MONITORING LAND SURFACE DEFORMATION USING PERSISTENT SCATTERERS INTERFEROMETRIC SYNTHETIC APERTURE RADAR TECHNIQUE

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In the name of Allah, Most Gracious Most Merciful

All praise and thanks are due to Allah Almighty and
peace and blessing be upon His Messenger

This thesis is dedicated to my parents

For their endless love, support and encouragement

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ABSTRACT

Land subsidence is one of the major hazards occurring globally due to several reasons including natural and human activities. The effect of land subsidence depends on the extent and severity. The consequences of this hazard can be seen in many forms including damaged of infrastructures and loss of human lives. Although land subsidence is a global problem, but it is very common in urban and sub urban areas especially in rapidly developing countries. This problem needs to be monitored effectively. Several techniques such as land surveying, aerial photogrammetry and Global Positioning System (GPS) can be used to monitor or detect the subsidence effectively but these techniques are mostly expensive and time consuming especially for large area. In recent decades, Interferometric Synthetic Aperture Radar (InSAR) technique has been used widely for the monitoring of land subsidence successfully although this technique has several limitations due to temporal decorrelation, atmospheric effects and so on. However, the uncertainties related to InSAR technique have been reduced significantly with the recent Persistent Scatterers Interferometric Synthetic Aperture Radar (PSInSAR) technique which utilized a stack of interferograms generated from several radar images to estimate deformation by finding a bunch of stable points. This study investigates the surface deformation focusing on Kuala Lumpur, a rapidly growing city and Selangor using PSInSAR technique with a set of ALOS PALSAR images from 2007 to 2011. The research methodology consists of several steps of image processing that incudes i) generation of Differential Interferometric Synthetic Aperture Radar (DInSAR), ii) selection of Persistent Scatterers (PS) points, iii) removal of noise, iv) optimization of PS point selection, and v) generation of time series deformation map. However, special consideration was given to optimize the PS selection process using two master images. Results indicate a complete variation of mean line-of-sight (LOS) velocities over the study area. Stable areas (mean LOS=1.1 mm/year) were mostly found in the urban center of Kuala Lumpur, while medium rate of LOS (from 20 mm/year to 30 mm/year) was observed in the south west area in Kuala Langat and Sepang districts. The infrastructures in Kuala Lumpur are mostly stable except in Kuala Lumpur International Airport (KLIA) where a significant subsidence was detected (28.7 mm/year). Meanwhile, other parts of the study area such as Hulu Langat, Petaling Jaya and Klang districts show a very low and non-continuous movement (LOS < 20 mm/year), although comparatively higher subsidence rate (28 mm/year) was detected in the mining area. As conclusion, PSInSAR technique has a potential to monitor subsidence in urban and sub urban areas, but optimization of PS selection processing is necessary in order to reduce the noise and get better estimation accuracy.

ABSTRAK

Pemendapan tanah merupakan salah satu bahaya utama yang berlaku di peringkat global kerana beberapa sebab merangkumi aktiviti semula jadi dan aktiviti manusia. Kesan pemendapan tanah bergantung kepada tahap dan keterukan. Kesan bahaya ini dapat dilihat dalam pelbagai bentuk termasuk kerosakan infrastruktur dan kehilangan nyawa manusia. Walaupun pemendapan tanah adalah masalah global, namun ia merupakan perkara biasa di kawasan bandar dan sub bandar terutamanya di negara-negara pesat membangun. Masalah ini perlu dipantau dengan berkesan. Beberapa teknik seperti ukur tanah, fotogrametri udara dan sistem kedudukan global (GPS) boleh digunakan untuk memantau atau mengesan pemendapan dengan berkesan tetapi teknik-teknik ini kebanyakannya mahal dan mengambil masa terutamanya bagi kawasan yang besar. Dalam dekad kebelakangan ini, teknik radar apertur sintetik interferometer (InSAR) telah digunakan secara meluas untuk memantau pemendapan tanah dengan jayanya walaupun teknik ini mempunyai beberapa batasan kerana nyahkolerasi masa, kesan atmosfera dan sebagainya. Walau bagaimanapun, ketidaktentuan yang berkaitan dengan teknik InSAR telah dikurangkan baru-baru ini dengan ketara dengan teknik radar apertur sintetik interferometer penyerak berterusan (PSInSAR) yang menggunakan timbunan interferogram dijana daripada beberapa imej radar untuk menganggar deformasi dengan mencari sekumpulan titik stabil. Kajian ini mengkaji deformasi permukaan dengan memberi tumpuan kepada Kuala Lumpur, bandar yang berkembang pesat dan Selangor menggunakan teknik PSInSAR dengan satu set imej ALOS Palsar dari 2007 hingga 2011. Metodologi kajian terdiri daripada beberapa langkah pemprosesan imej merangkumi i) penjanaan radar apertur sintetik interferometer berbeza (DInSAR), ii) pemilihan titik penyerak berterusan (PS), iii) penyingkiran gangguan, iv) pengoptimuman pemilihan titik PS, dan v) penerbitan peta deformasi siri masa. Walau bagaimanapun, pertimbangan khas telah diberikan untuk mengoptimumkan proses pemilihan PS menggunakan dua imej induk. Keputusan menunjukkan pelbagai variasi halaju min garis penglihatan (LOS) bagi kawasan kajian. Kawasan stabil (min LOS = 1.1 mm / tahun) didapati tertumpu di pusat bandar Kuala Lumpur, manakala kadar sederhana LOS (dari 20 mm/tahun sehingga 30 mm/tahun) dilihat di kawasan barat daya di daerah Kuala Langat dan Sepang. Infrastruktur di Kuala Lumpur kebanyakannya stabil kecuali di Lapangan Terbang Antarabangsa Kuala Lumpur (KLIA) di mana penenggelaman yang ketara telah dikesan (28.7 mm/tahun). Sementara itu, bahagian lain kawasan kajian seperti daerah Hulu Langat, Petaling Jaya dan Klang menunjukkan pergerakan yang sangat rendah dan tidak berterusan (LOS <20 mm/tahun), walaupun kadar penenggelaman yang agak tinggi (28 mm/tahun) telah dikesan di kawasan perlombongan. Kesimpulannya, teknik PSInSAR mempunyai potensi untuk memantau pemendapan di kawasan bandar dan sub bandar, tetapi proses mengoptimumkan pemilihan PS adalah perlu untuk mengurangkan gangguan dan mendapatkan anggaran ketepatan yang lebih baik.

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ϕ	Phase
k	Complex wave vector
R	Slant range
t	Time
ω	Wave angular frequency
γ	Complex correlation coefficient
$E[\,]$	Complex conjugate
ρ	Coherence
$|\gamma|$	Amplitude of the complex correlation coefficient
f_{DC}	Doppler centroid frequencies
$\Delta\varphi_{total}$	Total phase contribution
$\Delta\varphi_{ref}$	Phase related to flat-earth
$\Delta\varphi_{topo}$	Phase related to topography
$\Delta\varphi_{atmo}$	Phase related to atmosphere
$\Delta\varphi_{deco}$	Phase related to decorrelation
$\Delta\varphi_{noise}$	Phase related to Phase noise
$\Delta\varphi_{defo}$	Phase related to terrain deformation
$\Delta\varphi_{ref}$	Phase difference exists between two points
φ_{orb}	Phase due to the inaccurate orbits
π	Ratio of a circle's circumference to its diameter
$B_{\perp}$	Perpendicular baselines
ΔR	Range distance difference
λ	Wavelength
r	Slant range coordinate

θ	Elevation angle
h	Height
θinc	Incidence angle
γ_{total}	Sources of decorrelation effects
γ_{therm}	Thermal decorrelation
γ_{geom}	Geometrical decorrelation
γ_{DC}	Doppler centroid decorrelation
γ_{proc}	Processing decorrelation
γ_{temp}	Temporal decorrelation
ρ_{total}	Total correlation
$\rho_{temporal}$	Temporal correlation
$\rho_{spatial}$	Spatial correlation
ρ_{dopler}	Correlation in Doppler centroid frequency
$\rho_{thermal}$	Correlation in thermal noise
T	Temporal baseline
T^c	Phase related to atmosphere
$B_{\perp}^c$	Critical perpendicular baselines
F_{DC}	Doppler centroid frequency
F_{DC}^c	Critical Doppler centroid frequency
$f(x)$	Phase difference exists between two points
f	Phase due to the inaccurate orbits
i	Imaginary band
p	Power
r	Real band
I	Complex interferogram
M	Complex master image
S	Complex resampled slave image
$\emptyset_I$	Observed phase difference
$\emptyset_M$	Phase due to master image
$\emptyset_S$	Phase due to slave image
γ_c	Complex coherence
$E\{.\}$	The expectation
N	Number of images

R	Complex reference phase
D_a	Amplitude dispersion index
μ_a	Mean of the amplitudes
σ_a	Standard deviation the amplitudes
$\sigma_\emptyset$	PS candidates
γ	Coherence-like measure

LIST OF ABBREVIATION

1D	1 dimensional
2D	2 dimensional
3D	3 dimensional
ALOS	Advanced Land Observing Satellite
AOE	Atmospheric and orbit error
ASAR	Advanced Synthetic Aperture Radar
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVINIR	Advanced Visible and Near Infrared Radiometer
CalTech	California Institute of Technology
cm	Centimetre
COSMO-SkyMed	Constellation of Small Satellites for Mediterranean basin Observation
DCT	Discrete cosine transform
DePSI	Delft Persistent Scatter Interferometry
DEM	Digital elevation model
DInSAR	Differential Interferometric Synthetic Aperture Radar
DORIS	Delft object-oriented radar interferometric software
EDM	Electronic distance metres
ENVISAT	Environmental Satellite
ERS	European remote sensing satellite
ESA	European Space Agency
FBS	Fine Beam Single Polarisation
FBD	Fine Beam Double Polarisation
FFT	Fast Fourier Transform

GDEM	Global Digital Elevation Map
GIMP	GNU Image Manipulation Program
GUI	Graphical User Interface
GPS	Global Positioning System
InSAR	Interferometric Synthetic Aperture Radar
JAXA	Japan Aerospace Exploration Agency
KLCC	Petronas Twin Towers
KLIA	Kuala Lumpur International Airport
Km	Kilometer
LOS	Line-of-sight
MERIS	Medium Resolution Imaging Spectrometer
MLV	Mean Line of Sight velocity
m	Meter
mm	Millimetre
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PRC	Precise orbital data
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
PS	Persistent Scatterer
PSInSAR	Persistent Scatterer Interferometric Synthetic Aperture Radar
rad	Radian
Radar	Radio Detection and Ranging
ROI PAC	Repeat Orbit Interferometry Package
SAR	Synthetic Aperture Radar
SBAS	Small Baseline Subset
SCLA	Spatially correlated look angle
SLC	Single Look Complex
SNR	Signal-to-noise ratio
SRTM	Shuttle Radar Topography Mission
StaMPS	Stanford Method for Permanent Scatterers
SUBANG	Sultan Abdul Aziz Shah Airport
TerraSAR-X	German synthetic aperture radar Earth observation satellite
TU Delft	Delft University of Technology

viStaMPS	Visual Stanford Method for Permanent Scatterers
WGS84	World Geodetic System 1984
WRF	Weather Research and Forecast
yr	Year

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CHAPTER 1

INTRODUCTION

This chapter consists of several sections including research background, problem statement, objectives, study area, significance, scopes and outlines of the thesis. The aim of this study is determined after doing an extensive background study related to this research in order to develop the best model for land surface deformation monitoring using PSInSAR technique.

1.1   Background of Research

Ground movement is the change of shapes of the ground surface induced by natural or human-phenomenon internally or externally (Qiao *et. al*., 2011; Jensen and Cowen, 1999), which happens very slowly yet may have sudden and far-reaching effects that endanger infrastructures or even human lives (Liu *et al.*, 2008). Apparently, the topographic changes in one particular area can create and destroy the surface features surrounding the ground which can eventually impose some active deformation onto nearby structures as well as below the ground such as pipe lines

and tunnels (Fornaro *et. al*., 2009). In general, the damage due to the ground movement can be attributed by several factors such as shrinkage of soils, landslip, ground water extraction, mine collapse, settlement of land reclamation sites and poor/faulty construction of big infrastructures (Yoo and Lee, 2008; Akcin *et al*., 2010). However, deep excavation projects for high-rise buildings and subways are also the important factors for land surface deformation in the urban and sub-urban areas (Jensen and Cowen, 1999; Yoo and Lee, 2008).

The extensive as well as rapid infrastructure development in urban and sub-urban areas plays an important role in occurring the land subsidence around the world as various infrastructures in urban areas are most likely to subside due to several reasons especially the inability of the land to accommodate the pressure from the big infrastructures (Jensen and Cowen, 1999; Berardino *et al.*, 2002), the rapid conversion of natural properties (such as forest and agricultural land) into developed land (Berardino *et al.*, 2002), and over-extraction of ground water exploitation for domestic and industrial purposes (Sahu and Sikdar, 2011; Gupta and Srivastava, 2010). Additionally, studies found that there is an impact of natural hazards and anthropogenic activities on land subsidence. For example, remarkable engineered structures such as Taipei 101, the world's tallest building (Liu *et al*., 2001), Chek Lap Kok airport in Hong Kong (Lin, 2005) and Conza Dam in the southern Apennines, Italy (Martire *et. al*., 2014) were detected sensitive to force triggered not only by natural hazards but also human activities resulting the damage of infrastructures with cracking and sinkhole.

Indeed, land subsidence/deformation is global problem and monitoring this problem using an effective technology is essential especially in urban areas and sub-urban areas to ease the rising public concern on the effects of construction-induced as well as underground water exploitation movements to the environments (Ferronato *et. al,* 2006; Worawattanamateekul *et al.*, 2003). However, this monitoring/warning system should be in a long time acquisition resulting from continuous monitoring instrumentation to monitor different types of terrain deformation phenomena such as subsidence, landslides, seismic activity and underground deformation despite the

difficulties in operational conditions such as in remote areas and during heavy rainfall (Velez *et al.*, 2011; Wallace *et al.*, 2012).

In the past, monitoring surface deformation has been conducted using a variety of surveying techniques to track movements on the unstable areas (Wilson and Mikkelsen, 1978). Theodolite, electronic distance metres (EDM) and total station measurements give the point coordinates and changes of target and hence allow the detection of landslides features (Ashkenazi *et al.,* 1980). Tapes and wire devices have been used to measure changes in distance of crack walls (Gulla *et al.,* 1988). These ground surface movement measurement techniques are widely used but known to be time consuming and usually require large man power to complete the survey over a large area (Bonforte *et al.*, 2001). Aerial or terrestrial photogrammetry provides the point coordinates, contour maps and the cross-sections of the landslides with typical precision of 20 cm, however the process of acquiring aerial photograph is very expensive (Mikkelsen, 1996). Later, the Global Positioning System (GPS) is becoming progressively useful for monitoring deformation with the establishment of ground station. Several available GPS receivers have been used to detect the landslides features in the Swiss Alps and the precision obtained was about 1 cm (Bonnard *et al.,* 1996). However, the ground-based surface monitoring technique like GPS networks are often found less efficient in large areas and barely accessible in remote areas (Noferini *et. al.*, 2005). In addition, the availability of GPS stations in the area of interest is often poor; leading to strongly extrapolated data modelling (Lauknes *et. al.*, 2011).

The exploitation of Interferometric Synthetic Aperture Radar (InSAR) technique in the monitoring earth surface has started over the past few years and seems to be a great tool for rapid detecting surface change. This remote sensing technique is continuous and capable to monitor and detect surface displacement over large areas by utilizing the phase value of two observations separated in either time or space with millimetre accuracy (Colesanti *et al.*, 2003; Perissin and Rocca, 2006; Goel and Adam, 2014). Based on the previous studies, InSAR technique has been

used successfully to detect the movement or displacement caused by seismic events such as earthquakes (Massonnet and Feigl, 1993; Peltzer and Rosen, 1995) and volcanic eruptions ((Massonnet *et al.*, 1995; Remy *et. al.*, 2003). Common phenomena like landslides (Colesanti and Wasowski, 2006; Cascini*et al.*, 2010; Martire *et al.*, 2011; Herrera *et al.*, 2013), land subsidence (Jiang *et at*, 2010; Ferretti, 2000) and the characterization of behaviour of the surface motion in urban area (Webley *et al.*, 2002; Chen *et al.*, 2013; Colesanti *et al.*, 2003) have also been widely investigated over the time with this technique. As a matter of fact, this technique has been actively used to overcome the shortcomings of the ground-based measurement in remote area as well (Wang and Wright, 2012).

The technique of InSAR can be classified into two types *i.e*; i) along-track interferometry or known as single-pass interferometry, and ii) across-track interferometry or repeat-pass interferometry. It is well-known that the repeat-pass interferometry is the most sensitive to detect changes of the surface because the single-pass interferometry is taken under identical conditions at the same time; hence they are highly correlated, making it hard to determine the surface changes (Klees and Massonnet, 1999; Ebmeier *et., al.*, 2004). However, since the repeat-pass interferometry is acquired at different times, the images may be insufficient due to temporal and geometric decorrelation (Zebker and Villasenor,, 1992) and atmospheric artifacts (Zebker *et al.*, 1997; Hanssen, 1998; Hanssen, 2001).

The temporal decorrelation is caused by the temporal change in backscatter properties of the surface between the first and the second data acquisition, whereas geometrical decorrelation refers to the variations of reflectivity as a function of the incidence angle (Colesanti *et al.*, 2003; Perissin and Rocca, 2006). As for the atmospheric effects, the water vapour in the troposphere layer is actually introducing different delays at different times while signal is propagating through it (Noferini *et al.*, 2005). This atmospheric effect is not identical in different InSAR acquisitions, thus the effect cannot be easily cancelled out and leads additional shifts in phase signals (Li *et. al.*, 2005). Decorrelation often prevents InSAR from being an operational tool for surface deformation monitoring and topographic profile

reconstruction while interferogram images derived from repeat-pass spaceborne synthetic aperture radar systems exhibit artifacts due to the time and space variations of atmospheric water vapour which seriously affect the accuracy of the surface monitoring (Zebker *et al.*, 2007; Ferretti *et al.*, 2001).

The methods to mitigate the atmospheric delay in conventional InSAR data can be classified as 1) integration with dense GPS networks; 2) integration with multi-spectrum water vapor products, for example precipitable water vapor products from Moderate Resolution Imaging Spectroradiometer (MODIS) or Medium Resolution Imaging Spectrometer (MERIS); 3) integration with numerical weather forecast model, *e.g.* Weather Research and Forecast (WRF) model, and 4) using time-series InSAR techniques, *e.g.* Small Baseline Subset (SBAS), and Persistent Scatterer (PSInSAR) InSAR (Gong *et al.,* 2011). The GPS method often having difficulties in setting and maintaining GPS sites, while for optical satellite such as MODIS, a full water vapor column is hard to be obtained in most cases due to the persistent block from the clouds (Li *et al.*, 2005). Numerical weather model technique is usually required sufficient available boundary data in order to get accurate and better quality of the forecasts (Gong *et al.*, 2010). Furthermore, this method only aims to reconstruct the atmospheric state at SAR imagery acquisition time but do not solve the decorelation problem in InSAR data.

However, studies found that time series InSAR technique is an attractive option that can address decorrelation as well as atmospheric artifacts since in most of the cases, it is impossible to remove or overcome these two problems by using an individual interferogram (Massonnet and Feigl, 1998; Sandwell and Price, 1998). The time series InSAR technique processes multiple acquisitions in time and exploits the statistic properties of atmospheric phase components in time series of SAR observations (Gong *et al.,* 2011). There are several time series approaches for InSAR application of deformation monitoring. However one of the commonly used approach of time series is known as Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique which involves identifying "persistent scatterer" pixels whose scattering characteristics remain stable in time and when

viewed from different angles (Ferretti *et al.*, 2001; Hooper *et al.*, 2004; Hooper *et al.*, 2012; Kampes, 2005).

PSInSAR technique was first discovered in 1990s, where it utilizes the multi-interferogram framework of differential interferograms with respect to a single master image and estimates the displacement based on one or two dominant scatterers in the resolution cell (Ferretti *et al.*, 2000; Ferreti *et al.*, 2001). PSInSAR also takes benefits from isolated stable pixels which are almost unaffected by decorrelations within the resolution cell to estimate the atmospheric effects and mitigates it (Daniele and Fabio, 2006). The advantages of the PSInSAR technique can be seen from the several perspectives as compared to conventional InSAR (Ferretti *et al.*, 2001; Ferretti and Crespa, 2006; Velez *et al.*, 2011). But the drawback of this method is that it requires a large number of SAR acquisitions and prior knowledge of the study area properties (Tamburini *et al.,* 2010) although data requirement is not essentially a problem nowadays since there are many SAR sensors available, and data from these sensors can be obtained easily (Zibret *et. al.,* 2012).

Nevertheless, there are various applications that exploit PSInSAR method such as land subsidence (Ferretti *et al.*, 2000), monitoring ground deformation (Colesanti *et al.*, 2003), developing high accuracy Digital Elevation Model (DEM) (Daniele and Fabio 2006) and detecting slow-landslide (Feretti *et al.*, 2001). Several examples can be found in the literature where PSInSAR technique has been used for the monitoring of land subsidence in urban area. For example, Zhao *et. al.*, (2009) had successfully identified an active zone for ground deformation in the urban area of Guangzhou city in South China using PSInSAR technique with the maximum subsidence or the rise rate showed from -26 to 20 milimmeter/year. Meanwhile, a case study in Rotterdam, Netherlands, successfully identified urban subsidence due to gas extraction with a high PS density (159 PS/km^2) where the displacement rates were detected up to 7 mm/year (Katelaar and Hanssen, 2003). PSInSAR also has a potential of monitoring the deformation of different types of infrastructure with high accuracy as demonstrated by Lan *et al.,* (2012) who classified PS points based on

their corresponding urban structure types successfully and shown the potential of using PInSAR technique to monitor the regular fluctuation of deformation rate of complex urban infrastructures in one fast developing area.

The discussion about the background study of this proposed topic can be concluded by restating that the land surface deformation monitoring is vital for various purpose especially monitoring the sustainability of urban infrastructures and this can be done using InSAR technique considering its long term data availability, large scale coverage, cloud penetration capability, low cost and most importantly the effectiveness in detecting surface movement deformation with high accuracy. However, this technique is bounded with two major limitations known as decorrelations and atmospheric disturbance that often limits the applicability of InSAR tool in monitoring accurate deformation. Nevertheless, these limitations can be successfully mitigated with the use of time series technique, PSInSAR that utilizes the stable pixels within the interferogram with high spatial density and produce better estimation accuracy. The PSInSAR technique is performed well in urban as well as non-urban areas; however, there are still scopes for improvement of measurement as the capability of this technique varies according to different circumstances.

1.2   Problem Statement

The problem of ground deformation is quite obvious globally due to transformation of land cover, overexploitation of underground reservoir, natural disaster as well as massive infrastructure development. It is inevitable that any form of deformation can create potential risk for human life and properties, and this risk could be compounded if any damage of infrastructure occurs in urban areas due to the ground deformation. Therefore, it is essential to monitor the deformation or subsidence using an effective technology for the assessment of risk of urban subsidence, volcano dynamics, co-seismic and post seismic displacements along

faults, as well as slope instability especially when urban areas and infrastructures are involved (Ferronato *et. al*, 2006).

In Malaysia, there are a number of places such as Kuala Lumpur, Petaling Jaya, Ampang and Batu Caves which are growing very rapidly with the economic development and population growth. There are several reports that already indicated the problems in designing and maintaining the infrastructures of these cities. For example, the Petronas Twin Towers in Kuala Lumpur were shifted about 50 mm from their original planned positions due to intense fractures and limestone cavities in the foundation area (Ismail *et. al*, 2011). Furthermore, although Malaysia is generally safe from few natural disasters such as earthquake, typhoons and volcanic eruptions, nevertheless the country is still subjected to monsoon floods, sinkhole, landslides and land subsidence. The most common events in Malaysia are landslides which are triggered by rainfall or human activities on instable slopes and land subsidence due to over-pumping of ground water as happened in Ampang, Kuala Langat and Shah Alam areas (Stek, 2008). Although some big infrastructures in these cities may have been constructed with proper engineering and ground work, obviously many of the infrastructures have been build up without considering the risk of land deformation and need to be monitored in order to understand the probable risk and to take necessary precaution to avoid unexpected loss of property and life.

It is clear from the above circumstances that a continuous and long-term deformation monitoring system is required to identify hazardous areas and quantify the structural changes with quantitative interpretation to avoid the losses of properties and uncompensated lives. The use of space-born Synthetic Aperture Radar (SAR) is one of the best choices to monitor deformation for such a large area considering its long-term data availability, large-scale coverage and cloud-penetrating capability with a rather low cost. SAR data can be used for deformation monitoring using SAR interferometry (InSAR) technique. However, the only limiting factor of this technique is that the signal phase is sometimes biased with the

decorrelation problem and atmospheric contribution that introduce different delays at different times and in different points of the illuminated area (Noferini *et al.,* 2005).

Although there are many methods that can be applied to address these issues such as using GPS (Li *et al*., 2005; Webley *et al.,* 2002), MODIS water vapour measurement (Foster *et al.*, 2006; Li *et al.*, 2005) and WRF model (Gong *et al*., 2010); however, the advance technique of InSAR known as PSInSAR technique is the most attractive technique as it assists not only to overcome the decorrelation problems and atmospheric disturbance but it also has a capability in monitoring precise deformations that can hardly be achieved by using conventional technique by identifying the stable pixels based primarily on their phase variation in time (Lan *et al.*, 2012; Ferretti *et al.*, 2001; Kampes, 2005; Hooper *et. al*., 2006). The other particular interest of using PSInSAR technique is discriminating small scale features in such that various types of infrastructures are found in urban areas can be distinguished based on their spatial scale and enables the investigations of individual structural deformation (Crosetto *et al.*, 2010). Although the PSInSAR method is very effective in urban areas due to its main principle of selecting stable points which comes from permanent structures, there are still successful implementations of this technique for landslide monitoring (Sun *et. al,* 2015; Tantianuparp *et. al*, 2013), land subsidence (Li *et. al*, 2012) and slope assessment (Riddick *et al*., 2012).

There are many PSInSAR algorithms available; however, the first PSInSAR algorithm has been developed in 2000 by Ferretti *et al.,* (2000), which further enhanced by Colesanti *et al.*(2003) and followed by Adam *et al.*, (2003); Crosetto *et al.*, (2003); Lyons and Sandwell, 2003; Werner *et al.*, (2002). In these algorithms, an initial set of PS pixels with a high signal-to-noise ratio (SNR) is identified by amplitude variation analysis and accept only the stable pixel which has similar phase history to the assumed model of deformation (Liu *et al.*, 2010). Nevertheless, Hooper *et al.,* (2007) stated that these approaches can fail due to two reasons *i.e.* i) the large distance between neighboring PS pixels, and ii) due to the deformation deviations from the model that are large which will make unwrapping become unreliable. Furthermore, these algorithms only consider the analysis of phase amplitude during

PS selection for which makes the identification of PS pixels generally becomes too low to obtain any reliable results in natural terrains which are generally have low SNR scatters (Meisina *et al*., 2008).

In contrast, the Stanford Method for Permanent Scatterers (StaMPS), one kind of PSInSAR algorithm has extended the scope of PSInSAR to work effectively in urban as well as vegetated regions by incorporating spatial correlation of interferogram phase to find a network of stable pixels even with low amplitude stability without prior knowledge of temporal variations in the deformation (Marwa and Elisabeth, 2004; Hooper *et al.,* 2004; Hooper *et al.,* 2008; Liu *et al.*, 2010). In this algorithm, an initial filtering for the selection of PS pixels is done based on amplitude dispersion, and later the selection of PS pixel is finalized by several iterations of phase stability estimation and characterized the temporal model of deformation, rather than using an assumed model, which eliminates the need of a priori temporal model (Hooper *et al*., 2007; Tiwari *et al*., 2014). This approach is successful in finding PS pixels in both urban and non-urban areas, which makes it applicable in areas covered by forests and vegetation as well (Sousa, 2010).

Obviously, an effective PSInSAR algorithm requires several steps of processing for better estimation accuracy includes i) interferogram formation (data selection, image pairs, co-registration, phase unwrapping, *etc.*), ii) phase stability estimation, iii) phase selection, and iv) displacement estimation (Baer *et. al,* 1999; Hooper *et. al,* 2004; Hooper *et. al,* 2008). Although several studies have been made to retrieve reliable deformation parameters such as Vilardo *et al.,* (2010), Erten *et.al*, 2009 and Riddick *et al.*, (2012); nevertheless, these studies have only concentrated on the improvements of PSInSAR processing and mostly ignored the importance of other processing such as selection of data baselines, oversampling, co-registration, differential interferogram generation and geocoding. Furthermore, most of the studies are focused only on one type of terrain or land-use; hence the impact of the PSInSAR algorithm for different terrains is still remaining uncertain. In addition, no study has been conducted so far in Malaysia to monitor surface deformation in urban areas using InSAR technique.

Therefore, there is still a plenty of scope to evaluate or use this PSInSAR technique for monitoring the surface deformation or land subsidence in different land surface terrains (such as urban, vegetation, rural, mountain) considering not only PSInSAR processing technique but also effective procedure for the generation of enhance interferogram as well. However, this study investigates the surface deformation in Kuala Lumpur and nearby areas using PSInSAR technique considering the three important aspects *i.e.* i) the needs for the monitoring of deformation or land subsidence in this study area; ii) the effectiveness of InSAR technology for the monitoring deformation or land subsidence, and iii) finally the scope of the use of PSInSAR technology for the improvement of estimation accuracy by overcoming decorrelation and atmospheric effect. Necessity steps are going to be taken for the optimization of PS pixel selection in order to estimate deformation with high accuracy.

1.3   Research Objectives

The main objective of this study is to monitor surface deformation in Kuala Lumpur and neighbouring areas using PSInSAR technique. The sub-objectives of this research are listed as below:

1. to demonstrate the effectiveness of PSInSAR technique for monitoring long-term deformation using L-band SAR

2. to explore the potential of optimization of PSInSAR processing parameters in order to get better estimation of surface deformation

These considerations lead to the formulation of three research questions related to the objectives stated above.

1. How effective is the PSInSAR technique in monitoring deformation?

2. Does the optimization process of PS pixel selection improve the estimation of deformation in the study area?

1.4 Study Area

In this study, Kuala Lumpur and neighbouring areas was selected to test and evaluate the performance of PSInSAR technique for monitoring surface deformation as can be seen in Figure 1.1.
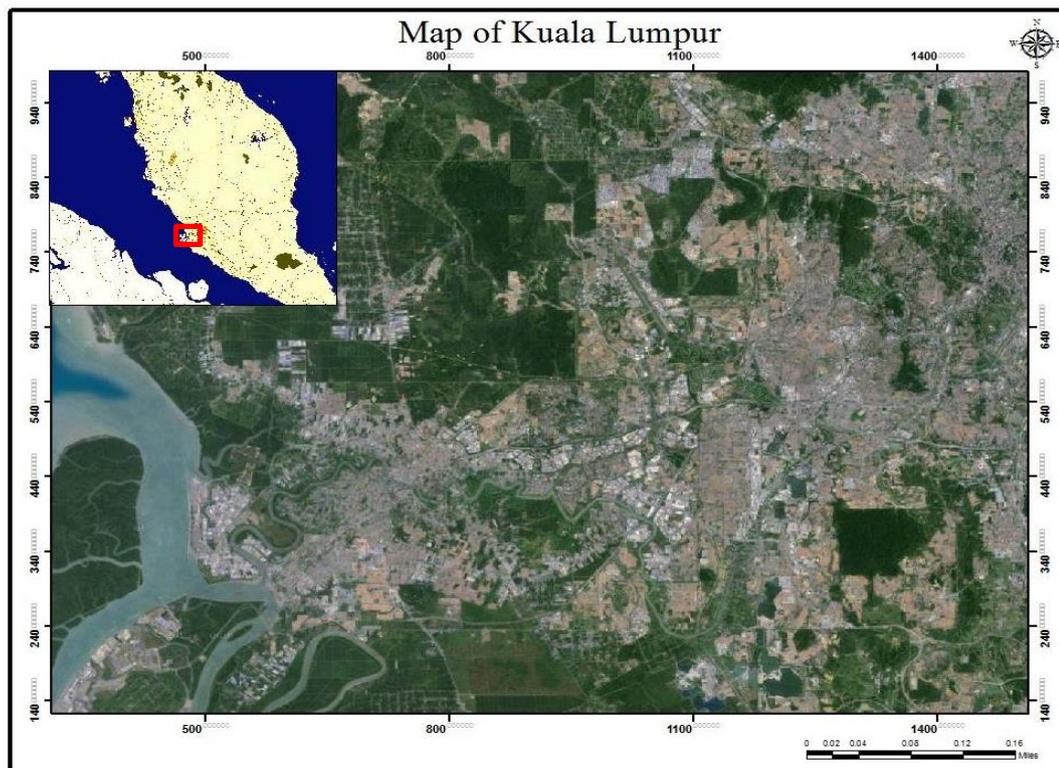
Figure 1.1: Location of Kuala Lumpur, Selangor

Kuala Lumpur (Figure 1.1), capital city of Malaysia, is considered as one of the fastest growing cities not only in Malaysia but also in South-East Asia. The land use in the study area is mainly peat swamp forest, plantation forest, inland forest, scrub, grassland, and ex-mining area (Konishi *et. al.,* 2006). The landform of the area ranges from very flat terrain, especially for the peat swamp forest, ex-mining, grassland and scrub area, to quite hilly area for the natural forest ranging between 0 and 420 m above sea level (Lee and Pradhan, 2007). Majority of the land use pattern consist of built-up areas include commercial, residential, institution, industrial recreational area, infrastructure and utilities (Khaki *et al.*, 2014). Since Kuala Lumpur is the ex-mining area, the geologic settings of Kuala Lumpur is mainly composed of limestone bedrock with estimated 1,850m thick, overlying graphitic schist known as Hawthornden Schis, granitic hills, and mine waste deposits especially in the Bandar Sunway area, a suburban of Kuala Lumpur (Kong and Komoo, 1990). Many building sites on limestone areas in Kuala Lumpur have encountered a weak soil zone that could possibly leads to dangerous situation such as sudden collapse especially when this city is made of numerous new and tall

buildings, with modern and postmodern architecture that filled the skyline, such as the Petronas Twin Towers.

1.5   Scope of Study

1. This study used ALOS PALSAR from ascending satellite tracks covering from February 2007 to January 2011. This sensor operated in longer wavelength (L-band, 23.6 cm) with 46 days repeat cycle. In general, ALOS PALSAR has high spatial resolution (8m of FBS and 16 m of FBD) as compared to other sensors such as ERS1/2 (25 m) and Envisat ASAR (30 m). Moreover, L-band sensor operated in longer wavelength (23.6 cm); hence, a better penetration in an object, resulting in high quality interferograms.

2. Apart from radar data, this study used precise orbital data (PRC) for accurate co-registration process and generation of flatten interferogram. Besides that, an external Digital Elevation Model (DEM) also was used for the generation of differential interferogram. This study used DEM from Shuttle Radar Topography Mission (SRTM) (90m at ground worldwide).

3. In order to fully evaluate the capability of PSInSAR processing for monitoring the surface deformation (uplift or subsidence), several parts of the study area were considered with their terrain characteristics and detected PS densities.

4. For the improvement of overall accuracy of the results, an optimization process was followed during the generation of interferograms. This includes selection of images pairs (reducing perpendicular and temporal baseline as

well as Doppler centroid difference), accurate co-registration process and phase unwrapping process.

5. An optimization of PSInSAR processing parameters settings was also carried out to remove the noisy PS and to get stable PS points. The strategy helps to increase the density of detected persistent scatterers and reduce noise especially in deforming areas. Based on previous studies, the optimazation was done considering several parameters *i.e.* 1) maximum acceptable spatial density (scatterers/km^2) of selected pixels with random phase, 2) maximum standard deviation of the phase noise, 3) spatially correlated filtering time window, 4) unwrapping grid cell size, 5) coarser resample size and 6) maximum standard deviation of the resampled pixels of phase noise.

6. This study was carried out in several districts in Selangor located in Peninsular Malaysia which is composed by limestone formation, granitic hills, and mine waste deposits. The study area has been selected due to the need of monitoring deformation in these areas considering their geological settings that generally has weak foundation for construction work and developments.

1.6   Significance of Study

The main contribution of this study is to evaluate the effectiveness of PSInSAR technique for monitoring deformation in different terrains, as current processes of conventional field based methods are too expensive, time consuming and requires long observation session considering the large area extend of the cities in order to get millimeter level accuracy (Genrich and Bock, 1992). Additionally, a long term land deformation monitoring using robust InSAR processing particularly

in the urban and sub-urban areas in Malaysia is hardly can be found in literature due to complexity of the processing technique and insufficient institutional support. Thus, findings from this study will promote the capabilities of PSInSAR technique as an important tool for surface deformation monitoring to quantify the structural changes in Malaysia together with quantitative interpretation. This technique (PSInSAR) can be optimized and eventually can be used potentially to assess hazards susceptibility at the regional scale with less effort as compared to other methods such as GPS.

In particular, this study is important as it can provide a fast and effective tool to local authorities to monitor ground deformation (slow/fast) and building behavior deformation at a relatively low cost. Slow deformation is usually hard to be detected as compared to fast deformation as it requires a long time observation. Hence, by taking the advantages of large achieves of radar data along with application of time-series technique such as PSInSAR, slow ground deformations as well as the historical deformation in the study areas can be easily detected and analyzed. This technique is particularly useful in Malaysia as the country is mostly suffered from slow deformations such as slow-landslides, subsidence, sinkhole and sediments which requires an accurate deformation analysis for implementing preventive measures. Furthermore, the use of PSInSAR for land deformation monitoring technique may also benefit the pace of development and maintenance of infrastructures in Malaysia by identifying safe areas for future infrastructures development which will ensure the safety of the civilians and the sustainability of the infrastructures.

1.7   Outline of Thesis

The thesis consists of six (6) main chapters. The chapters are as follows:

Chapter 1

This chapter which is the first chapter is basically a general overview of the research. This chapter introduces the report outlining the background of study, problem statement, study area, research objectives and significance of the research. The summaries of each chapter are also included in this chapter.

Chapter 2

The second chapter is about literature reviews. This chapter describes the essential definition as well as the history of radar satellites, followed by basic principles of synthetic aperture radar and reviews of InSAR basic theory and PSInSAR principles. This chapter also includes the details regarding the atmospheric delay and decorrelation of the signal and the proven capabilities of PSInSAR techniques to successfully resolve the limitation of previous used technique and also attempt to reduce the atmospheric and decorrelation noise signal.

Chapter 3

Third chapter discusses on the methodology and its procedures to fulfil the objectives of the research together with an overview methodology for validation of results. The DInSAR and PSInSAR processing are explained in details regarding the selected parameters and algorithm used in the processing based on the literature review, and the mathematical framework behind both processing are also included in Chapter 3.

Chapter 4

Chapter 4 is on the analysis of PSInSAR results in the study area. The preliminary results given by default settings are discussed followed by the optimization of several parameters. The study area has been classified into ten different areas and detail analysis of final PSInSAR results on each area was briefly discussed.

Chapter 5

Chapter 5 concentrated on the summarized and detailed discussion of the results using PSInSAR technique.

Chapter 6

This chapter conclude the findings of the study. For future work and references, some recommendations and comments were noted down.

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