^4	Power	1.1	1.8×10^6	0	5.2×10^4
Patch 21 (Original)	Gaussian	25230.27	2.2×10^1	3.2×10^5	128.55	Gaussian	2352.22	1.7×10^6	1.6×10^6	5.13
Patch 21 (Shifted)	Gaussian	14734.52	1.4×10^6	6.9×10^7	57.67	Gaussian	2147.2	4.0×10^3	0	157.48

Figure 3A. 7: Fitted variograms for OK and residual variograms for UK for four patches at key locations. Variogram names and their parameters are given in Table 3A.7.

Table 3A. 8: Comparison of interpolation results of four patches (patch 1, 5, 11 and 21) for both OK and UK.

	OK Prediction			UK Prediction		
	Mean Error	RMSE	R ²	Mean Error	RMSE	R ²
Patch 1	-0.00083	0.0050	0.99	0.00005	0.0008	0.99
Patch 5	0.00010	0.0007	0.99	0.00013	0.0007	0.99
Patch 11	0.00022	0.0010	0.96	0.00021	0.0010	0.96
Patch 21	0.00491	0.0168	0.98	-0.00039	0.0034	0.99

3A.4.4 The displacement map

The displacement maps constructed after combining the interpolation results of the 23 patches for both kriging approaches are shown in Figure 3A.9. The results for OK and UK were slightly different in terms of preserving the pattern of the displacement map. The UK results were relatively smooth, whereas the OK interpolated displacement map shows some noise.

Figure 3A. 8: Coseismic displacement (m) map obtained by integrating the interpolation results of 23 patches for ordinary kriging (a) and universal kriging (b). Displacement measurements (ranging -0.18 to 0.3 m) are classified into 32 classes with class interval of 0.015 m.

3A.4.5 Data inversion modelling results

The InSAR data inversion modelling results for both original and interpolated datasets are shown in Figure 3A.10. The modelled maps (Figure 3A.10(a) and (c)) show a slight underestimation of the measurements as compared to the observed displacement maps (Figure 3A.6 and 9(a)). This can also be verified from their respective residual maps (Figure 3A.10 (b) and (d)). The residual maps of both the original and interpolated datasets were approximately similar with maximum values of 9 cm and 8.3 cm respectively. The RMSE acquired from the interpolated dataset was slightly lower than the RMSE calculated using original dataset (Table 3A.9).

Table 3A. 9: Inversion results for both original and interpolated datasets.

	Max. Residual value	Prediction error	RMSE	Seismic Moment	Moment magnitude (M_w)
Original	9 cm	2.81 cm ²	2.68 cm	7.65×10^{18} N m	6.5
Interpolated	8.3 cm	2.69 cm ²	1.64 cm	7.39×10^{18} N m	6.5

The estimated slip distribution obtained from the inversion modelling on the earthquake causative fault is shown in Figure 3A.11. Most of the slip is on the major fault segment in the south of the Bam city, whereas the middle and northern segment show little slip for both datasets. The maximum slip is 3.16 m for the original data and 3.13 m for interpolated data are reached at a depth of 3000 m. The major gap of missing coseismic values was present at the location of Bam city that contains the northern part of the first fault segment and the whole middle segment. The difference map (Figure 3A.11 (c)) shows that major changes in the slip distribution occurred at locations where most of the interpolated coseismic values occur.

Figure 3A. 9: Displacement map resulted from the inversion of the surface coseismic values (m) using both the original dataset [(a) modelled and (b) residuals] and interpolated datasets [(c) modelled and (d) residuals].

Figure 3A. 10: Slip distribution model on the fault plane using (a) original, (b) interpolated datasets. Maximum slips equal to 3.16 m for the original data and to 3.13 m for interpolated data are reached at a depth of 3000 m. The difference of two slip distribution models is given in (c)

A comparison of the slip values for both datasets plotted at selected depths along with their respective sigma values is shown in Figure 3A.12. Apart from the shaded regions, the slip values for both datasets were similar up to 4000 m depth (Figure 3A.12(a) and (b)). The shaded region defines the location that contains the interpolated coseismic displacements. It is clear from the Figure 3A.12, that slip and sigma values for the original and the interpolated show significant differences in the shaded region. The sigma values of the original dataset are higher as compared to the interpolated dataset (shaded region in Figure 3A.12 (c) and (d)). This demonstrates that slip distribution model for the interpolated dataset has a lower sigma value and hence is more accurate than the model using the original data. The seismic moment predicted using the inversion procedure was almost equal for both datasets and it is also in agreement with previous studies (Jonsson et al., 2004; Fialko et al., 2005).

Figure 3A. 11: The line plots at the left column [i.e. (a) and (b)] are the slip values at selected depths. The plots in the right column [i.e. (c) and (d)] represent their respective sigma values. The dash line is for original dataset whereas the solid line is for interpolated dataset. The most of the interpolated values lies in the grey region.

3A.5 Discussion

This study has utilized geostatistics for interpolating missing values in an InSAR-derived displacement map. Empirical variograms were fitted well, particularly near the origin, by the available authorized models. Fitting accuracy near the origin is important because values interpolated by kriging are based on the local spatial dependence which is mostly reflected by the first few lags (Kleijnen and van Beers, 2005). The OK models for most of the patches did not reach a finite sill, indicating the presence of a trend (Webster and Oliver, 2008).

Variograms with small nugget values give more accurate interpolation results than those with larger nugget values (Karl, 2010). All variogram models, used for interpolating missing values in this study, had a nugget variance either equal to or approaching zero. This showed that the measurements were highly dependent on their neighbourhood values. In contrast to the nugget variance, the structured variance represents the auto-correlated part of the variability in the variogram model (Zhang et al., 2007). The variogram models for OK revealed the presence of a regional trend in the measurements. To make the data stationary the trend removal is necessary. This is implemented in the UK. After removing the trend, the range of the fitted residual variogram reduced, demonstrating the effect of the trend.

The quality of OK and UK was assessed by validating against actual values for shifted patches (1, 5, 11 and 21). The ME and RMSE values for all patches of artificially generated missing values were close to zero. Therefore kriging is an effective technique for interpolating the actual missing displacement values. Furthermore, OK and UK led to more accurate interpolation than IDW, demonstrating the utility of kriging for interpolating the missing coseismic values. Unlike IDW, kriging is based on an explicit model (the

variogram) for the spatial structure, the parameters of which are estimated from the data.

Next, OK and UK were used to interpolate the actual missing coseismic displacement values for all 23 patches. Interpolated values were more accurate for small and medium sized patches than for bigger patches with a lower sample size. The results of the four patches (i.e. patch 1, 5, 11 and 21) were less accurate than for the other patches. Patch 1 and 11 could not be modelled properly due to their location on the geological fault, which caused heterogeneity in the observations. The use of inaccurately fitting variogram models may produce inaccurate interpolation results (Kleijnen and van Beers, 2005). For the other two patches, the number of missing values was large and the spatial configuration of the sample points was also uneven i.e. most of them were located on the patches edges. The sample density with respect to the study area, their statistical distribution and spatial configuration affect the reliability of the empirical variogram (Lark, 2002; Zhu and Lin, 2010).

The integrated results in the lower half of the displacement image were similar for both OK and UK. There were some subtle differences however, in the upper half of the displacement image, in terms of following the specific pattern (concentric lobe) of the displacements. UK results deviated at some locations from the pattern of the displacements. The reason may be that in these locations the first-order trend was not an accurate model for the background process. This led to results that were less accurate (higher RMSE) than for OK, even though this assumes a constant trend within the local area. Finally, the reader may note that the analysis in this paper assumed isotropy in the spatial structure. This is a simplification of the real situation but, nevertheless, yielded accurate unbiased results, as shown in Table 3A.6. The nature and severity of the anisotropy varied between patches and a full exploration and analysis lies outside the scope of this paper. It is left as a topic for future research.

Kriging interpolated the missing coseismic values along the geological fault that are of importance for characterizing the earthquake causative fault. From the interpolated values of the patch north of the city of Bam, the fault apparently extends below the city. The obtained coseismic displacements may be used to calculate the fault parameters at the subsurface, which in turn would help to understand the fault behaviour during the earthquake. The present study focused on line-of-sight (LOS) displacements using the descending orbit ASAR images. LOS contains mainly the vertical component of the displacement.

Perski and Hanssen (2006) investigated the kinematics of Bam fault. According to Figure 5 in their paper second-order faults correspond to the patches (patch 9, 10, 18, 19, 22, 23) surrounding the northern fault segment (patch 11) in our study. While southern fault segment (patch 1) lacks such

second-order faults, due to the presence of thick alluvial deposits. The negative and positive flower structures mentioned in their study correspond to areas of subsidence and uplift respectively in the displacement map given in our study.

The comparison of inversion models demonstrated that slip model for the interpolated dataset was more accurate (i.e., low RMSE and sigma values) than the original dataset model. Although, the differences in both the slip maps were smaller due to various reasons: (1) in order to perform inversion, the datasets had to be substantially subsampled to avoid computational constraints (Atzori and Antonioli, 2011). In this study, both the coseismic displacements and the interpolated missing values were obtained at a 25 m grid, whereas the data were subsampled at a 200 m grid for running the inversion routine. As averaging of the displacements was carried out, this might affect the inversion results. (2) The Okada slip model assumes elastic dislocation in a homogeneous half-space. In reality, however, the Earth is neither elastic nor homogenous and faults do not consist of rectangular planes (Atzori and Antonioli, 2011).

The findings of the slip distribution pattern on the fault are in agreement with the previous studies on the Bam earthquake (Funning et al., 2005; Peyret et al., 2007). The maximum slip generated in the current study, however, is approximately 0.5 m higher than the previous studies. The reason may be that an inverse solution is never unique and different slip configurations will provide nearly the same surface displacements. In the inversion modelling, the setting of different parameters like damping and roughness can change the results at the expense of the obtained RMSE values. Therefore, there is always trade-off between the model smoothness and accuracy for each fault patch.

3A.6 Conclusions

Both OK and UK are useful for interpolating coseismic displacements for missing pixels. The measurements are spatially auto-correlated and show a highly continuous process except at the fault location. Variograms prepared for OK indicated the presence of a trend and thus justified the use of UK. The results of UK were more accurate than OK based on the comparison of ME and RMSE values. Furthermore, kriging gave more accurate interpolations than IDW and allowed insight into the spatial variation of the displacements.

The coseismic displacement map prepared after integrating interpolation results for each kriging approach of the 23 patches showed, in general, that the interpolated values follow the natural pattern of the displacements. The interpolation results of the patches that are either large in size with a low sample size or located on the geological fault, are less accurate.

The validation and cross-validation results showed accurate estimates of the coseismic displacements. Therefore, the study demonstrated that kriging serves as a powerful tool to interpolate the missing values accurately.

The InSAR data inversion using interpolated dataset resulted into a more accurate slip distribution model as compared to the model obtained using the non-interpolated dataset.

Part B: LOS Displacements from ASAR images from the Ascending orbit

Abstract

Coseismic displacements help in characterizing the earthquake causative fault and understanding earthquake dynamics. These are measured, typically, by comparing pre- and post-earthquake radar images using the InSAR technique. A displacement map thus obtained, however, may contain missing values due to lack of coherence of the individual radar images. This study focuses on interpolating these missing values in the coseismic displacement map obtained for the 2003 Bam earthquake using ordinary kriging (OK) and universal kriging (UK). The gaps of missing values were grouped into 26 patches. The Gaussian and power variogram models were fitted to empirical variograms of most of the patches. For both OK and UK, 4 out of 26 patches showed less accurate results. These four patches were either very large in size with a small sample size, or they were located on the geological fault where measurements were heterogeneous. Evaluation was done by taking 5 patches with artificially generated missing values at different locations of known values on the displacement map. Validation and cross-validation results of these patches were found, ME (-2×10^{-7} – 3.3×10^{-7}), RMSE (2.2×10^{-4} – 7.8×10^{-4}) almost equal to zero and high R^2 values (0.88 – 0.99). Accuracy assessment results for 26 patches were also found to be satisfactory with lower kriging variances and, lower cross-validation ME values and lower RMSE values close to zero. It was concluded that kriging serves as an effective tool for predicting the missing coseismic displacements.

Keywords: Coseismic displacements; InSAR; Kriging

3B.1 Introduction

Coseismic displacements play a key role in understanding the mechanism of earthquake sources (van Puymbroeck et al., 2000). Earthquake causative fault characterization and modelling depends on accurate measurements of these coseismic displacements. Coseismic displacements can be measured in the field using different instruments, or using remote sensing data. Field methods can provide accurate measurements but are time consuming and laborious (Kaneda et al., 2008). Remote sensing data and methods are fully capable of measuring coseismic displacements (Avouac et al., 2006).

Synthetic aperture radar interferometry (InSAR) is a well-known technique for measuring coseismic displacements using remote sensing data. InSAR, however, cannot measure coseismic displacements near the earthquake causative fault due to loss of coherence between the images at such locations (Fialko et al., 2005; Funning et al., 2005). Therefore, InSAR- derived coseismic displacement maps exhibit missing values at those locations. Prediction of missing values along the earthquake causative fault is of prime importance for fault characterization.

The objective of this study is to predict the missing coseismic displacements by applying the geostatistical method kriging. Accuracy of the prediction was evaluated by validation and cross-validation. Coseismic displacements were interpolated for the 2003 Bam earthquake. Prediction of missing values due to the loss of coherency between the SAR images, for an earthquake hit area, is not carried out previously.

3B.2 Methodology

Present study deals with 2003 Bam earthquake, the study area details are provided in chapter 1, section 1.2. For calculating coseismic displacements a pair of pre- and post-earthquake images from ENVISAT ASAR ascending orbit was selected. The images do not cover the full study area- the lower left part is missing (Figure 3B.1). Interferogram was generated by measuring the phase difference of two SAR images in the form of fringes. A phase unwrapping of the interferogram was done using region growing algorithm which converted the 2π cyclic fringes into a continuous displacement map.

Figure 3B. 1: Ascending orbit interferogram; (a) Wrapped interferogram and (b) Coherence image. Red line shows previously known Bam fault and blue line is the earthquake causative fault inferred by InSAR measurements. Inset shows location of Bam in south-east of Iran. Blue box is the footprint of ASAR images from ascending orbit.

The displacement map (Figure 3B.2) contained missing values due to the loss of radar signal coherence. There were 265 gaps (polygons of different sizes) constituting missing coseismic values (Table 3B.1). A patch was defined as a group of contiguous or nearby missing values surrounded by a sufficient number of known values. There were 26 patches made for predicting missing values.

Table 3B. 1: Missing coseismic displacements gaps in the displacement map

Category	Polygons	Pixels	Area (m ²)_upto
1	160	1-15	9375
2	44	16-32	20000
3	36	33-75	46875
4	12	84-132	82500
5	10	165-2372	1482500
6	3	>2375	
Total	265		

Coseismic displacements are an example of continuously varying random field, which can be explained by regionalized variable theory (Journel and Huijbregts, 1978). The variogram is a geostatistical tool to explore and model the spatial structure of the values of such a regionalized variable. It relates the dissimilarity of measurements as a function of spatial distance between them (Woodcock et al., 1988) given by equation 1

$$\hat{\gamma}(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [z(u_i) - z(u_i + h)]^2 \quad (1)$$

where $\hat{\gamma}(h)$ is the variogram, spatially separated by distance h , based on $m(h)$ pixel pairs at a distance approximately equal to h . $z(u_i)$ is value of the variable at location ' u_i ' and $z(u_i + h)$ value at location ' $u_i + h$ '.

Kriging uses the variogram to interpolate missing coseismic values by assigning weights to the observed neighbouring values in such a way that the variance is minimum (Curran and Atkinson, 1998; Addink and Stein, 1999).

$$\hat{z}(u_0) = \sum_{i=1}^n \lambda_i z(u_i) \quad (2)$$

The prediction of missing displacement value at location u_0 , is calculated from a linear combination of known neighbouring displacement observations at locations ' u_i ' by assigning the n number of weights λ_i which sum to unity.

Before interpolation of the actual missing coseismic values, the procedure was evaluated by generating artificial patches of missing values at locations of known coseismic values. A small patch was selected and repositioned at 5 different locations on the displacement map (Figure 3B.2). A pattern of missing values, same as in the original patch, was generated within each patch. Each shifted patch was then examined using its histogram, postplot and empirical variogram. The variograms were modelled by applying available authorized models to describe the spatial dependencies of values in each patch. Both ordinary kriging (OK) and universal kriging (UK) were used to interpolate the missing values. The accuracy assessment was performed by validating the results with the existing values of the patches.

All 26 patches with actual missing gaps were interpolated in a similar way as described above. Finally, accuracy assessment of interpolation results of actual missing coseismic values was carried out by cross-validation. After comparison, the results for the 26 patches were combined and a displacement map for each kriging approach was produced.

3B.3 Results and discussion

InSAR resulted in an interferogram of good quality (Figure 3B.1(a)) due to dry and flat area and short baseline (Gonzalez et al., 2009). The fringe pattern of the interferogram showed the displacements related to the Bam earthquake and location of the fault. Figure 3B.1(b) showed coherence of two radar images. The coherency, value ranges from 0 to 1 corresponding with lowest to highest, is visually good except at the urban and vegetated areas. Figure 3B.2 shows coseismic displacement map produced by unwrapping of the interferogram.

Figure 3B. 2: Bam earthquake displacements from ascending orbit images with 26 patches (black) of missing values and validation patches (red).

For interpolation of missing values of the five shifted patches, variogram models for each patch were prepared. For ordinary kriging (OK), the structure of spatial dependence of the measurements was represented by two types of variograms; Gaussian and power. The variograms showed parabolic behaviour near the origin, depicting a highly continuous process and presence of a regional trend (Webster and Oliver, 2008). Variogram model for patch-a for both OK and UK is shown in Figure 3B.3. For universal kriging (UK), after removing regional trend (drift), fitted residual variograms were again Gaussian and power, except for patch-a which was exponential.

Figure 3B. 3: Variogram models; model for ordinary kriging (a) and residual variogram for universal kriging (b) of patch-a one of five shifted patches

The missing values of these 5 patches were predicted using OK and UK. The results for both were similar for almost all of the patches. The accuracy assessment of the results was done by validating the results with true values at shifted locations. The cross-validation of these patches was also performed.

Validation results- ME and RMSE of the 5 patches were approximately zero for both OK and UK showed reasonable approximation of predicted to real observations (Table 3B.2). Patch-b has higher ME for OK, whereas patch-e shows higher ME for UK (Figure 3B.4). Correlation coefficient R^2 was also less for these two patches. The patch-b and patch-e have relatively higher errors due to their location near the geological fault.

Cross-validation (CV) for the 5 patches, the ME and RMSE were also almost zero, showing good accuracy of results. For CV, patch-b and patch-e again showed relatively higher values of the ME and RMSE. The interpolation of missing values and validation showed successful evaluation of kriging interpolation. Therefore kriging could be implemented with enough confidence for predicting missing values of all 26 patches.

Table 3B. 2: Validation results of the 5 shifted patches using ordinary kriging and universal kriging

Patches	OK Prediction			UK Prediction		
	ME	RMSE	R-sq	ME	RMSE	R-sq
Patch-a	-5.90×10^{-5}	0.000446	0.928	-8.09×10^{-5}	0.000407	0.942
Patch-b	1.3×10^{-4}	0.000946	0.998	-4.34×10^{-5}	0.000917	0.998
Patch-c	8.19×10^{-6}	0.000445	0.987	-7.51×10^{-5}	0.000236	0.997
Patch-d	6.49×10^{-5}	0.004988	0.996	2.32×10^{-5}	0.000306	0.997
Patch-e	-6.44×10^{-5}	0.000668	0.928	-2.3×10^{-4}	0.000903	0.885

Interpolation results, obtained by applying both OK and UK, are shown in Table 3B.3. For OK the spatial dependence of 19 out of 26 patches was represented by the Gaussian model, 3 variogram models by the power model and the remaining 4 are represented by pentaspherical model. Shape of the fitted models showed an evidence of regional trend. Variogram models for UK, after removing the regional trend, were mostly Gaussian. The kriging variances of 14 patches were smaller for OK, whereas 12 patches had smaller values for UK.

Patches 1, 5, 11 and 21, showed higher mean kriging variances both for OK and UK than the other patches. These were the patches which either lay on the geological fault (patches 1, 11) or their sizes were very large (patches 5, 21) with high percentage of missing values and with a small sample size (Table 3B.3). Variogram models for these four patches were relatively less accurately modelled, example is shown in Figure 3B.5 for patch 21. The reliability of empirical variogram depends upon samples density, distribution and spatial configuration in study area (Lark, 2002). Variogram models for Patch1 and 11 could not properly model because of their heterogeneous observations. Whereas for patches 5 and 21 models were less accurate due to large number of missing values and uneven spatial distribution. Therefore prediction results were also less accurate for these patches due to less accurately modelled variograms.

Figure 3B. 4: Comparison of mean error (ME) and root mean square error (RMSE) of both ordinary kriging (OK) and universal kriging (UK) for the five shifted patches

The quality of interpolation results of 26 patches was assessed from their respective kriging variance and cross-validation using their sample points (Table 3B.4). Based on kriging variance, the OK results for 14 patches were accurate with less kriging variance, whereas for other 12, UK gave low kriging variances. Based on kriging variance, patch 5 interpolation result was better than that of patch 21 because patch 5 had less number of missing values as compared to patch 21. Patch 5 sample configuration and distribution was also more even than patch 21.

The cross-validation results- ME and RMSE for all patches were close to zero (Table 3B.3). Patches 9, 10, 13, 14, 23, 24 and 25 show relatively higher ME, which may be due to their small size with fewer samples or location on the fault. Patches 1, 9, 10, 19 and 23 have relatively higher RMSE values as these patches were located on or near the geological fault or their sizes were very small.

Figure 3B. 5: Variogram model for ordinary kriging (a) and residual variogram for universal kriging (b) of patch 21

The displacement maps were constructed after combining the results of the 26 patches for both kriging approaches. The displacement maps for OK and UK were similar. OK Map showed (Figure 3B.6) better preservation of natural pattern of the coseismic displacements than UK, whereas UK map was smoother.

The study demonstrated that kriging predicted the missing coseismic values with confidence. Kriging is a well-established technique supported by sound theoretical background. Non-availability of validation dataset for this study was compensated by carrying out an evaluation process.

Table 3B. 3: Results of interpolation for 26 patches using ordinary kriging (OK), universal kriging (UK) and cross-validation (CV). Cross-validation could not be performed for patch 5, 16 and 21 due to their large number of sample values (computationally- prohibitive)

Patches	Total	Samples	% Missing	Variogram Fitted (OK)	Variogram Fitted (UK)	Cross-Validation	
						Mean Error	RMSE
Patch 1	4642	3139	32%	Gaussian	Gaussian	3.34×10^{-8}	0.00364
Patch 2	4244	3427	19%	Gaussian	Pentaspheical	2.68×10^{-8}	0.00066
Patch 3	1542	866	44%	Spherical	Pentaspheical	-4.83×10^{-7}	0.00042
Patch 4	63	50	21%	Gaussian	Gaussian	-8.24×10^{-7}	0.00029
Patch 5	46343	19846	57%	Power	Power		
Patch 6	1184	976	18%	Gaussian	Pentaspheical	-2.85×10^{-7}	0.00024
Patch 7	255	176	31%	Pentaspheical	Pentaspheical	1.09×10^{-7}	0.00025
Patch 8	95	83	13%	Gaussian	Gaussian	-4.51×10^{-7}	0.00039
Patch 9	5218	4863	7%	Pentaspheical	Pentaspheical	1.37×10^{-6}	0.00182
Patch 10	158	139	12%	Gaussian	Gaussian	2.72×10^{-6}	0.00156
Patch 11	3412	2744	20%	Gaussian	Gaussian	3.27×10^{-7}	0.00137
Patch 12	286	260	9%	Pentaspheical	Pentaspheical	6.03×10^{-7}	0.00029
Patch 13	411	287	30%	Gaussian	Gaussian	-3.53×10^{-6}	0.00040
Patch 14	874	790	10%	Power	Gaussian	2.36×10^{-6}	0.00040
Patch 15	4022	3238	19%	Gaussian	Gaussian	-3.85×10^{-9}	0.00093
Patch 16	9089	6103	33%	Power	Spherical		
Patch 17	3533	3011	15%	Gaussian	Exponent	-3.54×10^{-7}	0.00137
Patch 18	3198	2906	9%	Pentaspheical	Pentaspheical	-2.28×10^{-6}	0.00125
Patch 19	2338	2105	10%	Gaussian	Gaussian	-5.94×10^{-7}	0.00244
Patch 20	131	128	2%	Gaussian	Gaussian	-5.62×10^{-8}	0.00014
Patch 21	67718	22703	66%	Gaussian	Gaussian		
Patch 22	985	802	19%	Gaussian	Gaussian	-7.42×10^{-7}	0.00028
Patch 23	55	39	29%	Gaussian	Gaussian	-4.62×10^{-6}	0.00307
Patch 24	40	38	5%	Gaussian	Gaussian	3.09×10^{-6}	0.00022
Patch 25	133	124	7%	Gaussian	Gaussian	-3.95×10^{-6}	0.00046
Patch 26	787	459	42%	Gaussian	Gaussian	-3.63×10^{-7}	0.00042

Figure 3B. 6: Interpolation results generated by integrating 26 patches for OK

3B.4 Conclusions

- This study concludes that for interpolation of missing coseismic values ordinary and universal kriging techniques can be used. Results interpolated by these were satisfactory based on their validation and cross-validation.
- Variogram models for ordinary kriging revealed a trend in the observations and thus rationalize the use of universal kriging.
- The interpolation results of the patches that are either large in size with fewer sample size or located on the earthquake causative geological fault, were comparatively less accurate than other patches.

Chapter 4: Applying pixel tracking for horizontal coseismic displacements and anisotropic kriging to interpolate the missing displacement values

This chapter has two parts, A and B; each of which has been written as an independent case study. Part-A describes all the theory and methodology for descending orbit image pair. This part has been published in a peer-reviewed ISI journal*. Part-B is mainly a replication of the work in part-A but applies to the ascending orbit image pair. There is some repetition of text in part-B so that the reader does not have to look back and forth to part-A for reference.

* **Yaseen, M.**, Hamm, N.A.S., Tolpekin, V., Stein, A., 2013. "Anisotropic kriging to derive missing coseismic displacement values obtained from synthetic aperture radar images" Journal of Applied Remote Sensing 7.

Part A: Horizontal Displacements from ASAR images from the Descending orbit

Abstract

Coseismic displacements play a vital role in the characterization of geological faults and understanding earthquake dynamics. This study demonstrates the utility of anisotropic geostatistics to interpolate their missing values. These were due to non-coherence of pre- and post-earthquake ASAR images obtained from the earthquake affected area around the city of Bam in Iran. A spherical function was used for modelling the variograms. Directional variograms revealed geometric and zonal anisotropy. The geometric anisotropy was reduced to isotropy by applying a linear transformation of the coordinates, whereas the complexity of zonal anisotropy is discussed. Results from the geometric anisotropy model indicated a continuation of the geological fault towards the north underneath the city of Bam. Cross-validation gave a mean error close to zero whereas the RMSE value was approximately 0.1 m, well below the detection limit of pixel-tracking technique. We conclude that ordinary kriging using a variogram model corrected for geometric anisotropy produced more accurate interpolation results than an isotropic model.

Keywords: Earthquakes; Coseismic displacements; Geostatistics;
Kriging; Anisotropy

4A.1 Introduction

Coseismic displacements are static deformations caused by earthquakes, due to the release of accumulated energy in the Earth subsurface along geological faults (Crippen, 1992; Massonnet et al., 1993). They are an important source of information for characterizing geological faults and for understanding the physical phenomenon behind earthquakes (Michel et al., 1999; Fialko et al., 2001). The displacement depends mainly on the magnitude, depth and the movement mechanism (e.g. dip-slip or strike-slip) of an individual earthquake. Conventionally coseismic displacements are measured by levelling and triangulation surveys in the field. Global positioning systems (GPS) are able to measure these displacements accurately but at a limited number of locations. They also require deployment of a GPS network in earthquake prone areas prior to the event (Gonzalez et al., 2009). Coseismic displacements can also be measured by applying space borne geodetic techniques using both optical and synthetic aperture radar (SAR) remotely sensed data (Crippen, 1992; Massonnet et al., 1993; van Puymbroeck et al., 2000). Remotely sensed data are preferred because they require limited prior information and do not rely on field work. In this study we consider two main techniques: SAR interferometry (InSAR) and sub-pixel correlation (also called pixel tracking).

InSAR is an advanced signal processing technique (Massonnet et al., 1993; Peltzer et al., 2001; Peyret et al., 2006) applied to measure coseismic displacements projected along the line of sight (LOS) direction. The LOS observation of a displacement is sensitive mainly to vertical component of a displacement (Fialko et al., 2001; Elliott et al., 2007). InSAR has some severe limitations. First, it fails when coherence is lost between two images due to temporal changes or when the gradient of deformation is high (e.g., near the fault). Second, it does not measure displacements when the gradient of displacements (fringe rate) exceeds the limit of half a fringe per pixel (Michel et al., 1999; Avouac et al., 2006; Qu et al., 2010).

Coseismic displacements can also be determined by correlating two SAR images of pre- and post-earthquake using "pixel tracking". This technique uses cross-correlation between the two SAR images (Michel et al., 1999; Jonsson et al., 2002; Simons et al., 2002; Sarti et al., 2006). Its accuracy depends on the pixel size of the SAR images (Gonzalez et al., 2009) and is an order of magnitude lower than InSAR; however, it is more robust against decorrelation as compared to InSAR and can estimate coseismic displacements near the geological fault (Michel et al., 1999). It estimates horizontal displacements in the azimuth (parallel track) and range (cross-track) directions of the satellite viewing geometry. Similar to InSAR, the range offsets (ROs) are measured LOS displacements (Simons et al., 2002; Hashimoto et al., 2010; Yan et al., 2010). Azimuth offsets (AZO) estimate

coseismic along-track displacements for which InSAR is insensitive. As the pixel size is larger in the range direction than in the azimuth direction, ROs are less accurate than AZO. Furthermore ROs are more strongly affected by stereoscopic and orbital parameters than AZO (Funning et al., 2005).

Despite its robustness pixel tracking can still fail due to temporal decorrelation, for example caused by the collapse of buildings, vegetation, water-body changes and damage to urban infrastructure (Fialko et al., 2001; Pathier et al., 2006). Therefore offsets measured by pixel tracking can have missing coseismic displacements. Interpolation of these missing values can improve characterization of the earthquake causative fault and understanding of the earthquake source mechanism. Kriging can be applied to interpolate these missing coseismic displacements. It offers a superior solution as compared to other methods because it interpolates based on the spatial structure of the displacements. A proper interpretation of the variogram may also provide insight into the physical phenomena (Webster and Oliver, 2001).

This study is about the 2003 Bam earthquake (details are given in section 2). Previously, InSAR derived LOS displacements were analyzed and missing values were interpolated using kriging (Yaseen et al., 2013). There are several reasons to select this area. Bam is located in an arid environment. It has little topography, in particular the main site of deformation is flat. Therefore a displacement map is expected to have a relatively small number of missing coseismic values caused by temporal decorrelation. Interpolation of those may help to characterize the earthquake causative fault that passes directly under Bam city (Stramondo et al., 2005). Furthermore, ample reference literature is available as this earthquake is extensively studied by InSAR and other geodetic and geophysical techniques. In the present study, horizontal coseismic displacements were determined using ENVISAT-ASAR pre- and post-earthquake SAR images from the descending orbit using pixel tracking. Note that there was no evidence of any post-seismic displacement after the Bam earthquake within the period of ASAR post-earthquake image (Fialko et al., 2005; Jackson et al., 2006; Motagh et al., 2006; Peyret et al., 2007).

As described above, ROs would be noisy for an earthquake of a moderate magnitude, due to the coarse range resolution (20 m) of the ASAR images. They would also give redundant information because InSAR provides the same component of the displacement at a much finer resolution (Simons et al., 2002). Therefore the AZO were considered only for the north-south horizontal displacements in this study. Pixel tracking fails to produce AZO due to the loss of coherence between some parts of radar images. Interpolation of these missing values is a prerequisite for the accurate characterization of the earthquake causative fault.

The main objective of this research was to determine horizontal coseismic displacements using pre- and post-earthquake ASAR images. In order to do so, we used pixel tracking, followed by interpolating missing coseismic displacements by applying kriging after investigating and accounting for anisotropic effects. This interpolation of missing coseismic displacements, derived by pixel tracking, is the main novelty of the present work.

4A.2 Dataset

This study deals with coseismic displacements of the Bam earthquake struck in south-east Iran in 2003. The study area details are provided in chapter 1, section 1.2.

The 2003 Bam earthquake is the first earthquake for which the ENVISAT ASAR data was made available. A pair of ENVISAT ASAR images from descending orbit, bracketing the earthquake, was selected. The pre-earthquake SAR image is of 3 December 2003 and the post-earthquake image is of 11 February 2004, hence with a time interval of 70 days. The perpendicular distance between the orbits of two scenes, called the baseline, is 4 m. The critical baseline for ENVISAT ASAR images is 941 m; beyond this value a comparison of SAR images does not produce sensible results.

The images are in IS2 mode, having an incident angle of 23° , VV polarization and single look complex format (Table 4A.1). The AMPCOR (amplitude correlation) algorithm embedded in the ROI_PAC software (Rosen et al., 2004) was used to calculate the horizontal displacements from a pair of ASAR images.

Preliminary InSAR studies demarcated the earthquake causative fault to the south of the city (Hoffmann et al., 2004; Jonsson et al., 2004; Talebian et al., 2004; Wang et al., 2004; Fialko et al., 2005). The post-earthquake ASAR image was recorded 47 days after the earthquake. There was no evidence of any post-seismic displacement within that period (Fialko et al., 2005; Motagh et al., 2006; Peyret et al., 2007). It has been postulated that the earthquake causative fault had an extension towards the north, passing below the city (Stramondo et al., 2005; Peyret et al., 2006).

Figure 4A. 1: Azimuth offsets (horizontal coseismic displacements) measured in meters using pre- and post-earthquake ASAR images from descending orbit for 2003 Bam earthquake. The red box shows area of interest with major displacements due to the earthquake. Black arrows show azimuth and line-of-sight directions of the sensor mounted on ENVISAT satellite.

Table 4A. 1: ENVISAT-ASAR images from descending orbit having incidence angle 23° , swath IS2 and VV polarization.

Track	Orbit	Acquisition date	Baseline	Time difference	Pixel size	
					Azimuth	Range
120	9192	3 Dec 2003	4 m	70 days	4 m	20 m
120	10194	11 Feb 2004				

4A.3 Methodology

This section is divided in two parts. Section 4A.3.1 describes, the coseismic displacements that were determined by correlating the pre- and post-earthquake ASAR images using pixel tracking. Section 4A.3.2 describes the interpolation of missing values by applying kriging.

4A.3.1 Measuring horizontal coseismic displacements

Horizontal coseismic displacements can be obtained from sub-pixel correlation of pre- and post-earthquake SAR or optical images (Crippen, 1992; Scambos et al., 1992; Michel et al., 1999; Fialko et al., 2001; Pathier et al., 2006; Wei et al., 2011). It uses the normalized cross-correlation (NCC) to estimate the horizontal shifts in image lines (ROs) and image column (AZO) directions by comparing both images. (Figure 4A.2) A small subset of the master image, called the reference template $f(x,y)$ of size r rows and c columns, is searched for in the slave image within the defined search area (window). The reference template is moved by Δx and Δy within the search window in order to find its match. At each step the NCC between reference template $f(x,y)$ and search template $g(x,y)$ is computed by Equation 1, and the best match is defined as the match where the correlation between the templates is maximal.

$$\rho(\Delta x, \Delta y) = \frac{\sum_{x=0}^{r-1} \sum_{y=0}^{c-1} (f(x,y) - \bar{f})(g(x-\Delta x, y-\Delta y) - \bar{g})}{\sqrt{\sum_{x=0}^{r-1} \sum_{y=0}^{c-1} (f(x,y) - \bar{f})^2} \sqrt{\sum_{x=0}^{r-1} \sum_{y=0}^{c-1} (g(x-\Delta x, y-\Delta y) - \bar{g})^2}} \quad (1)$$

where $\rho(\Delta x, \Delta y)$ is a correlation coefficient with a value $[-1, 1]$ range, equal to 1 when both templates are identical, 0 if they are unrelated and -1 if they are opposite. Note that is for the ordinary correlation coefficient, a positive multiplicative coefficient or a constant value added to g does not change the correlation between f and g in the equation (1). Further, $\bar{f}$ and $\bar{g}$ are mean values of the reference and search templates respectively.

Figure 4A. 2: Schematic diagram of NCC procedure for sub-pixel shift measurement. Solid boxes show templates and dashed is the search window

The difference (Δx , Δy) of coordinates of the reference and search template at its match position gives the integer pixel shifts in azimuth and range directions. A sub-pixel shift can be determined by fitting a second order polynomial function to the neighbouring correlation values around the best matching location of the two templates within the search window (Vosselman et al., 2004). The peak of the fitted polynomial function provides the coordinates of the best matching location at the sub-pixel level. In this way, the total displacement vector can be drawn by calculating the Euclidean distance from the coordinates of both templates at their best matching location. The offsets at specified intervals were calculated for the whole image by repeating this procedure after moving the reference template along all image lines and columns.

The precision of the measurements depends on the signal to noise ratio (SNR), coregistration errors, and geometric and radiometric distortions of the images (Michel and Rignot, 1999; van Puymbroeck et al., 2000). It may be at a size of 1/20 pixel (Berenstein et al., 1987; Crippen, 1992; Peltzer et al., 1999; Strozzi et al., 2002; Leprince et al., 2007). The SNR is affected by the strength of the correlations between the search template and the reference template. The measurements with a low correlation are usually dropped, commonly using a threshold equal to 0.9 to select successful correlations for measuring coseismic displacements.

Choices of the search window and template size depend upon the type of application, data and offset characteristics. The template size should be such that the SNR is at a maximum and small enough to catch the minimum offsets gradients (Kanade and Okutomi, 1994). The search window size should be large enough to cover maximum potential shift but also small enough for efficient processing. The loss of correlation (decorrelation) between the templates may occur due to various factors. Among these are low SNR or physically unrealistic measurements, ground features that are of template window size, temporal decorrelation, terrain distortions, drastic changes or lack of texture (pattern or features) in the template windows.

Horizontal coseismic displacements for the 2003 Bam earthquake were measured by applying pixel tracking using a pair of ENVISAT-ASAR images from the descending orbit (Table 4A.1). Pixel tracking uses raw data (level 0); from which both pre- and post-earthquake images were processed to single look complex format. It used the orbital and other auxiliary information such as satellite attitude, velocity, altitude and mode of acquisition as provided by the European Space Agency (ESA). The baseline, defined as the perpendicular distance between the two orbits at the time of acquisition of both images, was calculated to be 4 m and the main deformational area along the earthquake causative fault is flat. For these reasons, the topographic effects on coseismic displacements would be small (Fielding et

al., 2005; Jackson et al., 2006). However a 3 arc seconds (~ 90 m) SRTM DEM was used to remove the stereoscopic effects caused by the topography.

Pre- and post-earthquake images were coregistered and offsets were measured in the range and azimuth directions. A template window size of 100 pixels in the azimuth direction and 20 pixels in the range direction was adopted, being well adapted to this study. AZO were geocoded using the DEM coordinates with WGS-84 and UTM zone 40 projection system.

A subset comprising the deformation signal due to the earthquake was prepared (Figure 4A.3). Decorrelation of images producing no displacement values due to collapse of buildings, were mostly in the urban areas of Bam and Baravat. Field observations and previous studies on this earthquake revealed that the earthquake ruptured the blind right-lateral strike-slip fault with a maximum displacement of 1 m at the surface (Jonsson et al., 2004; Talebian et al., 2004; Perski and Hanssen, 2006). Therefore, the higher values were filtered by keeping displacement values ranging from -1 to 1 m. A few random higher displacement values, even within the range -1 to 1 m, were present in the urban area only. These values were masked as they were produced due to building damages and did not belong to the fault displacements. The final displacement image after subsetting, filtering and masking was prepared. The filtered and masked values were termed missing values. The missing coseismic displacement values need to be interpolated in order to assess the continuity of the fault below the city of Bam.

4A.3.2 Interpolating the missing coseismic displacements

Here we provide a brief description on variogram, kriging and anisotropy as these are used widely and well explained in the geostatistical literature. Therefore the interested reader is referred to the books of Journel and Huijbregts (1978) and Cressie (1993) for details. Discussions of geostatistics in a remote sensing context are given by Woodcock et al. (1988), Curran and Atkinson (1998), Addink and Stein (1999) and van der Meer (2012).

Interpolation can be used to estimate missing values in imagery (Addink and Stein, 1999; Zhang et al., 2007; Zhang et al., 2009). Geostatistical methods offer superior performance than the conventional methods like inverse distance weighting, because they model explicitly spatial dependence of the variables (Curran and Atkinson, 1998; Addink and Stein, 1999; Stein et al., 1999). The nature of spatial dependence is evaluated using the semivariogram (or simply variogram).

Figure 4A. 3: Horizontal coseismic displacements (m) (a), Azimuth offsets (AZO); the displacement values that does not belong to the fault movement were filtered (explained in the text) and termed as missing values as shown in (b), the coseismic displacements were categorized into positive and negative values with missing values as black squares.

The variogram relates the dissimilarity of observations as a function of spatial separation distance h between them as:

$$\hat{\gamma}(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [z(u_i) - z(u_i + h)]^2 \quad (2)$$

where $\hat{\gamma}(h)$ is the variogram, and $m(h)$ is the number of pixel pairs at distance h .

Kriging is a geostatistical interpolation method that uses the variogram. Kriging interpolates values at unobserved locations by assigning weights to the observed neighbouring values in such a way that variance is minimum. The weights are based on the variogram and the sample configuration. The kriging interpolator is:

$$\hat{z}(u_0) = \sum_{i=1}^n \lambda_i z(u_i) \quad (3)$$

The interpolation at an unvisited location u_0 , is thus a linear combination of observed data values $z(u_i)$. For kriging, unbiasedness is ensured by constraining the weights, λ_i , to sum to unity. Ordinary kriging (OK) assumes a constant unknown mean while universal kriging (UK) estimates a trend before the interpolation (Cressie, 1993). In our case, interpolation of the missing displacements was carried out using OK, because it is a relatively simple model based on spatial dependence of the coseismic displacements.

The omnidirectional (isotropic) variogram averages the spatial variability in all directions. The isotropic variogram depends only upon the separation distance ($|h|$), not upon the orientation. The structure of spatial dependence may vary in different directions thus showing anisotropy. Taking anisotropy into account improves the application of kriging as it reflects the possible anisotropy of the underlying random field. Corrections can be made by reducing the anisotropic variogram to an isotropic one (Journel and Huijbregts, 1978). Two types of anisotropy are distinguished: geometric anisotropy, where the range parameter changes in different directions and the sill is constant, and zonal anisotropy, where both sill and range change with direction. A phenomenon can exhibit one or both types of anisotropy.

Geometric anisotropy can be reduced to isotropy by identifying the directions of maximum and minimum ranges and taking them as major and minor ellipse axis respectively. In order to do so, first the major axis of the ellipse is aligned to the coordinate axis and the minor axis is elongated to become equal to that axis, thus forming the circle. The first step is accomplished by a linear transformation of the coordinates and the second step by multiplying the lag distance by the ratio of the minimum and maximum range. Figure 4A.4 depicts the geometric anisotropy. Suppose $a_{\max}$ is the maximum range and $a_{\min}$ is the minimum range of spatial continuity forming the major and minor axis of an ellipse (Figure 4A.4). The major axis makes an angle θ with the coordinate axis y (north direction), whereas the minor axis makes an angle $\varphi = \theta + 90^\circ$ with y -axis. The geometric anisotropy is reduced to isotropy by the linear transformation and anisotropy ratio given as follows:

$$h' = D_\beta \cdot R \cdot h \quad (4)$$

where h is a lag distance vector in two dimensions, $R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$ is a rotational matrix and $D_\beta = \begin{bmatrix} 1 & 0 \\ 0 & \beta \end{bmatrix}$ is a diagonal matrix for the anisotropy ratio $\beta = \frac{a_{\min}}{a_{\max}} < 1$.

Figure 4A. 4: Schematic diagram for correction of geometric anisotropy

Zonal anisotropy can be approximated by preparing a variogram for each zonal component and combine these into a final model, called the nested variogram. First, the empirical variogram with a small sill in all directions is modelled as an isotropic or a geometrically anisotropic variogram. Second, each zonal component is fitted having higher sill values in other directions. The goal is to specify structures of larger sills which contribute exclusively in particular directions to the main model. Let us consider a nested model (Journal and Huijbregts, 1978) as a sum of two components given below:

$$\gamma(h) = \gamma_1(|h|) + \gamma_2(h_\phi) \quad (5)$$

where the first component $\gamma_1(|h|)$ is an isotropic or model corrected for geometric anisotropy, and the second $\gamma_2(h_\phi)$ is a zonal component. A variogram model $\gamma(h)$ may have multiple components, each with its own anisotropy. A general expression for such model can be written as follows:

$$\gamma(h) = \sum_{i=1}^n \gamma_i(|h_i|) \quad (6)$$

A $\gamma(h)$ has a summation of n nested components.

A variogram map and directional variograms were determined to evaluate the spatial dependence. The directional variograms were determined using cutoff values of 12000 m and a bin size of 500 m at angles (0°, and 90°) with tolerance value $\pm 45^\circ$. As the fault movement was in the north-south direction (0° angle) so it would be a direction of maximum spatial continuity whereas the minimum spatial continuity would be perpendicular to this direction (i.e. at 90° angle). A rose diagram was prepared showing the variogram range. The geometric anisotropy was investigated by directional variograms and the rose diagram. The variogram corrected for geometric anisotropy was determined fitting a spherical model to the empirical variogram. The model was fitted in the direction of maximum continuity. It uses the anisotropy ratio that was determined as the ratio of the minimum to the maximum range of spatial dependence. The spherical model is linear at short lags and reaches the sill at the finite range 'a'. It is given by the Equation (7):

$$\gamma(h) = \begin{cases} 1.5 \frac{h}{a} - 0.5 \left(\frac{h}{a}\right)^3 & \text{if } h \leq a \\ 1 & \text{otherwise} \end{cases} \quad (7)$$

In order to assess the effect of anisotropy further, directional variograms at angles (0°, 30°, 60°, 90°, 120° and 150°) with directional tolerance of 15° were determined. The fitted spherical model was compared to the individual empirical variogram for different angles. The analysis of fitted variograms demonstrated that along with geometric anisotropy there also exists a zonal component of anisotropy.

Interpolation of missing coseismic values was carried out by applying OK, based on the isotropic and the geometric-anisotropy-corrected variogram models. The interpolated values were combined with the existing values and two displacement maps were prepared for the isotropic and geometric anisotropy corrected variogram models respectively. The difference image of interpolated values, based on the geometric-anisotropy-corrected model with reference to the interpolated values based on the isotropic model, was prepared.

The accuracy of the interpolated values was assessed using cross-validation. In cross-validation one sample point is removed and the model is estimated using the remaining data. The removed sample point is interpolated using the estimated variogram model. Then the difference between the actual and interpolated value is calculated and the process is repeated for all sample points. This is called leave-one-out cross-validation (LOOCV) and deviations are summarized in the form of the mean error (ME) and the root mean square error (RMSE). RMSE provides an average measure of difference between the observed values and the estimated values, whereas ME quantifies bias and shows whether the predicted values are systematically

higher or lower than the reference values. They were calculated by Equation (8) and Equation (9).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (\hat{z}(u_i) - z(u_i))^2}{n}} \quad (8)$$

$$\text{ME} = \frac{1}{n} \sum_{i=1}^n (\hat{z}(u_i) - z(u_i)) \quad (9)$$

where $z(u_i)$ is the observed value, $\hat{z}(u_i)$ is the estimated value at location u_i and n is total number of values.

4A.4 Results

Azimuth offsets (AZO), for the Bam earthquake area, measured from pre- and post-earthquake ASAR images using pixel tracking are shown in Figure 4A.1. The earthquake signal south of the Bam city can clearly be seen. Figure 4A.1 shows displacements along the north-south oriented (Fialko et al., 2005; Stramondo et al., 2005; Motagh et al., 2006) earthquake causative fault that were previously unknown (Jonsson et al., 2004). Higher values in the urban, mountainous and vegetated areas are due mainly to temporal decorrelation and earthquake induced damages.

A subset of the displacement map is shown in Figure 4A.3(a). This subset covers a 15 km wide and 30 km long area showing the major earthquake displacements. Beyond 15 km perpendicular to the fault line, the displacements diminish. As described in section 4A.3.1, the larger displacements were filtered or masked. The filtered and masked values are termed as the missing displacements and are shown in Figure 4A.3(b) together with the actual values. The earthquake causative fault can clearly be demarcated as a discontinuity south of the city (Figure 4A.3) and has displacement values in the range of [-0.5, 0.5] m.

An isotropic variogram, modelled by a spherical function, is shown in Figure 4A.5. It shows a smooth curve that fits well near the origin, whereas deviations are observed at the transition of the shoulder towards the sill. A variogram map, for assessing the directionality of spatial dependence, is shown in Figure 4A.6(a). It shows a clear major spatial dependence of displacement values in north-south direction. The empirical directional variograms (at angles 0° and 90°) were modelled individually by spherical function (Figure 4A.6(b)). The fitted models show spatial dependence is minimum (range ≈ 6424) in the direction perpendicular to the direction of maximum spatial dependence (range ≈ 11790). This shows the presence of geometric anisotropy as both directional variograms have similar sills, but have different ranges. This was also demonstrated by the elliptical rose diagram (Figure 4A.7(a)). Figure 4A.7(b) shows a fitted spherical model after accounting the geometric anisotropy using empirical variogram in the

direction of highest spatial continuity and anisotropic ratio (0.54). This converted the geometric anisotropy model to an isotropic one, showing similar model parameters as of isotropic model (Table 4A.2).

Figure 4A.8 shows the anisotropy if directional variograms are prepared at narrower angles (30°) and tolerance values ($\pm 15^\circ$). The variogram at 0° angle shows a considerably lower sill value as compared to sill values of the other variograms (Figure 4A.8(a)). Comparison of individually modelled spherical variograms (Figure 4A.8(b)) show multiple components of anisotropy. Variograms at 30° angle shows the highest sill values and the variogram at 150° , 90° and 0° angles have lower sill values in decreasing order respectively. This constitutes a multiple structure of geometric and zonal anisotropies. The variograms have different sill values indicating that the variance varies with direction.

Figure 4A. 5: Fitted isotropic empirical variogram with cutoff value 15000 m and bin size 500 using the spherical model. It is fitted well near the origin while showing some deviations around the sill. The model parameters are given in Table 4A.2.

Table 4A. 2: Spherical models parameters for OK when using isotropic and geometric anisotropic variograms

	Range	Partial Sill	Nugget	SSE*	Anisotropy
Isotropic	8196	0.0294	0.0087	5.97×10^{-7}	
Geometric anisotropy	8174	0.0294	0.0086	1.68×10^{-5}	Anisotropy ratio = 0.54 and variogram in the direction of maximum continuity (0°)

* SSE = sum of square of error

Figure 4A. 6: (a), Variogram map showing the spatial dependence in the north-south direction. Spherical model fitted individually to directional empirical variogram at 0° (b), and at 90° (c). Both models show there is a geometric anisotropy with approximately same sill values with different range values. Variograms at 0° and 90° show the maximum and minimum range of spatial dependence respectively.

For interpolating the missing values, OK was applied using the isotropic and geometric anisotropy corrected variogram models. The coseismic displacement maps prepared by combining interpolated missing values with the existing values are shown in Figure 4A.9(a) and Figure 4A.9(b)

respectively for the two variogram models. Interpolated values are different for both models as shown by its difference image (Figure 4A.9(c)). A displacement map (Figure 4A.9(b)), produced with geometric anisotropy corrected variogram, shows a relatively clear indication of the continuity of the geological fault below the city of Bam as compared to the interpolated values of the isotropic model.

Cross-validation values are shown in Figure 4A.10. The lower inset image gives a histogram of the residuals, whereas the upper inset image shows the distribution of the residuals. The $ME = 2.33 \times 10^{-5}$ m being close to zero, whereas the $RMSE = 0.1046$ m. The 0.1 m RMSE is well below the detection limit (0.2 m) of the pixel-tracking technique for ASAR images. The coefficient of correlation (R^2) has moderate value (0.65), as interpolated values around extreme values show higher deviations from the actual values (Figure 4A.10). These values are shown on the residual plot (upper inset, Figure 4A.10) and are at the edges of missing values groups, particularly occurring at Bam and Baravat cities.

Figure 4A. 7: (a), A rose diagram with range values at angles (0° and 90°) for fixed sill value (0.35) showing elliptical pattern corresponding to geometric anisotropy. (b), Fitted spherical model after accounting the geometric anisotropy. Model parameters are given in Table 4A.2.

Figure 4A. 8: (a), Directional empirical variograms at angles (0° , 30° , 60° , 90° , 120° and 150°) with tolerance $\pm 15^\circ$. (b), Comparison of fitted spherical models to the individual empirical variogram for different directions. It is showing a mixture of geometric and zonal anisotropy.

4A.5 Discussion

This study demonstrates the use of geostatistical interpolation for deriving missing coseismic values, after investigating and accounting the effects of anisotropy. The coseismic values showed a clear directional variability (anisotropy). It is important to account for the effect of anisotropy in order to have the spatial dependence structure of coseismic values best reflected.

For small distances, however, also the isotropic variogram model fitted well and clearly described the spatial structure. Its nugget effect equal to 0.009 may be due to micro-variability of the measurements such as the variation at a range that is less than the sampling intervals or due to measurement error (Cressie and Wikle, 2011). Plotted directional variograms at 0° and 90° directions showed geometric anisotropy. This anisotropy was addressed by reducing the directional variograms to an isotropic model using a coordinate transformation. When computing a directional variogram it is necessary to specify a direction (angle) and a tolerance, where the tolerance defines the area around each specific direction. Hence narrow direction angles imply narrow tolerances. Varying the directional angles and tolerance showed a complicated case of geometric and zonal isotropies. In our case, a tolerance value of $\pm 45^\circ$ revealed geometric anisotropy (Figure 4A.7), whereas a tolerance value of $\pm 15^\circ$ indicated the presence of zonal anisotropy (Figure 4A.8). A wide tolerance ($\pm 45^\circ$) had a smoothing effect and weakened the effect of zonal anisotropy, whereas a narrow value ($\pm 15^\circ$) allowed the zonal anisotropy to be identified. Note that specification of a narrow tolerance requires a sufficiently dense sample to enable a robust estimation of the variogram (Webster and Oliver, 2001). In our study the number of pixels in the image was large (9482). The sampling density of displacement values is high and has a strong spatial continuity due to the fault movement in the north-south direction. Therefore, narrower tolerances were required to identify this anisotropy.

Figure 4A. 9: Horizontal coseismic displacements (m) in azimuth direction (AZO offsets). (a), OK interpolated missing displacements using isotropic variogram and (b), OK interpolated missing displacements using geometric anisotropy corrected variogram model. (c). Difference between interpolated values when using an isotropic & a geometric-anisotropy-corrected model.

The isotropic model and the model corrected for geometric anisotropy had similar shapes near the origin up to the shoulder and differed in the transition of shoulder to sill. This demonstrates that the variance is constant at shorter lags showing isotropy while the behaviour of variance changes at a longer distances. The nugget effect was equal to 0.009 being equal to 22 % of the total variance for the two variograms.

OK interpolation, based on these two variograms, provided similar results because, for interpolation, the first few lags are the most important ones for assigning the kriging weights (Kleijnen and van Beers, 2005). The differences are due to variability at longer distances. The variogram corrected for geometric anisotropy produced results that were slightly different from the isotropic model. It indicated that the geological fault continues underneath Bam. Towards the south of the city the displacements show a clear discontinuity, whereas towards the north the values are less ordered. The

urban area of Bam (~4 km wide) is between these two regions and has 580 out of the 878 missing values. Our interpolation results based on the variogram corrected for anisotropy (Figure 4A.9(b)) indicated that the fault may continue underneath Bam city. Coseismic displacements, however, did not provide any clear pattern and were of lower magnitude north of the city.

The interpolated values at Bam showed that the fault apparently shifts slightly to the east (Figure 4A.9(b)). The discontinuity at Bam is weak (i.e. small difference in displacement values) and the uncertainty in the interpolated values is large (mean kriging standard deviation = 0.11 m). The eastward shifting may also be attributed to the hypothesis (Talebian et al., 2004; Stramondo et al., 2005) that the fault joins the northern fault segment underneath Bam. The northern fault segment (visible only on the LOS displacement map) is north-east of the earthquake causative fault. Additional geologic observations would help to determine up to which distance beyond the city the fault extends.

The directional variograms prepared at narrow angles and tolerance value showed a complex nature of zonal anisotropy that could not be modelled properly. It showed a geometric component along with four separate components of higher sill values in four different directions. In modelling such a variogram there are some practical difficulties in identifying the most appropriate model as no variogram model is correct in all directions. The variogram in the north-south direction (0°) had the highest spatial continuity, whereas the variogram in the north-east direction (30° angle) had the highest sill value with the shortest range of spatial dependence. It shows that spatial continuity was minimized even with only a small change of direction. This phenomenon may be explained by coseismic displacements occurring along the north-south oriented geological fault. Such displacement values would be close to each other along the fault. In particular, such displacements are dominant within an area of 4-5 km from the fault. This showed once again that the north-south direction of variability is more important for interpolating missing values than the other directions.

Figure 4A. 10: Linear models of predicted vs actual from cross-validation. The lower inset image shows histograms of residuals while the upper gives distribution of residuals.

The study was hampered by the absence of validation data for carrying out accuracy assessment. This deficiency was compensated by carrying out cross-validation (CV) using OK. CV produced higher inaccuracy at the boundaries of groups of missing values particularly at the urban areas of Bam and Baravat. This can be explained as the CV depends upon the number of neighbouring data points and results in larger error where sample density decreases (Falivene et al., 2010).

The study demonstrated the utility of OK; however, results may further be improved by rigorously accounting the complex zonal anisotropy. In the present study, the model corrected for geometric anisotropy gave missing values accurately as compared to the results of the isotropic model.

4A.6 Conclusion

Missing coseismic displacements were accurately predicted with ordinary Kriging after taking anisotropy into account. The regionalized variable “coseismic displacements” showed a geometric anisotropy at an angular tolerance $\pm 45^\circ$ and a zonal anisotropy at a tolerance of $\pm 15^\circ$, demonstrating that coseismic displacements are strongly anisotropic in the Bam area. Coseismic displacements have the longest variogram range in the north-south direction i.e. the direction in which the geological fault slipped during the earthquake. The isotropic variogram and the variogram corrected for geometric anisotropy were similar near the origin showing isotropy at smaller lags. They differed in shape at the transition to sill distance, thus revealing anisotropy at longer lags. The variogram model corrected for geometric anisotropy resulted in more accurate interpolation results than the isotropic model and showed that the geological fault may well continue underneath the city of Bam towards the north with a small shift to the east.

**Part B: Horizontal Displacements from ASAR
images from the Ascending orbit*****Abstract***

Understanding of the earthquake dynamics is based on accurate measurement of coseismic displacements. This study demonstrates the effectiveness of kriging for interpolating missing values in the coseismic displacement map. The interpolation of missing values was necessary in order to check continuity of the earthquake causative fault underneath the city of Bam. Variogram, the measurement variance, was modelled by a spherical function. Directional variograms indicated the presence of geometric anisotropy in the measurements. The geometric anisotropy was corrected before applying kriging. The interpolated results based on both isotropy and anisotropy corrected models showed the fault continuity at the city of Bam. Cross-validation results demonstrated that kriging serves as a powerful tool for interpolating the missing coseismic displacements. It gave the RMSE value approximately 0.1 m that is below the detection limit of pixel-tracking technique and mean error (ME) close to zero. The interpolated results, particularly the results based on the anisotropy corrected variogram, showed continuity of the geological fault underneath the Bam city.

Keywords: Earthquakes; Coseismic displacements; Geostatistics; Kriging; Anisotropy

4B.1 Introduction

The measurement of coseismic displacements is an important issue for earthquake source characterization. Coseismic displacements are static deformations caused by earthquakes (van Puymbroeck et al., 2000). Typically these are measured in the field by geodetic surveys. Field methods can provide accurate measurements but sparsely and are also laborious and time consuming (Kaneda et al., 2008). In contrast to field methods, remote sensing data and methods are capable to measure coseismic displacement densely (Michel et al., 1999; Fialko et al., 2001; Leprince et al., 2007).

Synthetic aperture radar interferometry (InSAR) can provide spatially continuous measurements of ground deformation with high accuracy of millimetre scale. However, InSAR has some limitations like loss of coherence due to temporal and geometrical decorrelation (Sarti et al., 2006). The loss of coherence may also be due to high gradient of deformation in vicinity of the earthquake causative fault. This is the major hurdle in getting the coseismic displacements near the fault (Funning et al., 2005).

Coseismic displacements can, alternatively, also be measured by cross-correlating the pre- and post-earthquake images (Michel et al., 1999; van Puymbroeck et al., 2000; Jonsson et al., 2002; Simons et al., 2002). The cross-correlation technique is called pixel tracking. Although pixel tracking is less precise in order of magnitude than InSAR, it is more robust against coherence loss of two images (Michel et al., 1999). It gives horizontal coseismic displacements and can produce measurements near the seismogenic fault for which InSAR fails. The pixel tracking results may be affected by temporal decorrelation due to landcover changes or earthquake damages. Hence the coseismic displacement map has missing data due to decorrelation of the images. Keeping in view the importance of coseismic displacements for understanding earthquake source and fault dynamics, the missing displacement values must be interpolated in order to have a complete displacement map.

Kriging, a geostatistical method, can be applied to interpolate the missing displacements. It interpolates based on spatial structure of the existing values that makes it superior to other interpolation methods such as inverse distance weighting (IDW). Furthermore kriging may also provide understanding of the physical system under investigation (Webster and Oliver, 2001). Interpolation of the missing values in coseismic displacement can improve the characterization of earthquake causative fault.

In the present study, the coseismic displacements for 2003 Bam earthquake are addressed. The study area details are provided in chapter 1, section 1.2.

The main objective of the present research is to derive horizontal coseismic displacements for 2003 Bam earthquake. For this purpose, first, pixel tracking technique was used and then missing displacements were interpolated using kriging after analysing the spatial dependence structure of the measurements. Accuracy of the interpolated displacements was assessed by cross-validation procedure. Interpolation of the missing displacements in vicinity of the earthquake causative fault is an innovation of the present research.

Figure 4B. 1: Location of the Bam area in south-east of Iran (upper right side). The horizontal coseismic displacements (azimuth offsets) measured in meters using pre- and post-earthquake ASAR images from ascending orbit bracketing the 2003 Bam earthquake. The measurements were grouped into positive and negative values whereas the missing values are shown in Black.

4B.2 Methods

A pair of pre- and post-earthquake ENVISAT ASAR from ascending orbit was selected for 2003 Bam earthquake. The Bam earthquake is the first earthquake for which ASAR data was made available. The pre- and post-earthquake images were acquired on 16 November 2003 and 25 January 2004 respectively with a difference of 70 days. A perpendicular distance between orbits of the two images, called baseline, was measure as 77 m. A pixel tracking technique "AMPCOR" embedded in the ROI_PAC software was applied to measure the horizontal displacements.

The methodology section is divided into two parts. First part describes the principle of normalized cross-correlation for measuring horizontal coseismic displacements. While the second part throw light on kriging interpolation technique and its implementation for deriving the missing values.

4B.2.1 Normalization cross-correlation for measuring coseismic displacements

The pre- and post-earthquake ASAR images are cross-correlated in order to calculate the shift in image lines and columns. These shifts or offsets caused by the earthquake are called coseismic displacements. The normalized cross-correlation (NCC) procedure is illustrated in Figure 4B.2.

A reference template $f(x,y)$ of size r rows and c columns from the master (or pre-earthquake) image, is searched for in the slave image (post-earthquake) within the defined search window. In order to find the match of reference template in the slave image, it is moved by Δx and Δy within the search window. A correlation between the reference template $f(x,y)$ and search template $g(x,y)$ is calculated at each step (equation 1). The step where both templates have maximum correlation is called the best match.

$$\rho(\Delta x, \Delta y) = \frac{\sum_{x=0}^{x=r-1} \sum_{y=0}^{y=c-1} (f(x,y) - \bar{f})(g(x-\Delta x, y-\Delta y) - \bar{g})}{\sqrt{\sum_{x=0}^{x=r-1} \sum_{y=0}^{y=c-1} (f(x,y) - \bar{f})^2} \sqrt{\sum_{x=0}^{x=r-1} \sum_{y=0}^{y=c-1} (g(x-\Delta x, y-\Delta y) - \bar{g})^2}} \quad (1)$$

where $\rho(\Delta x, \Delta y)$ is a correlation coefficient with a value $[-1, 1]$ range, equal to 1 when both templates are identical, 0 if they are unrelated and -1 if they are opposite. Further, $\bar{f}$ and $\bar{g}$ are mean values of the reference and search templates respectively given below.

$$\bar{f} = \frac{1}{xy} \sum_{x=0}^{x=r-1} \sum_{y=0}^{y=c-1} f(x,y) \quad (2)$$

$$\bar{g} = \frac{1}{xy} \sum_{x=0}^{x=r-1} \sum_{y=0}^{y=c-1} g(x-\Delta x, y-\Delta y) \quad (3)$$

Figure 4B. 2: NCC procedure illustration for sub-pixel shift measurement. Templates are solid boxes whereas dashed box shows the search window

At the location of the best match of the two templates, a difference (Δx , Δy) of coordinates gives a integer pixel shift (offset). For sub-pixel shift a second order polynomial function can be fitted to neighbouring correlation values around the best match within the search window (Vosselman et al., 2004). The sub-pixel level shift is determined by the peak of the fitted function. This procedure was repeated for the whole image for calculating the sub-pixel offsets at specified intervals. The low correlation measurements were dropped using a threshold of 0.9. The search and template window sizes depend on type of application and data. The search window size should be large enough to cover maximum potential shift while the template size should be such as to capture the small offset gradients (Kanade and Okutomi, 1994).

The above mentioned procedure implemented in pixel tracking technique was applied to ASAR images to calculate the horizontal coseismic displacements for 2003 Bam earthquake. Pixel tracking accepted level 0 data and processed it to single look complex format after removing orbital variation with the use of auxiliary information. The topographic effects, which were small due to flat area and short baseline, were removed by using 3 arc second (90 m) SRTM DEM. The calculated offset image was geocoded using the UTM zone 40 projection system and WGS-84.

A subset of coseismic displacement map was prepared that contained the seismogenic fault and main deformational area. Previous studies on the Bam earthquake revealed that the maximum coseismic displacement was around 1 m, the higher values in the displacement map were due to temporal differences or collapse of buildings in the cities (Jonsson et al., 2004;

Talebian et al., 2004; Perski and Hanssen, 2006). Such higher values were filtered out and the coseismic displacement range was kept between -1 and 1 m. A few random higher displacement values that do not relate to fault movements were also removed. A final displacement map with missing values due to either decorrelation or filter of higher values was prepared (Figure 4B.1(b)). These missing coseismic values need to be interpolated in order to investigate continuity of the seismogenic fault underneath the Bam city.

4B.2.2 Interpolating the missing coseismic displacements

Statistical interpolation methods may be used to predict missing coseismic displacement values. Geostatistical methods offer superior performance because they explicitly model the spatial dependence of variables (Curran and Atkinson, 1998; Addink and Stein, 1999).

Coseismic displacements derived by pixel tracking are spatially distributed and represent continuous stochastic (random) phenomena. The displacements were considered as a regionalized variable, having the intrinsic properties of continuity and randomness. A continuously varying random field is explained by regionalized variable theory (Journel and Huijbregts, 1978) by taking spatial dependence of the variable into account. The variogram is a tool to explore and model the spatial structure of values of the regionalized variable (Curran and Atkinson, 1998) relating the dissimilarity of measurements as a function of spatial distance between them (Woodcock et al., 1988).

Kriging is a geostatistical interpolation method that uses the variogram. Kriging interpolates values at unobserved locations by assigning weights to the observed neighbouring values in such a way that variance is minimum. Hence, kriging is described as the best unbiased linear predictor (BLUP). Kriging is based on the spatial structure of displacement values such that values close to each other are more similar than the farther values. This relationship is specified by a model: the autocorrelation function, covariance function or variogram. The variogram defines the relation between the variance of measurements and their separation distance:

$$\hat{\gamma}(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [z(u_i) - z(u_i + h)]^2 \quad (4)$$

where $\hat{\gamma}(h)$ is the variogram, that gives dissimilarity between the measurements spatially separated by distance h , based on m pixel pairs.

The variogram describes the spatial structure of the observations. Given only one realization of the random process, it was impossible to measure covariance and then variogram from single data point. To solve this problem, second order stationarity was assumed which requires keeping the mean and

the variance of samples as constants within defined distance. An authorized model was then fitted to the experimental variogram. The most commonly used models are the Spherical, Circular, Exponential, Gaussian and Power models (Isaaks and Srivastava, 1989). The variogram is related to the well-known covariance function given as

$$\gamma(h) = C(0) - C(h) \quad (5)$$

Where $C(0)$ is a covariance at lag 0 and $C(h)$ at lag h (separation distance).

Kriging is termed as the optimal (unbiased) interpolator because it gives minimum kriging variance. It is given by the following equation:

$$\hat{z}(u_0) = \sum_{i=1}^n \lambda_i z(u_i) \quad (6)$$

The interpolation at ' u_0 ' is made by linear combination of data values ' u_i ' and for kriging the unbiasedness is ensured by assigning the weights λ_i that sum to unity. The equation (6) can be set up, as a general kriging equation, in matrices notation with C is an $n \times n$ matrix of covariance among observations, C_0 is a vector of covariance between each observation (u_i) and the point to be interpolated (u_0).

$$\hat{z}(u_0) = X\hat{\beta} + C_0^T C^{-1} (z - X\hat{\beta}) \quad (7)$$

Where $\hat{\beta} = (X^T C^{-1} X)^{-1} (X^T C^{-1} z)$ and all the parameters (β) of the trend are estimated by generalized least squares (GLS), X is a design matrix, z is a column vector of the n known observations and $(z - X\hat{\beta})$ is the residual from GLS model.

Equation (7) can be written for ordinary kriging (OK) by replacing design matrix X with 1 and $\hat{\beta}$ to $\hat{\mu}$, whereas X reduces to a vector of 1's. The interpolation error variance is given by following equation

$$\sigma^2 = \text{Var}[\hat{z}(u_0) - Z(u_0)] = C_0 - C_0^T C^{-1} C_0 + X^T V^{-1} X \quad (8)$$

Where $X = X_0 - (C_0^T C^{-1} X)$ and $V = (X^T C^{-1} X)$. The kriging variance depends only on variogram and configuration of the sample (Curran and Atkinson, 1998).

The isotropic variogram averages the sample variance in all directions. It depends upon the separation distance ($|h|$), and not upon the orientation. However spatial dependence of samples may vary in different directions. If spatial dependence of a phenomena is stronger in a particular direction is as compared to other directions, this phenomenon is said to be anisotropic. Kriging interpolation can be improved by accounting for the anisotropic effects. The anisotropy can be handled by reducing the anisotropic variogram to an isotropic one (Journel and Huijbregts, 1978). Anisotropy has two types: geometric and zonal anisotropy. In geometric anisotropy, range of spatial

dependence varies in different directions with constant sill while in zonal anisotropy both range and sill vary with direction.

Geometric anisotropy can be corrected by identifying the directions of maximum and minimum ranges and taking them as major and minor ellipse axes respectively. Then ellipse is transformed into a circle by elongating the minor axis to major axis of the ellipse (Figure 4B.3).

Figure 4B. 3: a) Isotropic variogram modelled by spherical function. b) Variogram map showing the spatial continuity in north-south direction.

Suppose $a_{\max}$ is the maximum range and $a_{\min}$ is the minimum range of spatial dependence forming an ellipse with major and minor axis respectively (Figure 4B.4). The equation 9 shows transformation of geometric anisotropy to isotropy:

$$h' = D_{\beta} \cdot R \cdot h \quad (9)$$

where h is a lag distance vector in two dimensions, $R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$ is a rotational matrix and $D_{\beta} = \begin{bmatrix} 1 & 0 \\ 0 & \beta \end{bmatrix}$ is a diagonal matrix for the anisotropy ratio $\beta = \frac{a_{\min}}{a_{\max}} < 1$.

Zonal anisotropy can be accounted for by preparing a nested variogram model having each zonal component of variability. For example a two component nested model (Journel and Huijbregts, 1978) is given as:

$$\gamma(h) = \gamma_1(|h|) + \gamma_2(h_{\phi}) \quad (10)$$

where the first component $\gamma_1(|h|)$ is an isotropic or model corrected for geometric anisotropy, and the second $\gamma_2(h_{\phi})$ is a zonal component. A general expression for such model can be written as follows:

$$\gamma(h) = \sum_{i=1}^n \gamma_i(|h_i|) \quad (11)$$

A $\gamma(h)$ has a summation of n nested components.

Figure 4B. 4: Schematic diagram for correction of geometric anisotropy

A variogram map and directional variograms were prepared to evaluate the spatial dependence of the measurements. The empirical directional variograms were calculated at angles (0° , and 90°) with cutoff value of 12000 m, a bin size of 500 m and tolerance value as $\pm 45^\circ$. Since the fault movement was in the north-south direction (0° angle), the spatial continuity would be maximum in direction of 0° angle and minimum in its perpendicular direction (90° angle). The geometric anisotropy was investigated by directional variograms and the rose diagram. The geometric anisotropy was corrected for by fitting spherical function to empirical variogram in the direction of maximum continuity. The ellipse's minor axis was made equal to major axis using anisotropy ratio. This ratio was determined as the ratio of the minimum to the maximum range of spatial dependence. The spherical function relates the lag distance h and finite range of spatial dependence ' a ' and is given below:

$$\gamma(h) = \begin{cases} 1.5 \frac{h}{a} - 0.5 \left(\frac{h}{a}\right)^3 & \text{if } h \leq a \\ 1 & \text{otherwise} \end{cases} \quad (12)$$

Ordinary kriging was applied to interpolate missing coseismic values using isotropic geometric-anisotropy-corrected variogram models respectively. Finally, coseismic displacement maps for both variogram models were prepared respectively by combining the interpolated values with the existing values

4B.2.3 Accuracy assessment

Cross-validation (CV) was applied to existing coseismic displacements in order to assess the accuracy of the interpolation. In cross-validation one displacement value is removed and the remaining data are used to estimate the model. The removed sample point is interpolated using the estimated variogram model. The difference between the actual and interpolated value is calculated and the process is repeated for all sample points. This is called leave-one-out cross-validation (LOOCV) and deviations are summarized in the form of the mean error (ME) and the root mean square error (RMSE). RMSE provides an average measure of difference between the observed and the estimated values, whereas ME quantifies bias and shows whether the predicted values are systematically higher or lower than the reference values. They were calculated by Equation (13) and Equation (14).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{z}(u_i) - z(u_i))^2}{n}} \quad (13)$$

$$ME = \frac{1}{n} \sum_{i=1}^n (\hat{z}(u_i) - z(u_i)) \quad (14)$$

where $z(u_i)$ is the observed value, $\hat{z}(u_i)$ is the estimated value at location u_i and n is total number of values.

4B.3 Results

Horizontal coseismic displacements calculated using pixel tracking are shown in Figure 4B.1(b). It is a 15×30 km area containing the main deformation site. A clear discontinuity can be marked in south of the city of Bam, that is known as the earthquake causative fault. The missing values are mainly at the urban areas of Bam and Baravat shown in black. In south of the city, the coseismic values are scattered and are of low magnitude. An isotropic variogram modelled by spherical function, shows average variability of measurements in all directions. It is fitted well near the origin by a smooth curve, whereas there are some deviations near the sill.

A variogram map revealed that the spatial continuity of measurement is in north-south direction (Figure 4B.3(b)). A rose diagram (Figure 4B.4(a)) shows the variability of the measurements in four directions (0°, 45°, 90°, 135°). It gave highest spatial continuity in north-south direction (0°), whereas minimum in east-west direction (90°). This was identified as a

geometric anisotropy with different range of spatial continuity for the fixed sill value. It was corrected by taking the variogram in highest spatial continuity (0°) and anisotropic ratio of the range of 90° variogram to the range of 0° . This converted the geometric anisotropy model to an isotropic model. Now the empirical variograms in 0° and 90° were modelled by one spherical function (Figure 4B.5). The 90° variogram was modelled better as compared to 0° empirical variogram. Its reason may be that the 90° empirical variogram has much shorter range than the 0° variogram.

Figure 4B. 5: Fitted spherical model after accounting the geometric anisotropy. The empirical variograms (at 0° and 90°) showing approximately same sill value with different range of spatial dependence.

The missing values were interpolated by applying OK based on isotropic and geometric anisotropy corrected variogram models respectively. The coseismic displacement maps, for the each variogram model, were prepared by combining the existing values with interpolated values. The prepared displacement maps are shown in Figure 4B.6. The coseismic displacement maps for the model show the continuity of the seismogenic fault underneath the city of Bam. The map produced with geometric anisotropy corrected

model (Figure 4B.6(a)) show more clear pattern of the fault continuity than the map of isotropic model (Figure 4B.6(b)). This demonstrated the effect of anisotropy correction for interpolating the missing coseismic displacements.

Figure 4B. 6: Horizontal (AZO offsets) coseismic displacement (m) maps. (a), OK interpolation based on isotropic variogram and (b), OK interpolation based on geometric anisotropy corrected variogram model.

Figure 4B.7 shows the accuracy assessment of OK interpolation using the cross-validation. The majority of points for interpolated vs actual are close to 1:1 and regression line. The ME = -5.89×10^{-7} m being close to zero, whereas

the RMSE = 0.11 m. These results demonstrate that the OK interpolated the missing coseismic values accurately. The 0.1 m RMSE is well below the detection limit (0.2 m) of the pixel-tracking technique for ASAR images. The lower inset image give histogram of residuals that shows the difference of actual and interpolated values is close to zero for most of the measurements. The upper inset image shows the spatial distribution of the residuals. It represents that the residual is high where there are less neighbouring measurements.

Figure 4B. 7: Cross-validation results plot for predicted vs actual. The lower inset image shows histograms of residuals while the upper gives spatial distribution of residuals.

4B.4 Discussion

The present study demonstrated that OK interpolated the missing coseismic displacements accurately. The interpolation results based anisotropy corrected variogram showed more clear discontinuity than the isotropic model results. This necessitates that the anisotropy correction is important in order to represent the true spatial dependence structure of the measurements.

The isotropic variogram was fitted well particularly near the origin and described clearly spatial structure. The variogram fitted well near the origin is important as fitting accuracy near the origin is important because OK interpolates based on the local spatial dependence which is mostly reflected by the first few lags of the variogram (Kleijnen and van Beers, 2005). The nugget effect was also very small (0.009). This showed that the measurements were highly dependent on their neighbourhood values. The nugget value shows the unexplained variability by the model and it may be due to the micro-variability of the measurements (Cressie, 1993). The small nugget values produce more accurate interpolation results than those with larger nugget values (Karl, 2010).

The geometric anisotropy was addressed by reducing the directional variograms to an isotropic model. The directional variogram represents variability of the measurements in a particular direction using the samples from the defined area set by the tolerance value. In our case we used the tolerance value of $\pm 45^\circ$ because we were interested in variability of the measurements along and across the fault. Particularly the along fault variability was more important in order to investigate the fault continuity at the city of Bam. On the other hand narrow direction angles imply narrow tolerances and may produce other types of anisotropy e.g. zonal or combination of geometric and zonal. The shapes of both variograms (isotropic and geometric anisotropy corrected) were identical near the origin up to the shoulder and differed in the transition of shoulder to sill. This revealed that at shorter lags both variograms are isotropic i.e. the variance is constant while at a longer distances the behaviour of variance changes.

The coseismic displacement maps, based on the isotropic and anisotropy corrected models, were similar. This is because of the similarity of two variogram models near the origin as the first few lags of the modelled variogram are the most important ones for kriging interpolation (Kleijnen and van Beers, 2005). The differences are due to variability at longer distances that were small. The results of both models showed presence of discontinuity at the location of Bam city that contained the most of the interpolated values. However the interpolated results based on anisotropy corrected model gave clearer pattern of the fault discontinuity. This demonstrated the need of anisotropy correction for having true spatial continuity of the measurements along the geological fault.

The coseismic displacement maps showed that the continuity of the fault apparently is slightly eastward (Figure 4B.6(b)). The eastward shifting may be justified based on the hypothesis (Talebian et al., 2004; Stramondo et al., 2005) that the fault joins the northern fault segment underneath Bam. The northern fault segment (visible only on the LOS displacement map (Yaseen et al., 2013)) is north-east of the earthquake causative fault. The azimuth

offsets do not show the presence of such fault segment. It may be due to low magnitude of coseismic displacements which are below the detection limit of pixel tracking technique. For evidence of continuity of the fault beyond the city of Bam and join with northern fault segment, extra geological and geophysical investigation is needed.

The accuracy of the interpolation could not be assessed due to lack of validation dataset. Cross-validation (CV) was adopted for the assessment of the interpolation as an alternate to the actual validation. CV results showed accurate performance of the OK interpolation however higher inaccuracy at the boundaries of groups of missing values particularly at the urban areas of Bam and Baravat. This can be justified as the dependence of measurements on the neighbouring value play major role in the interpolation. Therefore the CV produced larger residuals where sample density decreases (Falivene et al., 2010) as the spatial configuration of the sample points affect the reliability of the variogram model for the interpolation (Lark, 2002; Zhu and Lin, 2010).

The study established the usefulness of OK for interpolating the missing coseismic displacements. In the present study, the interpolated missing coseismic values revealed the continuity of the earthquake causative fault underneath the Bam. The fault discontinuity was more prominent and clear from the interpolated results based on anisotropy corrected model as compared to the results of the isotropic model.

4B.5 Conclusion

The coseismic displacement measurements are spatially auto-correlated and show a highly continuous process. The coseismic displacements “regionalized variable” showed an anisotropy demonstrating the presence of the geological fault. Missing coseismic displacements were accurately interpolated based on anisotropy corrected variogram. The earthquake causative fault slipped in north-south direction (right lateral strike-slip) during the earthquake, the movement of the fault has manifested by the longest variogram range in the north-south direction. The isotropic and anisotropy corrected variogram models showed isotropy at smaller lags, as they have similar fitting shape near the origin. Whereas they differed at longer distance hence show anisotropy. The cross-validation results showed accurate estimates of the coseismic displacements demonstrating that kriging serves as a powerful tool to interpolate the missing values accurately. The interpolation results based on the variogram model corrected for geometric anisotropy were more accurate than the results of the isotropic model. The continuity of the seismogenic fault underneath the Bam city is clear from the interpolated results, particularly the results based on anisotropy corrected model.

Chapter 5: Application of a discontinuity-adaptive Markov random field to construct the 3D displacement field for the 2003 Bam earthquake

This chapter is based on:

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Abstract

A comprehensive understanding of earthquake processes needs a detailed analysis of coseismic displacements. A full 3D coseismic surface displacement field may then be helpful to obtain a better insight and detailed interpretation of the underlying earthquake dynamics. InSAR provides displacement vectors in the LOS (line of sight) direction, but it suffers from the limitation of not producing displacements near the seismogenic fault. It is, therefore, only partly suited for earthquake investigation studies. Azimuth offsets (AZO) provide horizontal displacements at an order of magnitude lower precision than InSAR, but more robust. This study demonstrates the applicability of a discontinuity-adaptive Markov random field (MRF-DA) for constructing a 3D displacement field. It combines LOS and AZO displacement vectors using the ascending and descending orbits of an ASAR image pair. In this way we were able to exploit the contextual information of neighbouring measurements of the input LOS and AZO displacement maps for the 3D surface displacement field. The MRF along with the SA algorithm provided the optimal solution by minimizing Gibbs energy functions. It showed a large improvement in results obtained by the MRF-DA model. Interpretation of the constructed 3D displacement field for the 2003 Bam earthquake revealed that the earthquake was along the right-lateral strike-slip fault, with a small component of thrust and a block rotation into the east-west direction. The study concludes that MRF-DA provides superior accuracy in 3D displacement results as compared to the conventional weighted least squares (WLS) model.

Keywords: Markov random field, InSAR, 3D displacement field, coseismic displacements, Bam earthquake

5.1 Introduction

Earthquakes occur due to a sudden release of long accumulated energy in the Earth's subsurface. This release of energy causes coseismic displacements of the Earth surface, usually on geological faults. Coseismic displacements refer to relative movements along the geological fault at the instant of the earthquake. Coseismic displacements can be measured in the field using conventional geodetic methods. Those methods can provide accurate measurements, but they are feasible only at a limited number of locations, being laborious and time consuming. As an alternative, remote sensing provides a synoptic view and is capable of producing a spatially dense continuous displacement field, because coseismic displacements are commonly distributed over a wider deformation zone along a geological fault (Michel et al., 1999). Such space geodetic observations are used to infer properties of the surface coseismic displacement field. In this way, a coseismic displacement field can provide detailed information on, for instance, the amount and distribution of a slip on the fault, the extent of a deformation, mechanical properties of the fault and the potential source mechanism of the earthquake (Fialko et al., 2001).

In this study we concentrate on the use of synthetic aperture radar (SAR) remote sensing data. SAR Interferometry (InSAR) is a commonly used SAR based technique to accurately measure coseismic displacements. InSAR measures line-of-sight (LOS) displacements that can be registered well, in particular in the vertical direction (Figure 5.1). The fact that InSAR does not produce a horizontal displacement component, can be complemented by using cross-correlations with SAR amplitude images (Fialko et al., 2001). The method of cross-correlations is called pixel tracking technique (Michel et al., 1999; van Puymbroeck et al., 2000; Ayoub et al., 2009). In this way, displacement components in the horizontal direction called azimuth offsets (AZOs) can be provided. InSAR exploits the phase information and provides measurements with precision being smaller than the radar wavelength, equal to 5.6 cm for C band SAR images. It thus provides an advantage with respect to pixel tracking (for azimuth offsets), for which the precision amounts a fraction of the azimuth spatial resolution, being e.g. equal to 4 m for ASAR sensor.

The 3D displacement field comprises three orthogonal components in north-south, east-west and vertical directions. InSAR and pixel tracking cannot measure these three components directly, because they give displacements into the range (LOS) and azimuth (AZO) directions respectively of the sensor. The measured LOS and AZO displacement vectors are the projection of the 3D displacement vector. A 3D displacement field can then be derived from these projections if we have three or more coseismic measurements from independent viewing geometries from both ascending and descending orbits.

In the past, a 3D displacement field was obtained by integrating the InSAR and pixel tracking results using images from ascending and descending orbits (Fialko et al., 2001; Wright et al., 2004; Funning et al., 2005; Pathier et al., 2006; Wang et al., 2007; de Michele et al., 2010). A conventional weighted least square (WLS) approach was applied to account for different accuracies of the observations. Studies so far considered the measurements as being spatially independent from each other. Such an assumption is not realistic, however, as displacements of the Earth surface have a strong spatial correlation, exhibiting discontinuities at faults. To accurately represent a 3D displacement field, there is a need to exploit the spatial dependence of the measurements. This can be done by using the contextual dependence of the measurements using Markov random field (MRF) theory (Geman and Geman, 1984). MRFs have been used for various applications including noise filtering and image classification (Li, 2009).

The objective of the present study is to use MRFs to reconstruct a 3D displacement field by integrating the four coseismic displacement maps obtained by InSAR and pixel tracking using both the ascending and descending orbit ASAR image pairs. The novelty of the study is that spatial dependence of the measurements are exploited through MRF for integrating LOS and AZO displacements in order to accurately retrieve the three orthogonal components of the coseismic displacements.

5.2 Data and pre-processing

The present study calculates the 3D coseismic displacement field for the 2003 Bam earthquake. The study area details are provided in chapter 1, section 1.2.

The present study was completed using ENVISAT-ASAR images of pre- and post-earthquake from both ascending and descending orbit. The pre- and post-earthquake images from the descending orbit are dated 3 December 2003 and 11 February 2004 respectively, with a difference of 70 days. For the ascending orbit, the pre- and post-earthquake images were acquired on 16 November 2003 and 25 January 2004, respectively, with a difference of 70 days. The images are in IS2 mode, having an incident angle of 23° , VV polarization and a single look complex (SLC) format. Satellite headings with respect to the north are equal to 192° and 348° for the descending and ascending orbits, respectively.

The LOS and AZO displacements were calculated using ROI_PAC (Repeat Orbit Interferometry Package) software (Rosen et al., 2004). The ascending orbit image, however, does not cover the lower left corner of the study area. LOS displacement maps were prepared on 25 m grid spacing calculated by using the phase information of pre- and post-earthquake images from the ascending and descending orbits. AZO displacement maps were prepared on

grid spacing of 200 m were calculated using pixel information (amplitude) and thus depend on the spatial resolution of the images used.

All LOS and AZO displacement maps have locations where the displacement values could not be measured due to the loss of coherence of pre- and post-earthquake images. Such displacement values were termed 'missing values' and before integrating the displacement maps for constructing 3D field, these missing coseismic values were interpolated. Derivation of coseismic displacements and the interpolation of missing coseismic values using kriging were presented in our previous work (Yaseen et al., 2013; Yaseen et al., 2013). After deriving the missing values, the LOS displacement maps were brought on a common grid spacing of 200 m for constructing the 3D coseismic displacement field.

5.3 **Methods:**

Let $F_i = [f_{i1}, f_{i2}, f_{i3}]'$ be the vector of the Earth surface displacement (in m) taking place between two dates for a location indexed by $i = 1, \dots, M$, where the prime denotes transposition. The locations represent centres of pixels in a raster image. The three components of F_i are the local north, east and vertical directions, respectively. We assume that displacement is much smaller than the distance between any two locations. Further, let $D_i = [d_{i1}, d_{i2}, d_{i3}, d_{i4}]'$ be the coseismic displacements (in m) for location i derived from SAR images using InSAR and pixel tracking (amplitude matching). The four components of D correspond to LOS descending, LOS ascending, AZO descending and AZO ascending directions, respectively. The acquisition geometry for the ascending orbit images is shown in Figure 5.1.

Figure 5. 1: The acquisition geometry for ENVISAT-ASAR scenes from ascending orbit. The ASAR antenna is right looking. A local frame of reference in East, North and vertical direction is shown in blue. The configuration of LOS and AZO displacement vectors (red) is expressed for a single pixel (i) from the ascending orbit image. The 3 orthogonal displacement components (green) in the same reference frame are the projections of the displacement vector F on the LOS and AZO direction. θ is a radar incidence angle from the vertical and α is an angle between satellite orbit heading and the North.

F_i and D_i are related by:

$$D_i = X \cdot F_i + e_i \quad (1)$$

where $e_i = [e_{i1}, e_{i2}, e_{i3}, e_{i4}]'$ is the noise and X is 4×3 projection matrix describing the acquisition geometry of the observations:

$$X = \begin{bmatrix} \sin \theta \sin \alpha_d & -\sin \theta \cos \alpha_d & \cos \theta \\ \sin \theta \sin \alpha_a & -\sin \theta \cos \alpha_a & \cos \theta \\ \cos \alpha_d & \sin \alpha_d & 0 \\ \cos \alpha_a & \sin \alpha_a & 0 \end{bmatrix} \quad (2)$$

Here θ is an incidence angle (same for the study area for ascending and descending orbits), α_d is a descending orbit heading and α_a is an ascending orbit heading. For a small extent image these angles can be assumed constant.

Our task in this study is to estimate F_i given D_i for every location $i = 1, \dots, M$. Under assumption of spatially uncorrelated displacements the weighted least square (WLS) solution for Equation (1) is

$$\hat{F}_i = (X^T \Sigma^{-1} X)^{-1} X^T \Sigma^{-1} D_i \quad (3)$$

where Σ is the matrix of weights employed to handle the different level of accuracy of components in D . The displacement values $\{d_{i1}, d_{i2}\}$ derived from InSAR have an accuracy of an order of magnitude higher than the displacement values $\{d_{i3}, d_{i4}\}$ that were derived from pixel tracking. Hence we define Σ as a diagonal matrix containing the variances of the observations. The weights can be derived from the analysis of the far field variance of each dataset as shown in (Wright et al., 2004; Funning et al., 2005). The variances are assumed to be independent of each other and are stored in the leading diagonal of the matrix.

To account for spatial dependence of the displacement vector F we model it as an MRF with the second order neighbourhood system N_r containing the 8 nearest neighbours of the pixel of interest. A probability density function for Markov random field F can be specified by the Gibbs random field (see Li (2009) for more details).

$$P(F) = \frac{1}{Z_p} \exp \left(-\frac{U(F)}{T} \right), \quad (4)$$

where Z_p is a constant independent of F , T is a constant termed temperature and the spatial dependence of F is described by the prior energy function

$$U(F) = \sum_{i=1}^M U(F_i | F_{N_i}) = \frac{1}{2} \sum_{i=1}^M \sum_{j \in N_i} w_j \frac{\|F_i - F_j\|^2}{a^2}, \quad (5)$$

where $\|\cdot\|$ is the norm of the argument, $a = 0.01$ m is a constant introduced for convenience, w_j is the weight associated with neighbour j in the neighbourhood N_i of pixel i , chosen inversely proportional to the distance between centres of pixels i and j and normalized as

$$\sum_{j \in N_i} w_j = 1 \quad (6)$$

The prior energy (5) favours smooth solutions for F and penalizes differences between the displacement values of the neighbours. The likelihood of D_i given F_i is modelled as:

$$P(D_i|F_i) = \frac{1}{Z_i} \exp\left(-\frac{U(D_i|F_i)}{T}\right) = \frac{1}{Z_i} \exp\left(-\frac{1}{2}(X \cdot F_i - D_i)' \Sigma^{-1}(X \cdot F_i - D_i)\right) \quad (7)$$

where Z_i is a constant independent of F . This model assigns the highest probability to the solution of (1) when the noise term equals zero, whereas probabilities decrease for higher noise magnitudes.

Combining the likelihood and the prior terms using Bayes' formula we get the posterior probability of F given D :

$$P(F|D) = \frac{1}{Z} \exp\left(-\frac{U(F|D)}{T}\right) = \frac{1}{Z} \exp\left(-\frac{\sum_{i=1}^M U(F_i|D_i, F_{N_i})}{T}\right) \quad (8)$$

with the local posterior energy function

$$U(F_i|D_i, F_{N_i}) = \lambda U(F_i|F_{N_i}) + (1 - \lambda)U(D_i|F_i) \quad (9)$$

where λ is the scalar smoothness parameter used to balance the prior and the likelihood terms.

A maximum a posteriori MRF (MAP-MRF) solution for the displacement field F is obtained by maximizing the posterior probability (8), or equivalently, minimizing the posterior energy function $U(F|D)$, with respect to F .

MAP-MRF provides a spatially smooth displacement field F based on the local spatial structure of the displacement measurements D . A wide range of physical phenomena are modelled by assuming a generic smoothness that is characterized by the coherence and homogeneities in it. For a coseismic displacement field, however, such smoothness is not desirable along the earthquake causative faults because it will not properly represent the geological fault (discontinuity). In earthquake studies detecting and characterizing the geological fault is one of the prime objectives. Hence, to preserve the discontinuity in the 3D coseismic displacement field, a discontinuity adaptive (DA) smoothness model is introduced. The prior energy or probability is responsible for smoothness by exploiting interaction between the neighbouring measurements. The DA model is implemented by defining a threshold value on the norm of the difference of displacements in (5):

$$U_{DA}(F) = \sum_{i=1}^M U_{DA}(F_i|F_{N_i}) = \frac{1}{2} \sum_{i=1}^M \sum_{j \in N_i} w_j \frac{\max(\|F_i - F_j\|^2, h^2)}{a^2}. \quad (10)$$

In this way, displacement differences smaller than h are considered as noise and penalized proportionally to the square of the difference while for the larger difference value the penalty is limited.

Minimization of the energy function $U(F|D)$ provides the optimized solution of three orthogonal components of the displacement field. This can be achieved

after constructing the global energy function, estimating the initial parameters and then calculating its MAP estimate. The analytical optimization of the problem is intractable due to the large number of possible configurations of F . Therefore simulating annealing (SA) was applied to obtain the MAP solution (Kirkpatrick et al., 1983; Li, 2009). For faster convergence of the algorithm, an initial 3D displacement solution, calculated by means of WLS, was provided. The temperature T is first set to an initial value T_0 , and then iteratively updated

$$T(t) = T_0 \times T_{\text{upd}}^t \quad (11)$$

where t is the iteration number. The Metropolis-Hastings sampling procedure (Geman and Geman, (1984) was applied with the candidate distribution chosen as normal, centred on the current displacement value F_i , and a constant standard deviation 0.05 for every component of the vector F . SA continues until the system is frozen, i.e. $T(t) \rightarrow 0$ and no updates in Metropolis-Hastings procedure are accepted during 3 consecutive iterations over the entire image.

The proposed model has two model parameters that must be estimated: λ and h . To estimate the optimal values of these parameters, a training dataset (a subset of the full dataset shown in Figure 5.2) is used.

In this area we define two areas of 3×8 pixels on the two sides of the discontinuity. The mean and the standard deviation of each of the 3 displacements components in those areas are used to optimize the parameters. We first identify the absolute value of the difference, G_i , between the mean values of the two areas in displacement component i . Next, we calculate the standard deviation σ_i of a displacement component inside each area. The optimal combination of parameter values then minimizes the standard deviation inside each area, while preserving the value of G_i .

5.4 Results

The 3D displacement results were extracted from the four input displacement maps (LOS_d , LOS_a , AZO_d and AZO_a) using the discontinuity adaptive MRF (MRF-DA) based model. Each of the four displacement maps has 148 lines and 69 columns with a grid spacing of 200 m. LOS_d and AZO_d displacement maps are shown in Figure 5.2. The figure shows that the AZO map is noisy, particularly 2 to 3 km away from the earthquake causative fault.

The MRF model parameters were determined first using a test area (red box in Figure 5.2) of 20×24 pixels containing the geological fault as a discontinuity (Figure 5.3). A final set of parameters was selected that produced the optimal solution in terms of the results that have minimum energy, fast convergence, lowest standard deviation, that preserved

discontinuity. They showed a smooth displacement values on either side of the discontinuity.

Figure 5. 2: (a) Line-of-sight (LOS) and (b) azimuth offsets (AZO) displacement maps from descending orbit images. The red box is a subset used for calculating the MRF parameters. The black lines are horizontal profiles drawn along which the displacement values are compared.

The four input displacement maps for the test area are shown in Figure 5.3. Both AZO_d and AZO_a are noisy and do not reveal the presence of any discontinuity. To find the optimal parameters for the SA algorithm, we used a test area subset. The test area was selected such that it contained the fault and one region to its east and one to its west. Figure 5.4 shows variations of G (the mean difference of displacements across the fault) with their respective standard deviations. The vertical and east-west component of

displacement show that threshold values ranging from 0.0001 to 0.07 do not affect G significantly. However, the north-south component shows G variations at a few points when choosing different threshold values. A threshold value of 0.08 provides the optimal prominence of the G for all three components of the displacement. The respective standard deviation values at the left side (open symbol in Figure 5.4) and right side (filled symbol) show almost similar values for vertical and east-west components, whereas for the north-south component it varies. The standard deviation attains its minimum value at the threshold of 0.08 for all three displacement components. Variations in north-south displacement component may again be attributed to intrinsic noise of azimuth offsets.

A similar analysis was applied for finding the optimal value of the smoothing parameter (λ). From Figure 5.4 (lower half) the value of 0.9 of the smoothing parameter shows the lower effect on the value of G for all three displacement components. The respective standard deviation is lowest at the value of $\lambda = 0.9$ for all three displacement components. Therefore optimal values of 0.08 for h and 0.9 for λ were obtained respectively. These values gave a compromise in preserving the discontinuity and smoothing the variation of the displacement field.

Figure 5. 3: Four input displacement maps for the test area. The red and yellow lines show horizontal and vertical profiles respectively.

Figure 5. 4: Comparison of different threshold (h) (fig. 5.4a) and smoothing parameter (λ), (fig. 5.4c) values against G (displacements difference across the discontinuity), whereas (fig. 5.4b & fig. 5.4d) show their respective standard deviation plots, for preserving the discontinuity. The open symbols in the graph show standard deviations on left side of the discontinuity while the filled symbols give standard deviation on right side of the discontinuity.

The values of initial temperature T_0 and updating T_{upd} were determined based on the results for the test area. The value T_0 agrees with that recommended in the literature (Geman and Geman, 1984; Tolpekin and Stein, 2009) and $T_0 = 3.0$, whereas the value of T_{upd} is higher (0.999). The SA took approximately 6500 iterations to converge and provided the optimised solution of 3D displacement field.

Using these parameters, the MRF-DA model was applied to the full dataset. Results are given in Figure 5.5 (panel C). The lower left part is missing for all three displacement components due to incomplete coverage of the scene from the ascending orbit. For comparison with MRF-DA, the results were also prepared using WLS and MRF without DA (MRF) models respectively and are shown in Figure 5.5 (A & B). The statistics of results from the three models are given in Table 5.1.

A comparison of the results from the three models shows that the WLS model provides a noisy output, particularly for the north-south displacement component. The geological fault is less prominent from the WLS model and also the displacements do not have a smooth variation on either side of the fault. It further blurs the natural pattern of displacements across the geological fault. The results of the MRF without DA model show a high degradation of discontinuity at the geological fault. The displacements vary smoothly, but have irregularities in the 3 displacement components. We attribute those irregularities to oversmoothing by MRF model. The natural pattern of the displacement is disturbed particularly in east-west displacement component. In contrast to the results of WLS and MRF without DA models, the MRF-DA model results show a well-preserved geological fault and smooth variation of displacements on either side of the fault. The displacements have their natural pattern as produced by an earthquake mechanism of the strike-slip movement with a small component of thrust. The north-south displacement component of the MRF-DA model shows some artefacts, mainly at interpolated values of Bam and Baravat urban areas, which do not fit into the neighbouring displacements.

We note that the east-west and vertical components show an asymmetric displacement pattern, thus indicating a stronger motion on the eastern side of the fault than on its western part. There is a subsidence of 15 cm to the north of Bam and a 24 cm uplift in the south. The highest displacement (63 cm) was calculated in the north-south direction. This makes the earthquake predominantly be caused by a displacement along the right-lateral strike-slip fault.

Table 5.1 shows the statistics from 3 model outputs for all displacement components. The standard deviation of the vertical component is much lower than that of the other two components. WLS underestimates the east-west and vertical components of the displacement more than MRF-DA. This may

be attributed to an inaccurate weight estimation in WLS approach. On the other hand, the MRF model results show a stronger underestimation in the north-south and vertical components of the displacement than the MRF-DA model. The displacement values of the east-west components are the same for both models, but the standard deviation is much higher for the MRF model. Interpretation of the results (Figure 5.5 and Table 5.1) shows that the MRF-DA model thus shows a smooth variation of displacement values with well-preserved discontinuity for all three displacement components. The WLS results are less smooth and show less prominent earthquake causative fault in comparison with the MRF-DA model.

Table 5. 1: Statistics for the three displacement components using MRF-DA, MRF, and WLS models. All measurements are in meters.

		min	max	mean	stdev
MRF-DA					
	North	-0.6341	0.6110	-0.0621	0.1085
	East	-0.4768	0.3237	-0.0219	0.1268
	Vertical	-0.1500	0.2405	0.0104	0.0585
MRF					
	North	-0.4085	0.5127	-0.0652	0.1080
	East	-0.4768	0.3237	-0.0428	0.1416
	Vertical	-0.1241	0.2250	0.0101	0.0573
WLS					
	North	-0.6353	0.5469	-0.0657	0.1365
	East	-0.2257	0.2392	-0.0235	0.1267
	Vertical	-0.1425	0.2348	0.0099	0.0587

Figure 5. 5: Three displacement components when using WLS model (A). The panel (B) shows MRF results without DA model. The panel (C) are the results derived through MRF based DA (MRF-DA) model.

For further analysis of displacements, the geological fault evidence and identification, the results of five horizontal profiles (P1...P5) shown in Figure 5.6 are used. The figure provides a quantified behaviour of the geological fault for MRF-DA, MRF and WLS models results. The profiles show abrupt changes in displacement values across the discontinuity (geological fault).

Figure 5.6 shows that the vertical component of the displacement has a smoother displacement variation for all three models as compared to the other two components. WLS results show more noise than the other two models results, particularly for profiles 1 & 2 that are in the north where the input maps are noisier. The WLS model for the north-south component of the displacement show the highest noise along all profiles and medium noise for the east-west component. The MRF model has more noise than the MRF-DA model for the east-west component along the profiles. Profile 3 shows a small break for the MRF-DA result for the north-south displacement component, due to the artefact present in that component at the location of Bam city. Profiles 4 and 5 show displacements only on the right side of the geological fault, because of shortage of the ascending orbit images. Hence the displacement values could not be produced reliably for the lower left corner of the study area.

The vertical grey bar shows the approximate location of the earthquake causative geological fault. Profiles 1 and 2, north of Bam city, show a small indication of the fault for MRF-DA model, that is absent in MRF and WLS models results. These profiles show east-west displacements (~ 6 cm) for MRF-DA results, for the vertical displacement there is no substantial movement for all models. Profiles 3, 4 and 5, south of Bam city, show mainly north-south displacements, medium east-west displacement and small vertical displacements. The vertical displacements are away and on the right side of the geological fault.

Figure 5. 6: Comparison of displacement values from MRF-DA, MRF and WLS models along the horizontal profiles (P1...P5 shown in Figure 5.1) for the 3 displacement components. The grey vertical column shows approximate location of the geological fault.

5.5 Discussion

The present study demonstrates the derivation of 3D coseismic displacement field by means of combining the LOS and AZO from ascending and descending ASAR images using a discontinuity adaptive MRF model. We have extracted the synoptic view of a 3D displacement field of earthquake-hit Bam area. In the past, this 3D displacement field was extracted from ascending and descending LOS and AZO displacement maps using the WLS approach. MRF exploits the spatial relationships of the neighbouring observations. It preserves the spatial correlation of the observations. In our study, in deriving the 3D displacement field by combining the four sets of observations (LOS and AZO from ascending and descending orbit images) having different level of noise, MRF worked on the concept that the observations are similar to their surrounding observations. Preservation and prominence of the earthquake causative fault was ensured by means of an MRF based discontinuity adaptive model. Calculation of model parameters is an important task for obtaining an accurate 3D displacement field.

We demonstrated how the smoothing parameter and the DA model threshold could be estimated (section 5.4). A compromise between noise reduction and oversmoothing is determined by selecting a smoothing parameter value of 0.9. It actually balanced the prior and likelihood energy functions of the MAP-MRF model. A threshold value equal to 0.08 m decided what minimum difference value of the displacements has to be preserved. The north-south displacement component show higher variation (Figure 5.4) in G and standard deviation (σ) as compare to the other two displacement components. It is because of a noisy AZO with a major contribution in north-south component.

The SA parameters, T_0 and T_{upd} , control the quality of the MAP-MRF solution and the computation time. We found that the value $T_0 = 3$ is similar to results of other studies (Geman and Geman, 1984; Li, 2009; Tolpekin and Stein, 2009), while T_{upd} was set to a higher value indicating a need for a slower SA to reach the global minimum of posterior energy function. We attribute that to the dimension of the solution space of our problem.

The 3D displacement field produced by MRF-DA showed smooth spatial variation particularly south of the city of Bam. The 3D displacement field revealed that the earthquake causative fault is mainly right-lateral strike-slip due to its largest movement (63 cm) in north-south direction with a small component of thrust. There is an uplift and subsidence at the edges of strike-slip fault as shown by the vertical component in Figure 5.5. Evidence of small block rotation in east-west direction is exhibited by the east-west displacement component. It shows that the southern part of the study area moves in south-east direction while the northern part moves in the south-west direction suggesting a shortening of ground in Bam area. This is also

demonstrated in the areas north of the city of Bam where a small discontinuity exists due to the westward ground movement. There a local pattern of deformation is revealed showing the complex thrust component along the fault.

Differences of the three methods (MAP-MRF with DA, MAP-MRF and WLS) were highlighted by a comparative analysis of the results for the three displacement components. Effectiveness of the MRF model is demonstrated from the horizontal profiles across the fault. The vertical component shows nearly similar results for all three models, whereas WLS results are noisier than the other two. For the east-west component, MRF and WLS are approximately similar whereas MRF without DA shows major deviations. The north-south displacement component represents the most noisy results for WLS whereas MRF-DA results are smoother. The vertical component results for MRF-DA, MRF and WLS have a high precision, the east-west component has a moderate precision, whereas the north-south component has the lowest precision. The reason is that the vertical component has its major contribution from the LOS image, and the east-west component has a medium LOS contribution. The north-south component has no LOS contribution and has its entire contribution from the AZO displacement maps (Fialko et al., 2001; Funning et al., 2005). Hence from this discussion once again it is evident that the MRF-DA model is comparatively more accurate than the other two models and less noisy.

MRF proved useful in deriving the 3D displacement field. It demonstrated that contextual information of observations along with application of discontinuity adaptive function can be helpful in getting the smooth displacement field with well-preserved earthquake causative fault. The study was hindered by the absence of exclusive validation dataset for accuracy assessment. Our results, however, are in close agreement to the results of previous studies (Fialko et al., 2005; Funning et al., 2005; Sarti et al., 2006; Erten et al., 2010; Hu et al., 2010) on the 2003 Bam earthquake. As the Bam earthquake is well studied geologically and with remote sensing data, therefore this deficiency was compensated to some extent. This can be further investigated with the use of auxiliary information, for example displacement values from additional pair(s) of images can be used.

5.6 Conclusions

The study demonstrated the successful derivation of a 3D coseismic displacement field using discontinuity adaptive Markov random fields (MRF). It showed that SAR Interferometry and sub-pixel correlation can be combined by means of MRF for determining the 3 orthogonal displacement components, even though their results are of a different precision. Further, it demonstrated that the use of spatial dependence of measurements can give

superior results as compared to the least square solution (e.g. WLS), which has been implemented in previous studies. Furthermore, noisy input data have a small influence on the derivation of the 3D coseismic displacement field, compared to WLS.

The precise coseismic displacement field derived in the present study showed an enhanced natural pattern of the displacement values and highlighted minor features of the fault. Hence it gave a better characterization of the earthquake causative fault than WLS. The 3D displacement field analysis also showed that the earthquake causative fault was a right-lateral strike-slip fault showing little block rotation in the east-west direction and had a small thrust component.

Finally, the MRF-DA model proved its applicability for obtaining an improved 3D field with a well-preserved geological fault. It did so in a consistent way, with smooth variation of displacements as compared to MRF without DA and WLS. Therefore MRF serves as a powerful statistical tool and is promising for future studies of active earthquake prone areas.

Chapter 6: Synthesis

6.1 Introduction

This chapter reviews the main elements of the thesis. It summarizes how aims and objectives of the thesis were achieved and how successfully they were accomplished. At the end it provides suggestions and recommendations for extensions of this research in future.

Detailed conclusions for the individual case studies have been presented in the individual chapters. In this chapter I summarize the general conclusions from the work and discuss the key findings of this research in relation to the research objectives.

The main objective of the research, as stated in Chapter 1, was to construct a 3D coseismic displacement field for the 2003 Bam earthquake. The objective was accomplished by combining the coseismic displacements calculated by means of InSAR and pixel tracking techniques, using pairs of ASAR images from ascending and descending orbits of the ENVISAT satellite. Prior to combining of input displacement results, interpolation of the missing coseismic values, caused by decorrelation of the images, was carried out by means of kriging. Markov random fields (MRF) were applied to combine the four input displacement results to extract the accurate 3D displacement field. These tasks were the sub objectives of the research. In the following paragraphs I present a summary of each of these, stating their importance and implications, and discussing different issues that I was confronted with when achieving them.

6.2 Research findings and conclusions

Research objectives 1: *To accurately measure LOS (line-of-sight) coseismic displacements through InSAR using ASAR images from ascending and descending orbits*

Coseismic displacements can be used for characterizing the earthquake causative geological faults. Remote sensing techniques are preferred over the field methods as they can measure coseismic displacements with a spatially dense, accurate and synoptic view. SAR interferometry (InSAR) is a remote sensing technique that can be used to detect and measure coseismic displacements accurately in the line-of-sight (LOS) direction.

I measured the LOS coseismic displacements for the 2003 Bam earthquake using InSAR (Chapter 3). The phase difference of two images generated interferograms for both descending and ascending orbits images pairs respectively. The unwrapping of the interferograms produced the spatially continuous LOS displacement maps.

During interferogram generation, a coherence image was obtained for the study area to assess degree of homogeneity of the two input SAR images.

The coherence image showed a good coherence for the study area except at the cities of Bam and Baravat, vegetated areas and at the location of the earthquake causative fault. Therefore coseismic displacements could not be measured, and hence were termed as 'missing', at these low-coherence areas. Interpretation of the interferograms and coherence images helped to distinguish the traces of the fault from the rest of the study area. Traces of the fault rupture on the surface showed a pattern of left stepping, describing a strike-slip fault movement.

The LOS displacement maps showed that major displacements were on the right side of the earthquake causative fault. They also indicated an uplift in south-east and subsidence in north-east of the city of Bam. The LOS displacements revealed that the earthquake causative fault lies just South of the city of Bam and is a blind fault i.e. its existence was not known before the earthquake because such a fault does not show any surface expressions. This has also been discovered by the preliminary InSAR studies for the Bam earthquake (Jonsson et al., 2004; Talebian et al., 2004; Stramondo et al., 2005). Previously it was believed that the earthquake happened on the mapped Bam fault (Fu et al., 2004) that is 5 km away in East of the earthquake causative fault.

Research objectives 2: *To estimate coseismic displacement values in LOS displacement map, that were missing due to decorrelation of ASAR images through interpolation by means of kriging*

The missing LOS coseismic displacements at the locations of the fault and city of Bam, needed to be obtained for accurate characterization of the fault and assess its spatial continuity underneath the city of Bam. These missing coseismic values were obtained individually for each location (or patch) by means of interpolation through kriging. Kriging used variograms in interpolating the missing values of the patches. Variogram model provides spatial dependence structure of the measurements. For example a variogram model showing the parabolic behaviour near the origin depicted a highly continuous process. Variogram models of some patches did not reach the sill value indicating the presence of a trend in the measurements. The nugget effect of the variogram model showed the variability of measurements at the micro-scale.

Accuracy assessment of interpolation was done in several ways (detail given in chapter 3). The accuracy of the results was quantified in terms of mean error and RMSE. The accuracy of interpolation was found to be satisfactory for different patches with small ME and RMSE values. An inversion procedure was applied using LOS displacements for determining the fault parameters at subsurface in which a comparison of displacements with and without interpolation was performed. The comparison demonstrated that the

displacement map with interpolated values gives a higher accuracy than the displacement map without interpolation.

After interpolation, the LOS displacement maps for both descending and ascending orbit image pairs showed the complete information. Validation results demonstrated that kriging serves as a powerful tool for interpolating the missing coseismic values.

Research objective 3: *To measure horizontal coseismic values through pixel tracking and to interpolate missing coseismic values after investigating and correcting for the anisotropy in the measurements*

InSAR provided displacement values only in the LOS direction which is sensitive for vertical and east-west directions but insensitive for the north-south direction. For obtaining the north-south displacement component (also called azimuth offsets), pixel tracking was used instead of InSAR. Pixel tracking cross-correlates the pre- and post-earthquake images to calculate the horizontal displacements.

I calculated azimuth offsets (AZO) for 2003 Bam earthquake using ASAR images pairs from both descending and ascending orbits respectively (chapter 4). The AZO (north-south) displacement maps also provided evidence of location of earthquake causative fault south of the city of Bam. The fault represented a relative displacement of approximately 63 cm in north-south direction demonstrating the strike-slip movement of the fault. The fault may as well continue under the city (Stramondo et al., 2005; Peyret et al., 2006). At the location of the city of Bam, however, displacements could not be obtained due to decorrelation of images caused by vegetation in the city and damages after the earthquake. Continuity of the fault, therefore, could not be verified at the city location. Missing coseismic values in azimuth offsets (AZO) displacement maps were needed particularly for checking the fault continuity at the city location.

The missing values in AZO displacement maps were interpolated for the full image by kriging. The variogram analysis revealed that variability of coseismic displacement changes with direction (anisotropy). Directional variograms were, therefore, applied to account for the directionality. The variogram in the north-south direction showed the largest range of spatial continuity of the measurements, thus demonstrating that the north-south movement of the fault. The AZO displacement map having interpolated values with a model corrected for geometric anisotropy showed a clearer pattern of the fault continuity than the map with the isotropic model.

The interpolated values at the Bam city location showed that the fault apparently shifts slightly to the east. This eastward shift may be attributed to the hypothesis that the fault joins the northern fault segment (visible only on the LOS displacement map) underneath Bam (Funning et al., 2005).

Additional geological observations would help to determine up to which distance beyond the city the fault extends.

The accuracy of interpolation results was assessed by means of cross validation. Cross validation results were found satisfactory with small RMSE values. Hence it was concluded that the coseismic displacements were accurately estimated and that kriging serves as a powerful tool to interpolate the missing values.

Research objective 4: *To develop a discontinuity adaptive MRF-based method for constructing the 3D displacement field by means of combining different sources of coseismic displacement data*

This objective was achieved by integrating three orthogonal displacement components in north-south, east-west and vertical direction. InSAR and pixel tracking techniques produced four displacement results from images of the ascending and descending orbits.

Conventional weighted least squares (WLS) used for combining four displacement results of different accuracies (Wright et al., 2004; Funning et al., 2005; Wang et al., 2007; de Michele et al., 2010; Hu et al., 2010) assumes independence in space with weights being calculated as inverse of variances of the measurements for each displacement result. Measurements, however, are spatially dependent. In our study, Markov random field (MRF) was applied in combining the four displacement results by modelling spatial dependences of the measurements. In order to preserve the geological fault a discontinuity adaptive MRF (MRF-DA) model was introduced.

A smooth 3D displacement field with well-preserved geological fault was obtained by optimizing the maximum a posteriori MRF (MAP-MRF) function by means of the simulating annealing (SA) algorithm. A set of model parameters, such as smoothness and threshold value for fault preservation and parameters for SA algorithm were calculated using the training subset.

Finally, estimated parameters values were used for the entire image to derive the MAP-MRF solution of 3D displacement field. It provided a smoothly varying 3D displacement field with well-preserved geological fault. As a comparison, WLS and MRF without discontinuity adaptation (DA) were applied. The WLS model provided a noisy output, particularly for the north-south displacement component. The geological fault is less prominent from the WLS model and also the displacement field is not smooth on either side of the fault. The MRF without DA showed a smooth displacement field, but with a high degradation of the discontinuity at the geological fault.

The final 3D displacement field obtained using MAP-MRF with DA showed an enhanced pattern of displacements in three orthogonal displacement components with minor details and well preserved earthquake causative

fault. The 3D displacement field indicated that the earthquake causative fault is predominantly a right-lateral strike-slip fault having maximum displacement of 63 cm in the north-south direction. The fault also showed a small component of thrust with subsidence of 15 cm to the north of Bam and an uplift of 24 cm in the south.

In conclusion, the constructed 3D displacement field showed that the use of spatial dependence of measurements can give superior results as compared to a least square solution (e.g. WLS). Furthermore, MRF-DA results were less affected by noisy input data, as compared to WLS. Thus MRF serves as a powerful statistical tool and is promising for future studies of active earthquake prone areas.

6.3 Reflections

This study aimed at constructing the 3D coseismic displacement field for the 2003 Bam earthquake. Missing coseismic values in four input displacement maps were interpolated by means of kriging before combining them into 3D displacement field through MRF.

The LOS and horizontal coseismic displacements were measured by InSAR and pixel tracking techniques respectively. These techniques could not measure coseismic displacements at some locations due to decorrelation of pre- and post-earthquake SAR images. Decorrelation in the images can be caused by several factors such as topography and landuse/landcover changes due to changes in vegetation, water-bodies or human activities (Funning et al., 2005; Gonzalez et al., 2009; Erten et al., 2010). It can also be introduced by large baseline i.e., perpendicular distance between orbits of the two acquisitions. A flat terrain with stable meteorological conditions has smaller chances of causing decorrelation in the images. In earthquake hit areas, decorrelation mostly occurs near the earthquake causative fault (Funning et al., 2005) due to violent ground shaking that causes high gradient of deformation, landslides, and destructions of infrastructure in urban areas. Thus, data relating to the deformation in the vicinity of the seismic fault are lost because chaotic ruptures destroy the InSAR signal coherence in these areas. Obtaining the displacement data along the earthquake causative fault, however, is crucial for fully understanding the earthquake faulting mechanism.

Coseismic displacements are distributed spatially and represent a continuous stochastic phenomenon. Therefore spatial statistics can serve as a powerful tool for interpolating the missing coseismic data. Such a use of kriging is a novel contribution in my research. Since coseismic displacements can be represented by a regionalized variable, the variogram was used to explore and model the spatial structure of the coseismic displacements, relating the dissimilarity of the displacement measurements as a function of spatial

distance between them (Curran, 1988). Kriging based on the variogram interpolates the missing values as a weighted sum of the neighbouring observations, in such a way that the variance of the interpolation error is minimized. Kriging proved its importance for interpolating the missing coseismic values and thus ensured spatial continuity of the measured displacement field which can ultimately help in determining the earthquake causative fault geometry.

While interpolating the missing values in LOS displacement maps, it was found that the measured displacements at locations near the fault were heterogeneous in magnitude due to abrupt fault movement and near-fault large gradient of displacements. Similarly, as compared to other parts in the image, a relatively higher proportion of missing values characterized by uneven spatial configuration was located near Bam and Baravat cities. After the analysis of the interpolated results it was discovered that accuracy of the results was affected by the number and proportion of missing values and the spatial configuration of the observed values. The results were also affected by the spatial location of the missing values, such as on or around the geological fault, and magnitude and gradient of measurements. For this reason, interpolations for the missing displacement values located at urban areas or on the fault, were found to be relatively less accurate than other areas.

Construction of the 3D coseismic displacement field was necessary for providing a detailed characterization of the geological fault and ensuring spatial continuity of the measurements. The 3D displacement field for Bam earthquake was constructed by combining 4 input displacement maps (LOS_{desc} , LOS_{asc} , AZO_{desc} , AZO_{asc}) and by exploiting spatial dependencies of the measurements by means of MRF. Since neighbouring measurements were spatially similar, the spatial dependence modelling exploited the neighbourhood information to suppress the noise and uncertainties of the measurements. In this way a smooth displacement field was provided. Smoothness is, however, undesirable in the measurements along the geological fault in order to preserve the fault's geometry. A discontinuity adaptive MRF model with the optimal smoothness and threshold parameter values was proved successful in producing smoothly varied displacements on either side of the geological fault and, at the same time, in preserving the geometry of the geological fault.

Analysis of the interpolated missing coseismic displacement values resulted in more accurate determination of slip distribution and fault geometry. The interpolated coseismic values and 3D displacement results showed indications of continuity of the geological fault underneath the city of Bam. The fault continuity, however, needs further geophysical investigations using seismology, resistivity or gravity survey. The obtained coseismic

displacements may be used to calculate the fault parameters at the subsurface, which in turn can help to understand the fault behaviour during the earthquake.

From interpretation of the three orthogonal components of displacement in the 3D field derived from the MRF-DA model, we found that the east-west and vertical components of displacement showed an asymmetric displacement pattern, thus indicating a stronger motion on the eastern side of the fault than on its western part. The fault showed a maximum displacement in the north-south direction. Therefore, the geological fault is a strike-slip fault with right-lateral movement in the north-south direction. It has a minor component of thrust with block rotation in the east-west direction.

The study underlines the importance of monitoring and understanding the mechanism of active faults existing prior to an earthquake. The 3D displacement field provided both accurate and fine spatial characterization of the earthquake causative fault for the 2003 Bam earthquake. It also presented valuable interpretation of the earthquake phenomenon responsible for producing the surface displacements. This research is therefore promising for future studies aimed at improving our knowledge on characterization of pre-existing active faults and understanding the earthquake-induced deformations in the study area.

In a spatial statistics context, the study demonstrates the usefulness of geostatistical techniques for interpolating the missing coseismic values after investigating and accounting for the effects of anisotropy. The coseismic values showed a clear directional variability (anisotropy). It was important to account for the effect of anisotropy in order to have the spatial dependence structure of coseismic values best reflected.

Apart from the several advantages, the study also suffers from some shortcomings. One of them concerns the directional variogram that was prepared at narrow angles. It reflected a complex nature of zonal anisotropy as it showed a geometric component along with four separate components of higher sill values in four different directions. In modelling such a variogram there are practical difficulties of identifying the most appropriate model.

The study was hampered by the absence of validation data for carrying out accuracy assessment. Although this deficiency was compensated by carrying out cross-validation during kriging, it was found that kriging resulted in larger errors where sample density decreased in the neighbourhood of missing values. The reason is that kriging interpolates by exploiting the neighbourhood information and thus produced predictions with higher inaccuracies at the boundaries of the patches of missing values, particularly at the patches located close to the urban areas of Bam and Baravat.

6.4 *Directions for future research*

Below we present some suggestions for future research:

To minimize the decorrelation in displacement maps, pre- and post-earthquake radar images with a shorter geometric and temporal baseline are to be provided. Persistent scatter interferometry (PSI) can be used to obtain more accurate LOS displacement results over longer periods, although this is possible only at sparse spatial locations of the persistent scatters. The sparse PSI displacement results require an even higher effort in spatial interpolation for the complete displacement field. Spatial interpolation from a combination of the conventional InSAR displacements with the PSI displacements might turn out becoming more successful than that from the individual methods. Another alternative is stacking of interferograms, which can produce LOS results with a minimum decorrelation and hence minimum missing coseismic values. It would require multiple interferograms that can be generated using different SAR pre- and post-earthquake images over time. Each interferogram would have a different decorrelation, both in location and in pattern. Combining coseismic displacements obtained from these interferograms would result into LOS displacement map having a smaller number of missing coseismic values.

Accuracy of pixel tracking results depends mainly on spatial resolution and coregistration accuracy of the images used. The technique is adequate to find changes in a fraction of pixel size (spatial resolution). Increasing the spatial resolution would provide finer details of coseismic displacement and fault geometry. Firstly, optical images of very high resolution such as QuickBird or IKONOS or areal images have to be selected in order to have detailed coseismic displacements for the 2003 Bam earthquake. Secondly, coregistration of pre- and post-earthquake images can improve the accuracy of the subpixel correlation and, in turn, of the coseismic displacements. Coregistration involves orthorectification and projection of two images on the common geometry and modelling of stereoscopic effects due to topography with the use of high resolution DEM and finer details of ancillary data related to the imaging system and the platform attitudes. Thirdly, availability of high resolution DEM (e.g. LiDAR DEM) and ancillary data is expected to greatly improve the accuracy of coseismic displacements measurement and the characterization of the fault geometry.

One limiting factor in the use of high resolution optical images may be the increased decorrelation due to shadowing differences and the high sensitivity to temporal changes particularly in urban areas. The temporal changes are mostly due to changes in land cover, differences of viewing angles of both images, presence of clouds or are related to the time difference of the image acquisitions. The increased chances of decorrelation of two images will lead to increase in the number of missing values. That would ultimately require

more efforts in interpolating the missing values. Moreover, spatial coverage of very high resolution optical images is limited. Multiple scenes would, therefore, be needed for measuring coseismic displacements around the geological fault. Hence it would involve high data costs.

The study detected geometric and zonal anisotropies in the displacement values by investigating the directional variograms. Geometric anisotropy was corrected using the ratio of maximum range of spatial dependence to the minimum, whereas zonal anisotropy correction could be more complex requiring a nested variogram model that contains separate model for the variability of each zone. This requires further research on investigating the anisotropic behaviour of the coseismic measurements at a local scale.

In our study the Bam earthquake was chosen for measuring earthquake induced displacements by InSAR and pixel tracking. This study area was ideal for the application of our methods and techniques. Due to its desert environment and relatively flat terrain, the coherence loss of SAR images was limited and produced fewer missing coseismic displacements. If the techniques used in our study for measuring earthquake displacements are applied to some earthquake hit area with dense vegetation or rugged topography the problem of missing coseismic measurements could become adverse. In such situations, the potential of kriging interpolation needs to be further explored for retrieving missing coseismic values.

Availability of more SAR data pairs can help in reducing the missing coseismic data. Each pair of SAR images would give different sets of coseismic measurements depending upon their baseline, and earthquake causative fault characteristics. Therefore it is expected that less coseismic measurements are missing if the coseismic measurements from all the SAR pair are combined. This would enhance the accuracy of interpolation and a comprehensive reliable set of measurement can be obtained.

Besides measuring earthquake deformation in the local area, the deformation can be monitored and measured at the regional scale over longer periods. This would enable to better characterize seismogenic active fault of the area by analyzing and interpreting the spatial pattern of deformation at different scales and different times in the area. Finally such a study would help in modelling the earthquake cycle, land sliding and earthquake hazard assessment and mitigation. This may also be beneficial in marking the earthquake hazard zonation and assessing the vulnerability of the damages to different areas or cities in the region.

Advances of new Radar systems are promising for future earthquake studies. Finer resolution SAR data will enhance the capabilities of such applications and will serve to better understand the physical phenomenon. It will in turn

improve the hazard mitigation measures beneficial for human society in the long run.

Our study presents techniques and methods that can be useful for several other applications such as measuring land surface deformations due to volcanic eruptions, landslides, glacier movements and sand dunes migration. It can also be used for monitoring coastal area changes, land surface subsidence due to mining activities and urban settlements and ground water aquifer monitoring etc.

Our study was hampered by lack of field data for validating the measured displacement results by remote sensing techniques and interpolated measurement by kriging. The validation data can come from GPS, Leveling and other geodetic field measurements. Seismological data can also be integrated. If such data could be more systematically available, it can be used to validate the results of our measured and interpolated coseismic displacements. It can also complement the measured and interpolated data for a complete characterization of the geological fault.

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Author's biography

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In 2007, he was awarded with MS leading to PhD scholarship for the Netherlands. He joined Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands to pursue higher education. He completed his MSc degree in Geo-information and Earth Observation from ITC, the Netherlands in March 2009. Subsequently he pursued his PhD on the topic "Geostatistical and space geodetic methods applied to a 3D coseismic displacement field: mapping earthquakes from space". His main research interests include SAR Interferometry, spatial statistics for measuring and interpreting coseismic displacement, and quantification of uncertainty. This thesis is the output of his PhD research.

Author's publications

Published ISI Journal Articles:

Yaseen, M., Anwar, S., 2013. "Sensitivity analysis of sub-pixel correlation technique for measuring coseismic displacements using a pair of ASTER images" *Journal of Asian Earth Sciences* 62 (0), 349-362

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Article under review:

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