

MONITORING LAND SUBSIDENCE OF AIRPORT USING INSAR TIME-SERIES  
TECHNIQUES WITH ATMOSPHERIC AND ORBITAL ERROR CORRECTIONS

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MONITORING LAND SUBSIDENCE OF AIRPORT USING INSAR TIME-  
SERIES TECHNIQUES WITH ATMOSPHERIC AND ORBITAL ERROR  
CORRECTIONS

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*A special mention to my beloved parent....*

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Hjh Nooraini binti Hj Yaacob ,**

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*To my siblings,*

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## ABSTRACT

Land subsidence is one of the common geological hazards worldwide and mostly caused by human activities including the construction of massive infrastructures. Large infrastructure such as airport is susceptible to land subsidence due to several factors. Therefore, monitoring of the land subsidence at airport is crucial in order to prevent undesirable loss of property and life. Remote sensing technique, especially Interferometric Synthetic Aperture Radar (InSAR) has been successfully applied to measure the surface deformation over the past few decades although atmospheric artefact and orbital errors are still a concerning issue in this measurement technique. Multi-temporal InSAR, an extension of InSAR technique, uses large sets of SAR scenes to investigate the temporal evolution of surface deformation and mitigate errors found in a single interferogram. This study investigates the long-term land subsidence of the Kuala Lumpur International Airport (KLIA), Malaysia and Singapore Changi Airport (SCA), Singapore by using two multi-temporal InSAR techniques like Small Baseline Subset (SBAS) and Multiscale InSAR Time Series (MInTS). General InSAR processing was conducted to generate interferogram using ALOS PALSAR data from 2007 until 2011. Atmospheric and orbital corrections were carried out for all interferograms using weather model, namely European Centre for Medium Range Weather Forecasting (ECMWF) and Network De-Ramping technique respectively before estimating the time series land subsidence. The results show variation of subsidence with respect to corrections (atmospheric and orbital) as well as difference between multi-temporal InSAR techniques (SBAS and MInTS) used. After applying both corrections, a subsidence ranging from 2 to 17 mm/yr was found at all the selected areas at the KLIA. Meanwhile, for SCA, a subsidence of about less than 10 mm/yr was found. Furthermore, a comparison between two techniques (SBAS and MInTS) show a difference rate of subsidence of about less than 1 mm/yr for both study area. SBAS technique shows more linear result as compared to the MInTS technique which shows slightly scattering pattern but both techniques show a similar trend of surface deformation in both study sites. No drastic deformation was observed in these two study sites and slight deformation was detected which about less than 20mm/yr for both study areas probably occurred due to several reasons including conversion of the land use from agricultural land, land reclamation process and also poor construction. This study proved that InSAR time series surface deformation measurement techniques are useful as well as capable to monitor deformation of large infrastructure such as airport and as an alternative to costly conventional ground measurement for infrastructure monitoring.

## ABSTRAK

Pemendapan tanah merupakan salah satu bencana geologi yang sering terjadi di seluruh dunia dan kebanyakannya disebabkan oleh aktiviti manusia termasuk pembinaan infrastruktur secara besar-besaran. Infrastruktur yang besar seperti lapangan terbang juga terdedah kepada masalah pemendapan tanah disebabkan oleh beberapa faktor. Oleh itu, pemantauan tanah mendap di lapangan terbang adalah penting untuk mengelakkan kerugian yang tidak diingini sama ada harta mahupun nyawa. Teknik penderiaan jauh, terutamanya radar apertur sintetik interferometer (InSAR) telah berjaya digunakan untuk mengukur perubahan bentuk muka bumi sejak beberapa dekad yang lalu walaupun artifak atmosfera dan ralat pada orbit masih menjadi isu dalam teknik pengukuran ini. Teknik multi temporal InSAR, iaitu lanjutan daripada InSAR, menggunakan set data pemandangan SAR yang besar untuk mengkaji evolusi temporal perubahan bentuk muka bumi dan mengurangkan ralat yang ditemui dalam satu interferogram tunggal. Kajian ini mengkaji pemendapan tanah untuk jangka masa yang panjang terhadap Lapangan Terbang Antarabangsa Kuala Lumpur (KLIA), Malaysia dan Lapangan Terbang Changi (SCA), Singapura dengan menggunakan dua teknik multi temporal InSAR iaitu garis asas bersubset kecil (SBAS) dan pengukuran siri masa InSAR pelbagai skala (MInTS). Proses asas InSAR dilakukan untuk menghasilkan interferogram dengan menggunakan data ALOS PALSAR dari 2007 hingga 2011. Pembedahan atmosfera dan orbit telah dijalankan ke atas semua interferogram menggunakan model cuaca iaitu julat pengantar ramalan cuaca pusat Eropah (ECMWF) dan teknik Peningkatan Secara Rangkaian sebelum membuat anggaran siri masa pemendapan tanah. Keputusan menunjukkan terdapat variasi pemendapan tanah selepas pembedahan (atmosfera dan orbit) serta perbezaan antara teknik-teknik InSAR (SBAS dan MInTS) yang digunakan. Selepas kedua-dua pembedahan dilakukan, pemendapan tanah antara 2 hingga 17 mm/tahun ditemui di semua kawasan yang terpilih di KLIA. Sementara itu, bagi SCA, pemendapan tanah kurang daripada 10 mm/tahun ditemui. Tambahan pula, perbandingan di antara kedua-dua teknik (SBAS dan MInTS) menunjukkan kadar perbezaan pemendapan tanah sebanyak kurang daripada 1 mm/tahun bagi kedua-dua kawasan kajian. Teknik SBAS menunjukkan hasil yang lebih linear berbanding dengan teknik MInTS yang menunjukkan sedikit corak serakan tetapi kedua-dua teknik menunjukkan arah aliran deformasi yang sama di kedua-dua kawasan kajian. Tiada deformasi permukaan yang ketara diperhatikan di kedua-dua tapak kajian dan sedikit deformasi permukaan dikesan iaitu kurang dari 20mm/tahun di kedua-dua kawasan kajian mungkin berlaku disebabkan oleh beberapa sebab termasuk penukaran guna tanah daripada tanah pertanian, proses penambakan tanah dan juga pembinaan yang tidak kukuh. Kajian ini membuktikan bahawa pengukuran siri masa deformasi permukaan menggunakan InSAR sangat berguna serta mampu untuk memantau deformasi di infrastruktur yang besar seperti lapangan terbang dan boleh digunakan sebagai alternatif kepada pengukuran konvensional di permukaan tanah yang mahal dalam pemantauan infrastruktur.

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## LIST OF SYMBOLS

|                     |   |
|---------------------|---|
| $\Delta\phi_{topo}$ | phase contribution from topographic phase   |
| $\Delta\phi_{defo}$ | phase contribution from some motion or deformation of the surface                   |
| $\Delta\phi_{flat}$ | phase contribution from the flat term   |
| $B_n$               | perpendicular baseline  |
| $B_p$               | parallel baseline   |
| $B_{\perp}$         | perpendicular baseline  |
| $\Phi_{ij}$         | pixel phase of the interferogram combining acquisition $i$ and $j$                  |
| $L^0$               | minimum spanning tree   |
| $L^1$               | minimum cost flow   |
| $R_1$ and $R_2$     | distance between the satellite and the target,                                      |
| $R_d$               | dry air specific gas constants (287.05 J.kg <sup>-1</sup> .K <sup>-1</sup> )        |
| $R_v$               | water vapour specific gas constants (461.495 J. kg <sup>-1</sup> .K <sup>-1</sup> ) |
| $S_1$ and $S_2$     | complex SAR images  |
| $S_k(i, j)$         | complex value of the master ( $k = 1$ ) or slave ( $k = 2$ ) scene pixel ( $i, j$ ) |
| $W_{ij}^{mn}$       | particular wavelet coefficient with index $mn$ in interferogram $ij$                |
| $d_{ij}(x, y)$      | value of the pixel at range $x$ and azimuth $y$                                     |
| $g_m$               | weighted average of the gravity acceleration between $z$ and $z_{ref}$              |
| $u_i$               | column vectors of U (M x M orthogonal matrix)                                       |
| $v_i$               | column vectors of U V(N x M orthogonal matrix)                                      |

|                    |   |
|--------------------|---|
| $Z_{ref}$          | reference altitude  |
| $\delta L_{LOS}^S$ | LOS single path delay   |
| $\delta\phi_n$     | pixel phase increment between acquisition time $n$ and $n + 1$    |
| $\rho_1$           | distance between satellite antenna and the pixel                  |
| $\sigma^o$         | backscattering coefficient  |
| $\omega_1$         | unknown phase due to the interaction of the wave and the ground   |
| $\omega_{mn}$      | reference frame shift for the interferogram                       |
| $\phi_{atmos}$     | phase contribution due to atmospheric phase delay                 |
| $\phi_{path}$      | phase contribution due to path length                             |
| $\phi_{pixel}$     | phase contribution due to individual scatterers within SAR pixels |
| $\Delta\rho$       | cross-track slant range   |
| $\Delta\phi$       | phase different   |
| $c$                | speed of light  |
| $e$                | altitude ambiguity  |
| $e$                | water vapour partial pressure in Pa,                              |
| $h$                | terrain height  |
| $H$                | spacecraft height   |
| $I(i, j)$          | interferogram phase of the $(i, j)$ pixel and                     |
| $L$                | length of radar antenna   |
| $N$                | geoid separation  |
| $P$                | dry air partial pressure in Pa                                    |
| $Q(u, v)$          | filter response   |
| $R$                | range   |
| $T$                | temperature in K  |
| $t$                | time  |
| $Z(u, v)$          | Fourier transformation of interferometric phase                   |
| $\Delta R$         | slant range resolution  |
| $\Delta\theta$     | look angle  |
| $\alpha$           | horizontal baseline angle   |
| $\alpha$           | filter parameter between zero and one                             |
| $\beta$            | radar bandwidth   |

|              |   |
|--------------|---|
| $\gamma$     | coherence                                   |
| $\delta\phi$ | phase corrected for the curved Earth effect |
| $\theta$     | off nadir radar look angle                  |
| $\theta$     | look angle                                  |
| $\lambda$    | wavelength                                  |
| $\pi$        | constant(3.142)                             |
| $\rho$       | nominal slant range                         |
| $\tau$       | pulse length                                |
| $\phi$       | phase                                       |

## LIST OF ABBREVIATIONS

|         |  |
|---------|--|
| 2D      | 2 Dimensional  |
| 3D      | 3 Dimensional  |
| ALOS    | Advanced Land Observing Satellite                    |
| APS     | Atmospheric Phase Screen                             |
| ASAR    | Advanced Synthetic Aperture Radar                    |
| AUIG2   | ALOS- PALSAR-2/ALOS PALSAR User Interface Gateway    |
| CPT     | Coherent Pixels Technique                            |
| DEM     | Digital Elevation Model                              |
| DInSAR  | Differential InSAR                                   |
| DORIS   | Delft Object-Oriented Radar Interferometric Software |
| DWT     | Discrete Wavelet Transforms                          |
| EB      | Evidential Belief                                    |
| ECMWF   | European Center for Medium range Weather Forecasting |
| ENVISAT | Environmental Satellite                              |
| ERA-I   | European Center for Medium-Range Weather Forecast    |
| ERS     | European Remote Sensing Satellite                    |
| FBD     | Fine Beam Dual Polarization                          |
| FBS     | Fine Beam Single Polarization                        |
| FM      | Frequency Modulation                                 |
| FR      | Frequency ratio                                      |
| FWT     | Fast Wavelet Transform                               |
| GAM     | Global Atmospheric Models                            |
| GIAnt   | Generic InSAR Analysis Toolbox                       |
| GPS     | Global Positioning System                            |
| HDF     | Hierarchical Data Format                             |

|          |   |
|----------|---|
| HKIA     | Hong Kong International Airport                                 |
| InSAR    | Spaceborne Interferometric Synthetic Aperture Radar             |
| ISBAS    | Intermittent Small Baseline Subset                              |
| ISCE     | InSAR Scientific Computing Environment                          |
| IWT      | Inverse Wavelet Transform                                       |
| JAXA     | Japan Aerospace and Exploration Agency                          |
| JERS     | Japan Earth Resources Satellite                                 |
| JPL      | Jet Propulsion Laboratory                                       |
| KLIA     | Kuala Lumpur International Airport                              |
| LCCT     | Low cost carrier terminal                                       |
| LOS      | Line-Of-Sight   |
| LS       | Least Square  |
| MAI      | Multiple Aperture Interferogram                                 |
| MERIS    | Medium Resolution Imaging Spectrometer Instrument               |
| MERRA    | Modern Era Retrospective-Analysis for Research and Applications |
| MInTS    | Multiscale InSAR time series                                    |
| MM5      | Mesoscale Meteorological Model                                  |
| MODIS    | Moderate Resolution Imaging Spectroradiometer                   |
| MT-InSAR | Multi-temporal InSAR  |
| NARR     | North American Regional Reanalysis                              |
| NASA     | National Aeronautics and Space Administration                   |
| NSBAS    | New-SBAS  |
| PALSAR   | Phased Array type L-band Synthetic Aperture Radar               |
| PolSAR   | Polar-orbiting satellite  |
| PS       | Permanent Scatterers  |
| PSI      | Persistent Scatterer Interferometry                             |
| PyAPS    | Python Atmospheric Phase Screen                                 |
| Radar    | Radio Detection and Ranging                                     |
| RADARSAT | RADAR SATellite   |
| RMS      | Root mean square  |
| ROC      | Rate of Change  |
| SAR      | Synthetic Aperture Radar  |
| SB       | Small Baseline  |

|        |  |
|--------|--|
| SBAS   | Small Baseline Subset  |
| SCA    | Singapore Changi Airport   |
| SCH    | S is the local along track direction, C is the cross track direction, and H is the height above the approximating sphere |
| SEASAT | Sea Satellite  |
| SLC    | Single Look Complex  |
| SNAPHU | Statistical-cost, Network-flow Algorithm for Phase Unwrapping  |
| SNR    | Signal Noise Ratio   |
| SRTM   | Shuttle Radar Topography Mission   |
| StaMPS | Stanford Method for Persistent Scatterers  |
| SVD    | Singular Value Decomposition   |
| TEC    | Total Electron Content   |
| UK     | United Kingdom   |
| WGS    | World Geodetic System  |

**LIST OF APPENDICES**

- Appendix A**            The interferograms pair of KLIA after atmospheric correction by using ECMWF for coherence threshold limit zero (0)
- Appendix B**            The interferograms pair of KLIA after atmospheric correction by using ECMWF for coherence threshold limit 0.2
- Appendix C**            The interferograms pair of SCA after atmospheric correction by using ECMWF for coherence threshold limit zero (0)
- Appendix D**            The interferograms pair of SCA after atmospheric correction by using ECMWF for coherence threshold limit 0.2
- Appendix E**            The interferograms pair of KLIA after the orbital correction for coherence threshold zero (0)
- Appendix F**            The interferograms pair of KLIA after the orbital correction for coherence threshold 0.2
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## **CHAPTER 1**

### **INTRODUCTION**

This chapter explores the background of the study, problem statement and research objectives. It describes in brief the significance of this research and the outline of this thesis.

#### **1.1 Background of the Study**

Over the last few decades, land subsidence has become a global problem due to several factors like groundwater extraction, sinkhole or underground mine collapse, rapid land development, natural hazard and so on (Zizzi, 2013). This phenomenon can take place slowly, becoming evident over a time span of many years, where the land surface starts to subside and sink due to either geological or human activities (Liu *et al.*, 2008). Land subsidence can lead to great economic losses (Motagh *et al.*, 2007; Liu *et al.*, 2008) and many other problems, including changes in elevation; damage to structures such as storm drains, sanitary sewers, roads, railroads, canals, levees, bridges, public and private buildings and so on. Additionally, land subsidence may cause serious harm to flood control drainage, land

use, urban planning, construction and transportations (Zhou and Zhao, 2013). The increasing development of land plays an important role in occurring land subsidence around the world. Abidin *et al.* (2009) discussed the relation between land subsidence and urban development activities and found that the spatial and temporal variations of land subsidence depend on the corresponding variations of groundwater extraction, coupled with the characteristics of sedimentary layers and building loads.

Land subsidence associate with groundwater level decline has been recognized as a potential problem in various parts of the world. Important cities such as London, Venice, Mexico, Jakarta, Tokyo, *etc.*, have experienced land subsidence due to over-extraction of groundwater for domestic and industrial purposes (Sahu and Sikdar, 2011). Most cities usually have big infrastructures like bridges, tunnels, highways, railways, airports, seaports, power plants, dams, wastewater projects, oil and natural gas extraction projects, public buildings, information technology systems, aerospace projects, and weapons systems (Gupta *et al.*, 2009). These infrastructures on the land are most likely to subside due to several factors especially the ability of the land to accommodate the pressure from the big infrastructures. For example, Mexico City has sunk about 30 feet in the last century due to its exponential growth (Huby, 2001) and severe land subsidence due to consolidation of the lacustrine aquitard caused by aquifer exploitation (Ortega-Guerrero *et al.*, 1999).

Monitoring land subsidence is very crucial especially in area where massive infrastructures have been developed in order to carry out different kinds of activities. Several methods are used to monitor the land subsidence, including levelling, total station survey, and Global Positioning System (GPS) field survey. Levelling survey has been traditionally used for monitoring the land subsidence (Odijk *et al.*, 2003) but this technique is expensive and time consuming since it requires a lot of field workers and only allows detection of subsidence over a very small area (Strozzi *et al.*, 2001). Moreover, the precise levelling is usually required a wide network of benchmark for the subsiding area. The used of total station is commonly seen since this method can maintain the considerable accuracy for many public works such as road, airport and city (Lee and Rho, 2001). Both levelling survey and total stations

survey can deliver 0.1mm height change accuracy (Ge *et al.*, 2004). Besides that, GPS is also used to detect deformation with millimeter to centimeter accuracy on localized areas (Cao *et al.*, 2008). However, GPS observations require logging times from one to several hours for each baseline to achieve high precision. This expenditure is also highly time consuming and impracticable for many engineering works and ground reconnaissance survey (Gili *et al.*, 2000).

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is a valuable technique for measuring surface deformation which has been introduced more than a decade ago and has become an important part of deformation monitoring (Hooper, 2008; Samsonov *et al.*, 2010). The technique of InSAR relies on combining phase information from two or more SAR acquisition of the same area captured at different times from a similar platform to produce an interferogram (Massonet and Feigl, 1998). This process shows range changes in the view direction between the platform and the Earth's surface, and can be further proceed with a topographic model to detect ground deformation up to cm or sub-cm level of precision (Massonet, 2008; Samsonov *et al.*, 2010; Liu *et al.*, 2014). InSAR offers the typical advantages like data acquisition over inaccessible areas, wide area coverage, its competitive cost, data availability, and its high vertical accuracy for remotely measuring the deformation of the ground and manmade structures from space (Crosetto *et al.*, 2008; Simon and Rosen, 2007).

Nevertheless, the InSAR phase is sensitive to the terrain topography and relative changes in the elevation occurring between two SAR antenna passes over the same area. If the terrain topography of the images scene are available, *i.e.* a DEM (Digital Elevation Model), the corresponding phase component can be subtracted from the InSAR phase, leaving the component due to the terrain surface deformation is a process called Differential InSAR (DInSAR) technique (Fan *et al.*, 2011). DInSAR technique provide high resolution ground deformation at regional level along the line-of-sight direction between the satellite antenna and the ground surface by exploiting the phase difference between two time-separated complex SAR image acquired under similar geometric condition (Massonet *et al.*, 1993,1995; Amelung *et*

*al.*, 2000; Fialko *et al.*, 2005; Shankar, 2013). It has been widely used in a number of types of applications like earthquake displacement (Massonet *et al.*, 1993), volcano deformation (Massonet *et al.*, 1995), glacier dynamics (Goldstein *et al.*, 1993; Joughin, 1996, Mohr *et al.*, 1998), and land subsidence (Strozzi and Wegmuller, 1999; Strozzi *et al.*, 1999; Fruneau *et al.*, 1999; Ferretti *et al.*, 1999; Strozzi *et al.*, 2000) considering its usefulness to monitor land subsidence effectively over the conventional InSAR technique.

Despite the successful use of InSAR/DInSAR technique for the deformation monitoring, the limitation as well as the complexity of the processing for this technology should not be taken lightly. The complexity of the processing include several steps of computation such as baseline estimation, focusing, coregistration, generation of interferogram, filtering and phase unwrapping which need to be performed carefully based on the data and type of surface feature under investigation. Besides, this technique is highly sensitive to atmospheric conditions (Wegmuller *et al.*, 2006; Meyer *et al.*, 2006; Chen and Zebker, 2012; Chapin *et al.*, 2006; Jung *et al.*, 2013) and orbital errors (Kohlhase *et al.*, 2003; Shirzaei and Walter, 2011; Liu *et al.*, 2014). The orbit influence can easily be distinguished from deformation influences but that error makes the interferogram look sloped and the deformation spots often cannot be recognized (Capková, 2005). Since satellite propagates the signals through the atmosphere, the signal might either have propagation delay or bending effect (Rosen *et al.*, 2000; Ding *et al.*, 2004; Balaji, 2011). However, most of the signals have the propagation delay because of the effect from the troposphere and ionosphere which are known as the main error in atmosphere (Ferretti *et al.*, 2001; Mora *et al.*, 2003; Werner *et al.*, 2003; Hooper *et al.*, 2004; Lanari *et al.*, 2004; Kampes, 2006; Chen and Zebker, 2012).

Recent development of numerous algorithms that combine phase information from multiple radar interferograms and produce internally consistent time-series of land surface deformation have the ability to overcome atmospheric as well as the orbital errors (Ferretti *et al.*, 2001; Berardino *et al.*, 2002; Hetland *et al.*, 2012). Combining multiple interferogram allows detection and quantification of both

secular and transient displacement and these methods also help to mitigate the effects of change in scatterer properties and phase delay introduced by the orbit and atmosphere between SAR acquisitions, resulting in measurements of surface deformation with subcentimeter accuracy (Hanssen and Klees, 1998; Bürgmann, 2000; Hetland *et al.*, 2012). Many efforts have been made to minimize troposphere error such as by computing the phase delay using global meteorological reanalysis data (Jolivet *et al.*, 2011), using wavelet transform (Shirzaei and Burgmann, 2012), formation of atmospheric model (Wadge *et al.*, 2002), and atmospheric phase screen filters (Puysegur *et al.*, 2007). Efforts have also been made to remove orbital error using a bilinear or biquadratic model (Amelung *et al.*, 2007), using a function in terms of the standard deviation of the velocity gradient in range and azimuth direction, (Fattahi and Amelung, 2014), using wavelet multiresolution analysis and robust regression approach (Shirzaei and Walter, 2011).

Nevertheless, the conclusion can be drawn from the above background information is that monitoring land subsidence is important and it can be done using InSAR technique although several limitations of this approach have been highlighted in the literatures. The use of time series InSAR technique is surely an attractive approach to measure the land subsidence which can incorporate several SAR interferograms and techniques to overcome atmospheric disturbance and the orbital decorrelation. Despite, the results of accurate measurements for land deformation from previous study demonstrated the usefulness of the InSAR time series approach for different types of land surfaces. However, hardly any study can be seen in the literature where this time series approach has been used to monitor big infrastructures such as airport although massive infrastructural development has been occurred in the airport area.

## 1.2 Problem Statement

It is overwhelmingly that land subsidence is a severer threat to large infrastructures such as buildings, dams, bridges, roads, and so on. Similar to the other infrastructures, airport, which is considered as the centre of the modern communication system, is susceptible to have land subsidence problem due to several reasons (Liu *et al.*, 2001; Jiang and Lin, 2010; Zhao *et al.*, 2011). Monitoring the subsidence of airport is important, not only considering the sustainability of the infrastructure but also in order to prevent undesirable loss of property and life because subsidence can cause severe accident during take-off and landing of airplanes. Remote sensing techniques specifically InSAR technique can be used to monitor land subsidence at airport with high spatial accuracy. Several studies have successfully demonstrated the capability of InSAR to monitor the land subsidence at airport but most of the studies investigation focused on airports that are built on the reclaimed land (Liu *et al.*, 2001; Ding *et al.*, 2004; Zhao *et al.*, 2011) or high latitude permafrost environment (Short *et al.*, 2014). Nevertheless, there are many airports that have not been developed on the reclaimed lands but can still be affected by the land subsidence due to natural or human activities especially underground water or hydrocarbon extraction (Ding *et al.*, 2004; Aly *et al.*, 2009; Bhattacharya, 2013), therefore, the airports area need to be investigated with an effective monitoring system in order to monitor the sustainability.

Kuala Lumpur International Airport (KLIA) and Singapore Changi Airport (SCA) are the two busiest airports in the South East Asia region and these airports are the main airport of Malaysia and Singapore respectively. KLIA was built in 1998 with an area about 100km<sup>2</sup> on an agricultural land which has the capacity to handle 70 million passengers and 1.2 million tonnes of cargo per year (Airports-Worldwide, 2004). On the other hand, SCA airport was built in 1981 at the eastern tip of the main island at Changi, where the airport would easily be expanded through land reclamation. It is about 17.2 km northeast from the commercial centre in Changi, on a 13km<sup>2</sup> site (Bonny, 2001). KLIA is 16 year old and due to the rapid pace of development, parts of Malaysia, especially in the Kuala Lumpur, have experienced

unprecedented growth rates with development areas increasing and because of the shortage of land, the city is expanded over high-risk ground, such as hilly terrain, areas with karstic bedrock, ex-mining land, peat and soft sediment areas. The existences of geohazards such as landslides and sinkholes have affected the urban dwellers (Chand, 1998). Besides that, SCA is a hydraulic sand filled project with associated soil improvement works and this man-made structure is still in expanded process from time to time due to high demands for air travel that expected to grow in the coming years (Choa, 1994). However, although these two airports are the busiest airport in the world, more than one decade old and several extending work have been done, no robust system have been developed to monitor the land deformation as well as the infrastructural sustainability especially using InSAR technique.

Indeed, monitoring the land subsidence of airport using InSAR technique is an attractive approach but this technique is not easy to implement without an appropriate data processing strategy in order to get better estimation accuracy. However, in general, the difficulties of InSAR data processing can be seen with respect to few perspectives which includes i) baseline determination, ii) co-registration, iii) coherence determination, iii) interferogram generation, iv) interferogram filtering, v) phase unwrapping (Zebker *et al.*, 1992), as there is no clear cut rule that can be followed for each processing step. As a matter of fact, the five aforementioned processing steps are mostly relied on several factors such as sensor and wavelength, data availability, types of land feature/target under investigation, accuracy requirement, and availability of the required software or algorithm.

Nevertheless, other than the SAR processing problem, an interferogram contain four error components due to orbital error, residual topography error, atmospheric noise (mainly tropospheric artefact) and decorrelation noise (Zebker *et al* 1997; Hanssen, 2001; Puyseegur *et al.*, 2007; Liu *et al.*, 2014). Although some errors such as topographic error and decoloration error can be reduced systematically, atmospheric noise (tropospheric artefact) and orbital errors are the major source of error in the SAR data that need to be treated carefully. The

troposphere contains approximately 75% of the atmosphere's mass and 99% of its water vapour and aerosol (Meteoblue, 2006). The major contribution to the phase delay is the highly variable water vapour content in the troposphere (Lofgren *et al.*, 2010). The spatial and temporal variability of tropospheric water vapour modifies the refractivity of radio wave passing between satellite and the ground (Wadge *et al.*, 2002; Jolivet, 2011). The pattern and amplitude of the atmospheric phase delay shows limitation on the measurement of low amplitude and large spatial wavelength signal related to interseismic deformation (Wright *et al.*, 2004). Besides that, the orbital error is considered as the main limitation in InSAR. The variations in the radial and cross-track components of the orbital error during the SAR acquisition generate the orbital fringes, the so-called phase ramp, which is often parallel to the satellite track and may also generate the perpendicular fringes (Hanssen, 2001). In order to reduce the effects of orbital error, for the case of topography height estimation, tie points or ground control points can be used to constrain the reference phase at certain points in each interferogram (Massonnet and Feigl, 1998; Hanssen, 2001; Lundgren *et al.*, 2009)

Multi temporal InSAR technique is an extension of InSAR that use large sets of SAR scenes to investigate the temporal evolution of deformation and mitigate errors found in single interferograms (Wortham, 2014). Stacking or averaging of interferograms is the simplest form of multi temporal processing (Sandwell and Price, 1998) which assumes that the deformation is linear, and uses the stack average to estimate a constant deformation rate. Other multi-temporal approaches include Persistent Scatterer InSAR (PS-InSAR) technique (Ferreti *et al.*, 2001; Werner *et al.*, 2003; Hooper *et al.*, 2004) which analyses the temporal signal on specific targets and small baseline (SB) (Berardino *et al.*, 2002; Mora *et al.*, 2003) technique which selects the most reliable pairs according to temporal and spatial baselines. Other than that, another multi-temporal technique proposed by Hetland *et al.* (2012) called as Multiscale InSAR time series (MInTS) which is based on wavelet decomposition of the interferogram in space and a general parametrization in time is a new multi temporal approach to extracting spatially and temporally continuous ground deformation from InSAR data (Agram, 2013).

Therefore, considering the several issues in the problem statement such as i) the necessity of monitoring land subsidence/land deformation of these two busiest airports, ii) the effectiveness of InSAR time series techniques especially SBAS and MInTS for the estimation of land subsidence/land deformation, iii) lack of investigations in the literature for monitoring land subsidence/land deformation using InSAR technology especially in the study areas, and iv) availability of long-term SAR data from different satellite sensors, this research is going to take an opportunity to study long term (2007-2011) land subsidence/land deformation at the KLIA and SCA using data from ALOS PALSAR satellite. Removal of atmospheric artificial and orbital error from the interferogram and the estimation of displacement were done using SBAS and MInTS techniques.

### **1.3 Research Objectives**

The overall objective of this research is to monitor the long term land surface deformation at KLIA and SCA using time series InSAR techniques. The sub-objectives of this research are listed as below:

1. To examine the impact of atmospheric (tropospheric) as well as orbital correction on the improvement of land deformation estimation accuracy
2. To compare the results of the land surface deformation between two different time series InSAR techniques which is SBAS and MInTS
3. To investigate the deformation pattern of the airports which was built on two different types of land which is in agricultural land (KLIA) and reclaimed land (SCA)

Regarding to objective one, the research questions are as follows:

- 1 How much is the impact of tropospheric and orbital errors on the land subsidence estimation?
- 2 What is the different of land subsidence estimation before and after both corrections are going to be applied?

Regarding to objective two, the research questions are as follows:

1. What are the different of land subsidence measurements obtained using these two techniques?
2. Which technique is the most stable for land surface deformation monitoring?

Regarding to objective three, the research question are as follows:

1. Do the different types of land uses affect the land subsidence at the KLIA and SCA?

#### 1.4 Scope of the Study

1. This study used SAR data since it has wide application in mapping of the surfaces of the Earth as well as monitoring ground subsidence from a variety of causes, in particular subsidence due to water extraction from underground reservoirs and subsidence in reclaimed land.
2. A long-term data were obtained in order to study the long-term deformation in the study areas. The data from ALOS PALSAR sensor were downloaded and used for this study as these sensors can provide data with reasonable spatial and temporal resolution.
3. KLIA and SCA have been chosen as the area of interest since these two airports are the most important infrastructures for both countries in context of communication, business, and social connection.
4. Due to its availability and the satellite revisit time at the study areas, the SAR data from 2007-2011 were used for both study sites which are KLIA and SCA. Start with 15 SAR raw data for KLIA and 14 SAR raw data for SCA, the data were processed using in order to generate DInSAR and further were continued to estimate the land subsidence at both study area.
5. An external data like Digital Elevation Model (DEM) were used to generate interferogram using DInSAR technique. Shuttle Radar Topography Mission (SRTM) (~90 m) data were used and this DEM data is free and spatial coverage is available for the study areas.

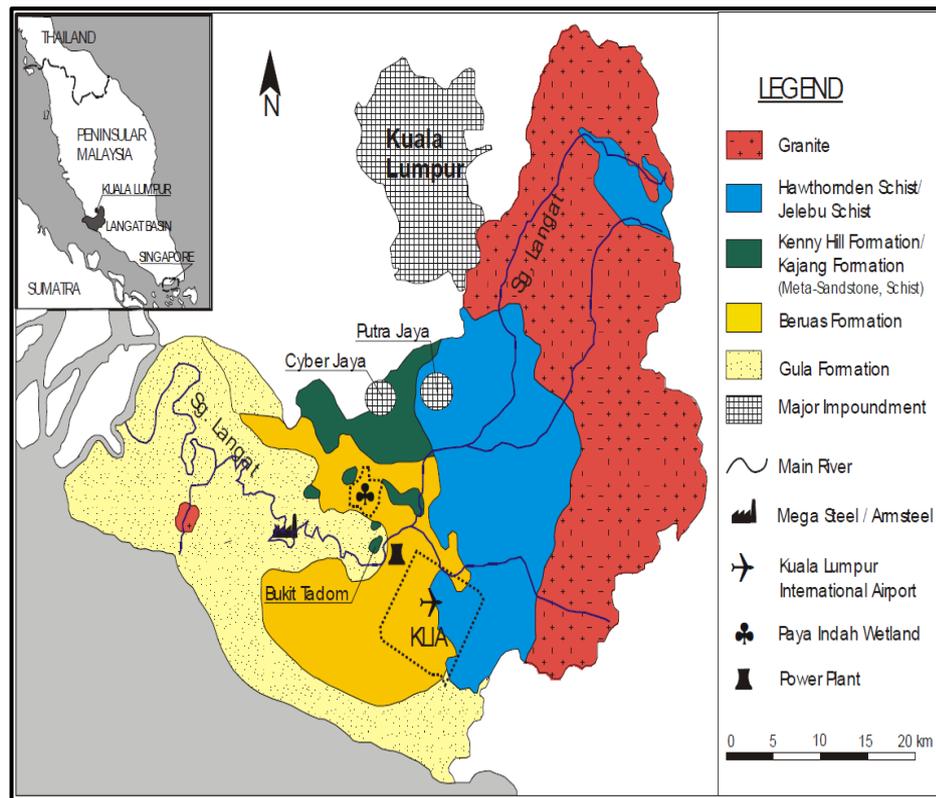
6. Generation of differential interferogram which involves focusing, coregistration, interferogram and coherence generation, filtering, phase unwrapping and geocoding were first done using InSAR Scientific Computing Environment (ISCE) software because it offers to the scientific community an open-source, modular and extensible computing environment.
7. After the interferogram were unwrapped, the atmospheric correction were applied to the unwrapped interferogram by using atmospheric weather model *i.e.* European Center for Medium range Weather Forecasting (ECMWF)
8. After the atmospheric correction was applied to each unwrapped interferogram, the orbital effects on interferograms were estimated independently using the network de-ramping method.
9. Time series estimation of land subsidence from the interferogram using 1) SBAS where data pairs were characterized by small spatial and temporal separation between acquisitions and 2) MInTS which operates in the spatial wavelet domain were used
10. Both atmospheric and orbital error corrections and also the deformation detection for both study area were processed in software named Generic InSAR Analysis Toolbox (GIANt).

## 1.5 Study Area

In this study, two study sites were examined in order to evaluate the land subsidence measurement. As can be seen in Figure 1.1, the first selected study site is the KLIA (02°44'36"N, 101°41'53"E) located in the Langat Basin. Langat basin can be divided into 3 distinct zones; the mountainous zone of the northeast corner of Hulu Langat district, the hilly area characterized by gentle slopes spreading widely from north to the east in the middle part of Langat basin and third zone is a relatively flat alluvial plane located in the southwest of Langat Basin (Idrus, 2004).

KLIA is the main and largest airport in Malaysia with an area about 100 km<sup>2</sup>. KLIA was opened officially on June 27, 1998. It is designed and built to be an efficient, competitive and world-class airport for the Asia-Pacific Region (Airports-Worldwide, 2004). KLIA is completed with the latest technology and state-of-the-art facilities, aims at providing maximum passenger safety, comfort and convenience. It is a unique airport which has facility for business, entertainment and relaxation.

Moreover, it is important to note that it was built on agricultural land which was used before for rubber and palm oil plantations and Langat Basin has a history of groundwater extraction (Bringemeier, 2001). Based on the results of the detailed hydrogeological, geophysical exploration and numerical groundwater modelling, the fractured, jointed and partially weathered meta-sandstone beds forming the Palaeozoic basement rocks at KLIA and KLIA2 has been identified as potentially productive fractured rock aquifers.



**Figure 1.1** Map of Langkat Basin (Source: Bringemeier, 2001)

The other selected study site is the SCA (Figure 1.2) which indeed the world's most highly acclaimed airports (Park, 1997). It was opened in 1981 with a design capacity of 12 million passengers a year. It is located about 17.2 km northeast from the commercial center in Changi, on a 13 square kilometres site. It has three passenger terminals with a total annual handling capacity of 66 million passengers (Bonny, 2001).

This airport could claim to be the region's first real international hub, being strategically located at the crossroads between Europe and the Far East, and the Far East and Australasia (Paylor, 1994). It is one of the largest single development projects in Singapore's history and was built in reclaimed land. The land reclamation work is a process of placing fill geomaterials on existing geological formations over a large extent. The geological conditions will significantly affect the planning, design and implementation of a land reclamation and ground improvement project (Bo and Chu, 2006). For Changi Airport, the land-reclamation was carried out to

extend the land at the foreshore of the eastern part of Singapore. The area reclaimed is about 2000 hectares and it is used for the airport runway, taxiways and the terminal buildings. The depth of seabed at the reclamation area ranges between 2 metres and 15 metres being much deeper at the northern edge of the area (Arulrajah, 2008).



**Figure 1.2** Singapore Changi Airport (red circle) which built on reclaimed land (Source: Utehas, 2016)

## 1.6 Significance of the Study

Monitoring of land subsidence is crucial for several purposes include avoiding unwanted damage of property and loss of valuable life. Airport is a big infrastructure where thousands of people are gathered together and used hundreds of flight in order to perform the valuable journey from one place to another place.

Ground surface of an airport especially the runway is very important and sensitive part. Any unexpected land subsidence at the runway or ground surface can cause severe threat to human life and property. Therefore, an airport needs to be monitored for land subsidence with an effective technique.

This study is going to find out an efficient technique for the monitoring of land subsidence of two busiest airports in Southeast Asian region, hence, undoubtedly this research is important and would be beneficial for Malaysia and Singapore and also for several agencies, in particular for those who are interested in land subsidence monitoring. Some of the specific significance of this study can be highlighted as follows:

- 1 As a new technique, the result can be very useful to improve the monitoring system of airport in Malaysia and Singapore and can obtain a great level of accuracy.
- 2 It can improve capability to predict future subsidence in new area or in the existing land subsidence areas at the airports.
- 3 This study would be very helpful for the airport management in order to detect the potential location of suspected subsidence area.
- 4 The method will be very useful source for any agencies who are interested to apply this method for the other airports or other infrastructures in Malaysia and Singapore.
- 5 As a reference for future research to explore more about InSAR technique for other purposes like landslide which occurs frequently in Malaysia.

## 1.7 Thesis Outline

This thesis has been divided into six chapters which are as follows:

**Chapter 1** provides general overview of the main topic of this research work, problem statement, research identification which includes research aim, objective and research questions, scope of the study, study area and significance of the study.

**Chapter 2** provide a literature review on related works including the InSAR technique, error in InSAR data like tropospheric and orbital effects, the used of SBAS and MInTS technique and also previous method used in order to correct both effects and the land subsidence monitoring at airports.

**Chapter 3** the methodology and details about the data processing and datasets are explained. The parameters related to this topic are described and advantages and disadvantages for the chosen method are stated in this chapter.

**Chapter 4** the results and analysis of the processing were shown which include the DInSAR generation, the corrected interferogram after the tropospheric and orbital correction were applied and the time series results for both technique.

**Chapter 5** the overall process from the start to end and the possible reasons for what is happening based on the results were discussed.

**Chapter 6** the conclusion and recommendation for this thesis were drawn.

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